Advanced Turbine System (ATS) Program Conceptual Design and Product Development

**Quarterly Report
December 1, 1995 - February 29, 1996**

Work Performed Under Contract No.: DE-AC21-93MC30244

For
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REPORTING PERIOD 12/1/95 - 2/29/96

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1.0 EXECUTIVE SUMMARY

GE Advanced Turbine Systems Program

GE has achieved a leadership position in the worldwide gas turbine industry in both industrial/utility markets and in aircraft engines. This design and manufacturing base plus our close contact with the users provides the technology for creation of the next generation advanced power generation systems for both the industrial and utility industries. GE has been active in the definition of advanced turbine systems for several years. These systems will leverage the technology from the latest developments in the entire GE gas turbine product line. These products will be USA-based in engineering and manufacturing and are marketed through GE Power Systems.

Achieving the Advanced Turbine Systems (ATS) goals of 60% efficiency, single-digit NO_x, and 10% electric power cost reduction imposes competing characteristics on the gas turbine system. Two basic technical issues arise from this. The turbine inlet temperature of the gas turbine must increase to achieve both the efficiency and cost goals. However, higher temperatures move in the direction of increased NO_x emissions. Improved coatings and other materials technologies along with creative combustor design can result in solutions which will achieve the ultimate goal.

GE's view of the market, in conjunction with the industrial and utility objectives, requires the development of Advanced Gas Turbine Systems which encompass two potential products: a new aeroderivative combined-cycle system for the industrial market, and a combined-cycle system for the utility sector that is based on an advanced frame machine.

The GE Advanced Gas Turbine Development program is focused on two specific products:

1. A 70 MW class industrial gas turbine based on the GE90 core technology utilizing an innovative air cooling methodology;
2. A 200 MW class utility gas turbine based on an advanced GE heavy-duty machine utilizing advanced cooling and enhancement in component efficiency.

Both of these activities require the identification and resolution of technical issues critical to achieving ATS goals. The emphasis for the industrial ATS will be placed upon innovative cycle design and low emission combustion. The emphasis for the utility ATS will be placed on developing a technology base for advanced turbine cooling, while utilizing demonstrated and planned improvements in low emission combustion. Significant overlap in the development programs will allow common technologies to be applied to both products. GE Power Systems is solely responsible for offering GE products for the industrial and utility markets. The GE ATS program will be managed fully by this organization, with core engine technology being supplied by GE Aircraft Engines (GEAE), and fundamental studies supporting both product developments being conducted

by GE Corporate Research and Development (CRD). GE's worldwide experience in commercialization of these products will ensure that the ATS program can proceed to the marketplace.

2.0 ATS PHASE 2 PROGRAM STATUS

GE Power Generation has continued work on the ATS Phase 2 contract. At the request of DOE/Morgantown, an expanded scope of work was proposed, and has been accepted. The tasks in the expanded work scope are shown in Table 2-1. The period of performance for Phase 2 has been extended from 8/25/93 - 9/15/95 to 8/25/93 - 3/31/96. GE Power Generation has requested an extension of the Phase 2 effort to 8/15/96 in order to continue to acquire data in Task 8.3 that is currently in progress.

The status of Task 1 through Task 8 is given in Table 2-2, and graphic representations are shown in Figures 2-1 and 2-2. The ATS Phase 2 program is on schedule for completion by 3/31/96, with the exception of the long-term testing. The final report is planned for submission 8/15/96.

Table 2-1

1	Preliminary Design	6
2	Coolant Purity	8.1
3	Advanced Seals	8.4
4	Rotational Heat Transfer	8.6
5	Effect of Hot Fuel on Combustion Dynamics	8.7
6	Rotor Materials Coolant Compatibility	8.2
6P	Nozzle Cascade Prel. Test & Facility Qualification	8.7
7	TBC Testing and Analysis	8.3
8	LCF Life and Crack Propagation	8.3
9	Turbulence Intensity Probes	8.7
12	Bond Coats for Improved TBC Thermal Cycle Life	8.3
13	Rotational Heat Transfer-Wheel-space Cooling	8.6
15	Short Liner	8.7
16	Turbulent Heat Transfer-Static Components	8.7
18	Critical TBC Properties	8.3
19	Increased Mach Number Diffuser Design	8.7
20	Transition Piece Design Tools	8.7

Table 2-2

Status Of Tasks 1 Through 8**Task 1: Project Plan**

The Project Plan, which develops and documents the overall work scope for the ATS Phase 2 Statement of Work Tasks 2 through 8, was submitted and approved by DOE.

Task 2: Information Required for National Environmental Policy Act (NEPA)

The NEPA report, which covers environmental impact assessments of the test facility sites, was submitted and approved by DOE.

Task 3: Selection of a Natural Gas Fired Advanced Turbine System (GFATS)**Task 3A: Selection of an Industrial Natural Gas Fired Advanced Turbine System (GFATS)**

The industrial GFATS cycle selection was completed last year, and was described in the last yearly report. The cycle selected is based on the GE90 aero engine, with intercooling and turbocooling. This engine also meets all of the ATS utility machine performance goals. A summary is given in the Annual Report.

Task 3B: Selection of a Utility Natural Gas Fired Advanced Turbine System (GFATS)

The utility GFATS cycle section was completed last year. A summary is included in the Annual Report. The cycle selected features closed-loop steam cooling in the first and second stages of its four stage turbine, 2600°F/1430°C class of firing temperatures, a higher pressure ratio compressor derived from the CF6-80C2 aircraft engine, and an advanced dry low NO_x combustion system. This machine meets all of the ATS performance goals.

Task 4: Conversion to a Coal Fueled ATS (CFATS)**Task 4A - Industrial CFATS**

Four gasifier systems were reviewed for constituent concentrations, coal gas heating value, required engine bleed flow, and the fuel flow required to maintain the required power level. A summary is given in the TAB 3 section.

Task 4B - Utility CFATS

The Utility CFATS analysis is in progress. Particular emphasis has been placed on integration with the Shell-based gasification system. A summary is given in the TAB 3 section.

Task 5: Market Study

The market study was performed with cycle information developed in Task 3A and Task 3B. This task has been completed, and a Topical Report was submitted to DOE/METC.

Task 6: System Definition and Analysis

The Industrial ATS (GE90 based) preliminary design was completed. A summary is contained in the Annual Report. The Utility ATS (7H) machine preliminary design task is completed. A status report is contained in the Annual Report section.

Task 7: Integrated Program Plan

Work was initiated on Integrated Program Plans for both the Industrial and Utility ATS Systems. Summaries are given in the TAB 4 Section.

Task 8: Design and Test of Critical Components

Work proceeded on the experimental evaluation that will enable implementation of advances in several areas critical to the Industrial and Utility ATS systems. Seven major subtasks (listed below) comprise this task. Each work effort is reported individually in the TAB 5 section.

Task 8.1	Particulate Flow Deposition
Task 8.2	Particle Centrifugal Sedimentation
Task 8.3	TBC Mechanical Test and Analysis
Task 8.4	Advanced Seal Technology
Task 8.5	Enhanced Impingement Heat Transfer
Task 8.6	Rotating Heat Transfer
Task 8.7	Turbine Inlet Nozzle Heat Transfer

ATS PHASE 2 PROGRAM STATUS

Figure 2-1

ID	Task Name	1993	1994	1995	1996	1997
1	Task 8 - Design/Test Critical Components	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
2	Task 8.1 - Particulates Flow Deposition	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
3	Task 8.1.1 - Coolant Purify	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
4	Task 8.2 - Particle Centrifugal Sedimentation	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
5	Task 8.2.1 - Materials Coolant Compatibility	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
6	Task 8.2.2 - Rotor Materials Coolant Compatibility	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
7	Task 8.3 - TBC Failure Mechanisms	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
8	Task 8.3.1 - TBC Testing and Analysis	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
9	Task 8.3.2 - LCF Life and Crack Propagation	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
10	Task 8.3.3 - Bond Coats for Improved TBC TCL	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
11	Task 8.3.4 - Critical TBC Properties-Thermal Conductivity	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
12	Task 8.4 - Advanced Seal Technology	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
13	Task 8.4.1 - Advanced Seals	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
14	Task 8.5 - Enhanced Impingement Heat Transfer	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
15	Task 8.6 - Rotational Heat Transfer	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
16	Task 8.6.1 - Rotating Heat Transfer - Bucket Cooling	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
17	Task 8.6.2 - Rotating Heat Transfer - Wheel-space Cooling	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
18	Task 8.7 - Heat Transfer and Combustion Instability	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
19	Task 8.7.1 - Turbine Inlet Nozzle Heat Transfer	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
20	Task 8.7.2 - Turbulent Heat Transfer	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
21	Task 8.7.3 - Nozzle End Wall Impingement	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
22	Task 8.7.4 - Nozzle Airfoil Impingement	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
23	Task 8.7.5 - 1st Stage Bucket	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
24	Task 8.7.6 - Combustion Instability	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
25	Task 8.7.7 - Effect of Hot Fuel on Combustion Dynamics	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
26	Task 8.7.8 - Turbulence Intensity Probes	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
27	Task 8.7.9 - Turbulent Heat Transfer - Static Components	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
28	Task 8.7.10 - Transition Piece Design Tools	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
29	Task 8.7.11 - Effects of High Mach Number Diffuser	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
30	Task 8.7.12 - Nozzle Cascade Preliminary Test & Facility Qualifications	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3

ATS PHASE 2 - TASK 8 STATUS

Figure 2-2

ID	Task Name	1993	1994	1995	1996	1997
1	Task 8 - Design/Test Critical Components	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
2	Task 8.1 - Particulates Flow Deposition	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
3	Task 8.1.1 - Coolant Purify	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
4	Task 8.2 - Particle Centrifugal Sedimentation	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
5	Task 8.2.1 - Materials Coolant Compatibility	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
6	Task 8.2.2 - Rotor Materials Coolant Compatibility	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
7	Task 8.3 - TBC Failure Mechanisms	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
8	Task 8.3.1 - TBC Testing and Analysis	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
9	Task 8.3.2 - LCF Life and Crack Propagation	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
10	Task 8.3.3 - Bond Coats for Improved TBC TCL	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
11	Task 8.3.4 - Critical TBC Properties-Thermal Conductivity	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
12	Task 8.4 - Advanced Seal Technology	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
13	Task 8.4.1 - Advanced Seals	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
14	Task 8.5 - Enhanced Impingement Heat Transfer	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
15	Task 8.6 - Rotational Heat Transfer	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
16	Task 8.6.1 - Rotating Heat Transfer - Bucket Cooling	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
17	Task 8.6.2 - Rotating Heat Transfer - Wheel-space Cooling	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
18	Task 8.7 - Heat Transfer and Combustion Instability	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
19	Task 8.7.1 - Turbine Inlet Nozzle Heat Transfer	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
20	Task 8.7.2 - Turbulent Heat Transfer	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
21	Task 8.7.3 - Nozzle End Wall Impingement	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
22	Task 8.7.4 - Nozzle Airfoil Impingement	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
23	Task 8.7.5 - 1st Stage Bucket	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
24	Task 8.7.6 - Combustion Instability	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
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26	Task 8.7.8 - Turbulence Intensity Probes	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
27	Task 8.7.9 - Turbulent Heat Transfer - Static Components	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
28	Task 8.7.10 - Transition Piece Design Tools	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
29	Task 8.7.11 - Effects of High Mach Number Diffuser	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3
30	Task 8.7.12 - Nozzle Cascade Preliminary Test & Facility Qualifications	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3

ATS PHASE 2 - TASK 8 STATUS

Figure 2-2

TASK 4 - CONVERSION TO A COAL FUELED ATS (CFATS)

Description

For both Industrial and Utility systems, select a coal fueled cycle based on adaptation of the GFATS and identify the work required to modify the GFATS to perform optimally in the CFATS.

Objectives

Select a CFATS that will be most marketable after the year 2005 by best using the basic GFATS design while optimizing the use of coal gas fuel. Define the changes that are required and identify necessary provisions in the GFATS design to accept those changes to minimize future conversion costs to coal fuel. Define development work necessary to promote successful operation of the CFATS.

Progress

Task 4A - Industrial CFATS

The effort to determine the impact of using coal gas in the engine configuration that resulted from Task 6 was completed. Cycle calculations show that engine power output levels can remain nearly the same for both the natural gas and coal gas fueled configurations. The following table gives a thermodynamic summary of the natural gas fueled engine compared to the coal gas fueled engine.

	Natural Gas Fueled	Coal Gas Fueled
Simple Cycle Power	132 MW	129 MW
Simple Cycle Eff.	50.1%	47.5%
Combined Cycle Power	158 MW	158 MW
Combined Cycle Eff.	60.1%	58.1%
High Pressure Turbine Inlet Temp	2685F	2685F
Compressor Bleed Flow (% of Compressor Inlet Flow)	12.1%	20.8%

TABLE 1

The resulting engine/cycle schematic is shown in Figure 3-1.

ATS COAL GAS ATC CIRCUITRY

Figure 3-1

The impact of flow path contaminants has been studied, and the results indicate that the use of present-day coatings technology should minimize any potential corrosion problems on the engine cycle and component design integrity.

TASK 4B - Utility CFATS

Background

The GE STAG (steam and gas) 107H combined cycle has been under continuing evaluation for use in an Integrated Gasification Combined Cycle configuration. Particular emphasis has been placed on integration with the Shell-based gasification system which has been selected for a potential repowering application. This represents a special case for the STAG 107H system and involves a careful study of matching the combined cycle's steam bottoming cycle, the gas turbine's steam cooling requirements, and the need for operation of the IGCC design with natural gas startup and backup fuel. In addition to this site-specific activity, work has been accomplished on a general "greenfield" IGCC system design, again using the Shell-based gasification technology, but incorporating the full, single-shaft STAG 107H configuration.

Progress During Reporting Period

Additional combined cycle system analysis was performed on the Advanced Turbine System to investigate the effects of operating a system designed for IGCC operation and operating it on a natural gas backup/startup fuel. NO_x abatement on the backup fuel was achieved through steam injection, resulting in almost a 3% increase in net combined cycle output over a GFATS configured system using DLN combustors. However, this also resulted in about a 5% decrease in net combined cycle efficiency relative to the GFATS. A process block flow diagram is shown in Figure 3-2.

Partial air extraction integration with the air separation unit (ASU) was also studied, showing a 4% increase in overall net IGCC output (compared to no air integration), while overall IGCC efficiency essentially remained the same. Preliminary findings indicate that additional investigation will be necessary in the area of air separation at pressures compatible with the ATS. This will be required for future overall CFATS/IGCC optimization.

NO_x emissions from the combined cycle using diffusion flame combustors were estimated with just the residual nitrogen injection from the ASU. It was found that additional dilution was required to achieve 25 ppmvd of NO_x, since there was not enough residual nitrogen from the Shell gasification process. Different configurations were evaluated, but the best one was low-level heat moisturization of nitrogen.

DOE Utility CFATS - Shell Based IGCC

Process Block Flow Diagram

Figure 3-2

Plans For Next Reporting Period

Overall CFATS performance will be completed for Shell coal-based IGCC system at ISO conditions.

TASK 7 - INTEGRATED PROGRAM PLAN

Work was initiated on Integrated Program Plans for both engine designs. The Industrial Machine Integrated Program Plan documents the required steps and timing needed to develop an aeroderivative, intercooled, combined cycle power system. The Plan outlines the timing from preliminary design to site testing, and is shown in Figure 4-1.

The Utility Machine Integrated Program Plan documents the transition from the Phase 2 (Conceptual Design and Product Development) work effort to Phase 3 (Technology Readiness Testing and Pre-Commercial Demonstration). The Phase 2 program extensions have led to a Phase 2/Phase 3 overlap, and consequently, this task will be used to plan the smooth transition from Phase 2 to Phase 3, and show how the advanced technology developments initiated in Phase 2 will be incorporated into the 7H/9H machine design and hardware. The program plan is shown in Figure 4-2.

ADVANCED INTERCOOLED AERO-DERIVATIVE ENGINE

Figure 4-1

Figure 4-2

QUARTERLY PROGRESS REPORT BY SUBTASK

Task 8.1 - Particulates Flow Deposition

Objective

The primary objective of this task is to characterize the particulate generated in an operating gas turbine combined cycle (GTCC) power plant whose configuration approximates that proposed for an ATS power plant. In addition, the task is to evaluate the use of full-flow filtering to reduce the steam particulate loads. Before the start of this task, GE had already negotiated an agreement with the candidate power plant, piping and a filter unit had already been installed at the power plant site, and major elements of the data acquisition system had been purchased, all with GE funds. The remaining work involves completing assembly and checkout of the system, and then conducting measurements to meet the stated objectives. Using coolant extracted from an existing plant that most closely simulates projected ATS conditions, we will determine filtration- and operating-performances for a candidate full-flow metal filter system operating at ATS entry conditions and characterize the coolant particulates into and out of the metal filter.

Approach

Using coolant extracted from an existing plant most closely simulating projected ATS conditions, determine filtration- and operating-performances for a candidate full-flow metal filter system operating at ATS entry conditions and characterize the coolant particulates into and out of the metal filter.

Progress for the Last Quarter

During this quarter, primary efforts were expended on the other Phase 2 work to get the centrifugal deposition rig on-line. However, new Millipore® filter holders were purchased to replace holders borrowed for the first measurements which had to be returned to their GE owners. New 0.1- and 0.45-micron filters were ordered and received for the upcoming steam exposures and sampling for the centrifugal deposition rig trials.

Plans for Remaining Work

The steam cartridge filter will continue to get exposure to steam flow to the centrifugal deposition rig in coming months. The flowrate will only be approximately 1/3 the flowrate of earlier exposures because of flow specifications for the centrifugal deposition rig tip turn specimens. The added exposure time will provide valuable material data and generate more opportunities for steam characterization.

Task 8.1.1 - Coolant Purity

Objective

The objective of this task is the exposure of typical ATS gas turbine airfoil cooling channel geometries to real steam flow to determine whether there are any unexpected deposit formations. The task is a static analog of the centrifugal deposition rig trials of Task 8.2, in which a bucket channel return bend is exposed to steam flow. Two cooling channel geometries are of primary interest in this static exposure.

The static specimens will be mounted in a coded pressure vessel (already available at the power plant from previous GE work) that would serve both to offer personnel protection because the specimens do not have standard ASME closure designs and to enable preheating of the specimens by flooding the vessel with steam as a heating medium before steam flow initiation.

Approach

This task is a static analog of the dynamic flows in the centrifugal deposition rig described in Task 8.2. Two particular cooling channel geometries are of primary interest in this static exposure. The first is a channel with heat transfer enhancement roughness structures such as pin arrays or "turbulator" boundary layer trips. The second is the impingement cooling distributor tube and the associated target wall which is being cooled. Such geometries have been called for in some nozzle cooling designs. After exposure, examination of deposit locations around the impingement holes and on the target surface will be examined.

Progress for the Last Quarter

During this quarter, the specimens were received, inspected, mounted, and pressure-tested to 500 psi. One specimen was briefly returned to the vendor to reinforce a flange and provide an assembly tack weld, but both specimens were then assembled in the apparatus and tested. Figure 8.1.1-1 shows the convection and impingement specimens mounted in series up-flow on the vessel base.

Figure 8.1.1-1. Convection (bottom) and Impingement (top) Static Flow Specimens

The specimens were vertically mounted to minimize opportunities for condensate to affect any deposits. In addition, the inlet line to the specimens was provided with a drain for startup. The pressure vessel is shown with specimens installed and insulation applied in Figure 8.1.1-2. The pressure vessel is employed to provide personnel protection for these non-ASME steam closures on the specimens and to enable the specimens to be preheated with steam within the vessel shell before the controlled steam flow is admitted to the inside of the specimens.

Figure 8.1.1-2. Static Specimen Vessel in Place

Plans for Remaining Work

The plan is to start flow to these specimens after the centrifugal deposition rig is commissioned. Then both the rotating- and static-specimens will be exposed to the same steam flows and contaminants during exposure.

Issues, Problems, Changes

The only current issue is the general problem of operating this increasingly complex, remote experiment in the face of powerplant load swings and shutdowns. At the least, it will be necessary for research staff to restart the equipment during the first few months of operation. Nevertheless, the project has been receiving considerable support from plant operating management, staff, and plant operators.

Task 8.2 - Particle Centrifugal Sedimentation

Objective

The primary objective of this task is to determine the settling characteristics of particles in a cooling stream from an operating gas turbine combined cycle (GTCC) power plant when that stream is ducted through a passage experiencing the G-loads expected in a simulated bucket channel specimen representative of designs proposed for an ATS gas turbine. GE has identified a target power plant at which to site the experiment. Prior to the start of this task, GE had completed a proprietary computational code that was proposed to be useful in predicting particle trajectories. A motor-driven centrifugal deposition rig that accepts coolant at ATS conditions accelerates it at conditions expected in specimens built to simulate ATS bucket coolant channels. Coolant flow conditioning and control will be provided by the filtration and control system already used for the Task 8.1 work effort. Deposits collected in the specimen tip channels will be compared to predictions and to desired times between outages for the ATS when the channels could be cleaned.

Approach

Build a motor-driven centrifugal deposition rig that accepts coolant at ATS conditions and accelerates it at conditions expected in specimens built to simulate ATS bucket coolant channels. Coolant flow conditioning and control is to be provided by the filtration and control system already utilized for the Task 8.1 work effort. Deposits collected in the specimen tip channels will be compared to predictions and to desired times between outages for the ATS when the channels could be cleaned. Using coolant extracted from an existing plant most closely simulating projected ATS conditions, determine filtration- and operating-performances for a candidate full-flow metal filter system operating at ATS entry conditions and characterize the coolant particulates into and out of the metal filter.

Progress for the Last Quarter

The steam flow system was tested for the first time since the centrifugal deposition rig was installed. Referring to the flowsheet in Figure 8.2-1, the steam was routed from the HP steam turbine drain, through the feed control valve, first orifice, the filter, the centrifugal deposition rig shunt pipe, the second orifice, the backpressure control valve, and then back to the LP turbine. Because of the reduced flowrates (0.35 lb/sec vs. 0.8 lb/sec), heat loss from the uninsulated pipes cooled the steam too much, so new insulation was placed on the supply piping, test section, centrifugal deposition rig piping, and the specimen vessel piping. The new insulation brought the supply temperature up to over 100°F superheat which is the temperature desired for the test to ensure that there is no condensation in the apparatus. Figure 8.2-2 shows the filtration/flow apparatus prior to being insulated for these tests. The feed valve and backpressure valve are at the top of the apparatus at the left and right, respectively. The filter housing being used is at the top in the middle. Plumbing at the left of the backpressure valve allows valving in the centrifugal deposition rig and static flow specimen sections as desired.

The steam and electrical heating systems for preheating the centrifugal deposition rig before steam admission were also tested. After fully insulating the centrifugal deposition rig, it was set rotating at 500 rpm while both the steam tracing (500 psig) and the electrical heaters (4500W) were turned on. The slow rotation was recommended by the centrifugal deposition rig vendor to improve heat dispersal in the rotor and seals. These measurements showed that the heat-up process from a cold start would require about six hours to reach steam admission temperature conditions. The centrifugal deposition rig is shown in Figure 8.2-3, with the insulated rotor housing at the left and the control station at the right.

Two persistent problems have delayed startup about three weeks. The first is an overheating of the 1 hp lube oil feed pump, even after changing out both the pump itself and the motor. The allowable circuit current has been raised from 1.7 to 2.1 amps per phase (leg), and the motor runs warmer than intended but seems not to present a system risk. The original motor has been left at the site for possible changeout if overheating affects lube oil system performance. The second issue is the faulty performance of the inlet flow control valve which does not open more than 20% regardless of the supplied signal. After seemingly fixing this problem at no flow several times but still getting erratic behavior at hot, high pressure operating conditions, the valve vendor has been called in to service it.

Figure 8.2-1. Steam Purity Equipment Flowsheet

Figure 8.2-2. Filtration, Characterization, Flow Control System

Figure 8.2-3. Steam Centrifuge Apparatus with Specimen Vessel in Background

Plans for Remaining Work

Once the flow system provides good flow- and pressure-control again, the centrifugal deposition rig itself will be tested under steam flow. The plan is to start up at low system pressure and slow rotation rates and then increase both to maximum stable operating conditions (4800 rpm, design steam flows and conditions). It is planned to accomplish this in March. Then the Phase 3 activity of operating the system would begin.

Issues, Problems, Changes

The rotary coolant seals remain the largest unknown until the system is put into operation.

Task 8.2.2 - Rotor Materials Coolant Compatibility

Objective

The objective of this task is to evaluate the effect of oxygen partial pressure on high-temperature crack propagation and crack tip oxidation in a material anticipated for structural application in ATS gas turbines. This evaluation will be accomplished by using hydrogen/water vapor/inert gas mixtures to control the equilibrium atmospheric oxygen partial pressure in the test chamber over a wide range of values. Compact tension specimens will be used to evaluate crack propagation properties.

Progress for the Last Quarter

Testing of the FTD CGR (fully time-dependent crack growth rate) of Inco718 subscale forging material as a function of the hydrogen-to-water-vapor ratio in the test atmosphere has been completed.

Transmission electron microscopy (TEM) and Auger electron spectroscopy (AES) were completed on specimens that were tested in dry hydrogen. Analyses of the fracture surface very near the crack tip indicate the presence of a single layer Cr-rich oxide scale.

Crack propagation specimens in which cracks were grown in Inco718 at 1100°F and in various environments were prepared for TEM and AES analysis.

Plans for Remaining Work

Characterization, through AES and TEM, of oxide scale compositions will continue during the next reporting period.

Reference

E. Andrieu, G. Hochstetter, and A. Pineau, "Superalloys 718, 625 and 706 and Various Derivatives," The Minerals, Metals and Materials Society, 1994, pp. 619-631.

Task 8.3 - DETERMINATION OF DRIVING FORCES FOR THERMAL BARRIER COATING FAILURE

Task 8.3.1 - TBC Testing and Analysis

Objective

Development of thermal barrier coatings (TBCs) with improved life and reliability will require a comprehensive understanding of the mechanisms of degradation that occur during gas turbine service. There are multiple objectives in this task. One objective is development and confirmation of methods to measure and predict TBC stress states as a function of thermal and mechanical strains. This capability is fundamental to all quantitative TBC design and life prediction methodologies. An additional objective is development of a practical, versatile laboratory-scale thermal gradient exposure facility that is capable of simulating the extreme thermal conditions anticipated for TBCs in an advanced gas turbine. This atmospheric E-beam high gradient test facility will then be used to evaluate TBC-coated specimens in the thermal and stress states expected in service.

The specimen design ("tophat" specimen) for the E-beam thermal gradient test facility requires further analysis and modification to ensure that it properly mimics the thermal and strain fields present in critical regions of a first-stage nozzle in an ATS gas turbine. Results from instrumented specimens will be used to compare observed versus predicted thermal and strain fields. Several geometric variables in the tophat design will be varied as necessary to confirm analyses and define improved specimen configurations.

Improved instrumentation and detectors will be developed for characterization of temperatures, fluxes, and strains in specimens tested in the E-beam thermal gradient test facility. Types of instrumentation and detectors to be further developed include thin-film thermocouples, thin-film strain gauges, IR pyrometers, surface profile monitors, and laser fluorescence of the thermally grown alumina layer. The measurement techniques must be compatible with the extremely harsh testing conditions and provide minimal interference with the intended temperature and thermal flux fields. The techniques will be used to further confirm validity of specimen designs and to provide monitors for feedback control during routine testing.

A new test specimen geometry for use with the atmospheric E-beam thermal gradient test facility will be designed and analyzed to simulate thermal and stress conditions in the TBC fillet region of the first-stage nozzle. The fillets are between the airfoil and the inner and outer bands. The specimen geometry will encourage creation of TBC microstructures of the type generated in regions such as fillets that have restricted plasma torch access. Also, the new specimen will be designed to approximate any geometry-dependent lifting stresses that are believed to contribute to TBC delamination.

TBC durability and reliability in fillet and leading edge regions (high positive and negative curvature) will be evaluated in room temperature mechanical tests to complement thermally loaded specimens such as the E-beam fillet specimen described above. New test specimen geometries that contain TBCs on surfaces with both high positive and high

negative curvature will be developed and analyzed. The specimens will be tested primarily in compressive stress/strain but, if allowed by the specimen grip design, they will also be tested in tension/compression cyclic loading to more accurately mimic service strain cycles. The new test specimen designs are expected to be based on prior design and testing experience at CRD of related mechanical test specimens that have little or no curvature.

Progress for the Last Quarter

TBC Specimen Development and Testing

Finite Element Model Validation

The post-test finite element analysis of validation specimens is complete. Overall, good agreement was obtained between thermocouple, pyrometer, and strain gauge readings in the experiment. The specimens were instrumented with strain gauges at 6 locations and with thermocouples at 13 locations. The strain gauge and thermocouple readings are compared with numerical simulations for a representative TBC surface temperature.

Finite Element Model of Material Creep Behavior

A previously tested specimen that had shown TBC was examined by ultrasound imaging and by sectioning. The post-test ultrasound image showed several regions of possible cracking, which was confirmed by sectioning the specimen.

Instrument Development

Flux Test and TBC Surface Temperature Calibration

A tophat specimen was constructed with 5 thermocouples imbedded in the interface between the bond coat and the metal and a corresponding set of thermocouples tack-welded on the cold side of the metal. After installation of the thermocouples, the specimen was bond coated and coated with TBC. The objective of this test was to check the error present in the estimates of the TBC surface temperature derived from the 10-micron Land Pyrometer. The combination of thermocouples results and the measured properties of the René N5 material should provide a measure of the 1D thermal flux through the system and allow us to back-calculate a TBC surface temperature assuming our best knowledge of the properties of the bond coat/TBC layer.

The specimen was instrumented (thermocouples) by HiTec. The measurements of the positions of the thermocouples on the top face were done by probing the surface with the tip of a soldering gun until we reached a position of maximum response. The specimen was coated with bond coat (11 mils) and then TBC coated (17 mils). Unfortunately, the post-TBC coating heat treatment destroyed 4 of the 5 thermocouples. The sample was tested to compare measured and predicted temperature values given known front side heating conditions and back side cooling conditions. Knowing the geometry, properties, and temperatures for the first-stage airfoil material, calculation of the thermal flux through the N5 and use of that flux to calculate the expected temperature of the top surface of the

TBC is possible. Given the uncertainties in the model, the agreement between the measured and calculated values is satisfactory.

Acoustic Emission Probe

As a consequence of the tests that have successfully induced TBC and metal failure into the tophat specimens, we have assembled an active acoustic emission probe attached to a tophat specimen. This will be used to determine if metal cracking below/within the TBC can be detected prior to an obvious TBC failure.

Thermal Conductivity by E-Beam AC wave

The possibility of using the E-beam facility to do a flash measurement of TBC thermal conductivity is being investigated.

TBC Optical Properties

Samples have been sent out for measurement of TBC optical properties as a function of wavelength in order to allow proper choice of wavelength for pyrometric measurements of temperature and provide thermophysical data for radiation heat transfer calculations. Reflectivity data (0.3-26 μm) are being obtained from porous and dense vertically microcracked (DV μC) TBC coatings as a function of temperature (25°C-1300°C [77°F-2372°F]). The data will be used to calculate transmittance and emittance.

Data for a complete optical description of porous and DV μC TBCs have been taken, and analysis is beginning to extract optical parameters. This will allow selection of wavelengths at which the TBC is opaque for unambiguous temperature measurement. In addition, we will evaluate diffusivity of the reflected light (to be used for emissivity determination at CRD). Measurements at the unconventional wavelengths of interest (based on literature data for polycrystalline sintered zirconia about 12 μm) are not available in standard pyrometers. A measurement facility is being set up at CRD using a HgCdTe-detector sensitive in the wavelength region of interest. This will be calibrated and the signal looked at with a lock-in amplifier. Here we can gain experience by measuring metal pieces with and without TBC at elevated temperature (probably flame heated from the back).

Zirconia TBC is opaque from about 0.25 μm to about 12 μm . More precise values for our material will be determined from reflectance data (in progress). The advantage of shorter wavelengths is greater sensitivity to temperature (as described above), but signal strength is a concern, since there is very little intensity in the ultraviolet range. There is sufficient signal at the longer wavelengths, but the loss of sensitivity is a disadvantage. The loss of sensitivity can be expressed in terms of a temperature uncertainty for a given uncertainty in emittance; e.g., at 1350°C a 5% uncertainty in emittance results in a temperature uncertainty of 4°C at 0.4 μm and 62°C at 15 μm . In addition, atmospheric absorption (mostly by carbon dioxide and water vapor) has to be taken into account when choosing an appropriate wavelength.

Fillet Region TBC Test

Work has started on the design of the mechanical test specimens.

Two molds of fillet tophats (Figure 8.3.1-1) have been received from the casting vendor. Fillet tophat APS deposition masks have been fabricated to ensure that the TBC deposited on the fillet tophat simulates that deposited on a GE Power Generation part in the fillet region. Robot programming for the APS runs has begun.

Figure 8.3.1-1. Regular Tophat and Fillet Tophat

Plans for Remaining Work

Analysis of TBC optical properties measured as a function of wavelength will continue.

Design of the fillet mechanical test samples will continue.

APS parameters for the deposition of TBC onto the fillet tophats will continue to be developed and parts will be coated.

Task 8.3.2 - LCF Life and Crack Propagation

Objective

The objective of this task is to evaluate the low cycle fatigue (LCF) life of the most critical regions of the ATS turbine inlet nozzle using representative geometries, thermal fields, and stress/strain fields. Testing will be performed under various conditions, with standard defined cycles and with accelerated cycles. Specimens will be tested as practicable to predicted life cycles, then accelerated until failure. Failure may be either TBC loss or crack-through of the metal substrate. Some specimens will continue to be tested after crack-through to determine the crack propagation rate, i.e., rate of leakage increase. All specimen data will be used in the validation and updating of life prediction models for TBC/metal systems.

Progress for the Last Quarter

One purpose of this task is to evaluate the LCF life of critical regions of the ATS Turbine Nozzle. High thermal gradient E-beam testing is being used to expose superalloy-TBC specimens to temperature and stress levels both representative of the ATS turbine inlet nozzle and far in excess of expected conditions, to determine LCF life of the metal within

reasonable test durations. Current efforts are focused on testing in support of the turbine nozzle development.

High Thermal Gradient Testing

LCF Testing

LCF specimen #3 has been tested under accelerated cyclic loading conditions that are the same as those used for testing LCF specimens #1 and #2. Like LCF #2, LCF #3 is coated with 250 μm (10 mils) of NiCrAlY bond coat and nominally 375 μm (15 mils) of air plasma sprayed (APS) dense vertically microcracked (DV μC) top coat. The specimen was examined with ultrasound prior to testing, as a baseline for possible crack detection via ultrasound at specified test intervals. The specimen was run for 350 cycles and removed for ultrasound inspection; no cracks were detected.

The specimen was then run for another 160 cycles (510 total cycles), at which time a small blister was observed in the TBC, about 5 mm (0.2 in) diameter.

Testing was halted, and the specimen sent for ultrasound inspection. LCF #3 will not be tested for further cycles.

Bond Coat Crack Propagation Tests

In addition to the LCF concerns associated with the superalloy substrate material of the turbine first-stage components, the bond coat between the substrate and the TBC has been identified as a possible source of crack initiation and propagation to the substrate. The current protective coating system to be used on the ATS turbine inlet nozzle calls for a NiCrAlY bond coat to be applied in a thickness of 0.25 to 0.50 mm (.010 to .020 in) prior to application of the TBC top coat. The bond coat provides both oxidation resistance and the roughened surface for top coat adhesion. The bond coat is only slightly diffusive and provides a mechanically compliant layer between the load-carrying substrate material and the weaker TBC material.

The NiCrAlY material is, however, not a single crystal material and is more prone to cracking. Using a PtAl diffusive bond coat in much thinner layers, GE Aircraft Engines has experienced the propagation of cracks into the load-carrying substrate that were initiated in the PtAl bond coat. PtAl is a much more brittle material than NiCrAlY. Based on the GE Aircraft Engines experience and the critical nature of the ATS turbine component protective system, it has been decided to perform confirmatory testing with the E-beam apparatus to determine the nature and extent of possible cracking in both PtAl and NiCrAlY coatings on N5 tophats specimens.

Three tophats will be prepared with various coatings, but without TBC. One tophat will receive about 75 μm (.003 in) diffused PtAl, the second will receive about 0.25 mm (.010 in) NiCrAlY, and the third 0.50 mm (.020 in) NiCrAlY. The test plan will expose the PtAl tophat to approximately 500 cycles, and the NiCrAlY specimens to about 800 cycles each. None of these specimens is expected to fail under these conditions, but each is expected to develop cracks within the bond coat. Post-test destructive measurements will determine the nature and extent of such cracking, and whether the cracks from NiCrAlY may be expected to propagate into the N5 substrate metal.

The NiCrAlY-coated specimens, known as DR1 and DR2, have been coated and heat treated. The PtAl specimen, DR3, has received Pt plating and is in the process of diffusion treatment at GE Aircraft Engines.

Calibration Testing

Tests have been performed with the first flux calibration tophat having imbedded thermocouples at the bond coat interface location and tack-welded thermocouples on the cold side. Results showed good agreement between the TBC surface temperature calculation using the thermocouple readings and assumed property data, and the 10- μ m pyrometer indication. During the heat treatment of this specimen prior to testing, all but one imbedded thermocouple was damaged, and the remaining thermocouple stopped reading at a TBC temperature of about 850°C (1560°F).

Non-Destructive Evaluation and Metallography

LCF Specimen #1

This specimen was sectioned previously for metallographic analysis. Nine sections were made through the damaged region of the substrate. Multiple cracks were identified in the metal along two predominant crack paths.

According to the orientation of the specimen crystal, cracks propagated along the $\langle 111 \rangle$ directions, which are the axes of highest Young's modulus, and hence also form the highest thermal stresses. Cracks were predominantly Stage II type, being perpendicular to the loading, with little or no Stage I type, though some curvature was present in the cracking. This result is typical of N5 in uniaxial loading. For this biaxially loaded LCF specimen, this tends to support the design life methodology of using principal stresses; i.e., life is controlled by the maximum thermal stress. Cracks were initiated at the bond coat/N5 interface where mechanisms such as recrystallization depletion and grit blast cratering may be contributors, though no definite crack initiator could be identified.

Observed bond coat cracking is thought to have little or no effect on LCF life, though many such cracks did correspond in location to metal substrate cracks.

LCF Specimen #2

This specimen, having been previously cycled to failure of the TBC, showed one visible large metal crack, with several other smaller cracks being observed via ultrasound imaging. The specimen was cut up to form a fatigue specimen, and then fatigued until fracture under well controlled conditions. Scanning Electron Microscope (SEM) observations were made to characterize the initial metal crack.

Macroscopically, the fatigue crack appeared to be heavily oxidized and had the classic "thumbnail" shape that is common for surface-initiated fatigue cracks (surface of the metal). The total crack depth was approximately 75% of the total metal substrate thickness. Well defined fatigue striations were clearly present on the fracture surface. There was strong evidence for multiple initiation sites on the main crack. It appears that at least three cracks initiated and linked up later to form the main crack. No obvious metallurgical flaw could be associated with initiation. It was not possible to conclude

whether crack initiation occurred in the TBC, bond coat, or substrate, though it can be said with confidence that the cracks did not initiate below the surface of the substrate.

A high resolution SEM was then performed to allow analysis of striations on the fracture surface. Both striation count and spacing were determined. The results showed the fracture surface to contain between 800 and 900 striations, and that the crack propagation rate was lowest when the crack length was short, and highest at crack lengths greater than 0.686 mm (.027 in). Striation spacing appeared to be very uniform.

Analyses

Creep analyses of the tophat specimen, under accelerated E-beam test conditions, have been performed to investigate the magnitude of the stress relaxation in the various materials, and the resulting stress redistribution in the specimen.

Pre-test analyses have been performed for specimens DR1, DR2, and DR3 defining the required conditions for testing to achieve the desired results.

Other Preparations

Tophat specimens have been fully prepared and instrumented for LCF #4 and #5 testing. Both specimens have DV μ C TBC, and have not been exposed to the previous masking tape.

Several calibration tophats have been prepared with fully imbedded thermocouples within the substrate metal at both metal interfaces, hot and cold sides. The purpose of these pieces is to obtain a more accurate calibration of metal temperature with E-beam power level, both with and without TBC. This calibration will allow more precise test setup and data interpretation, rather than relying heavily on a TBC surface temperature reading via pyrometer.

Specimen LCF #3 has received post-test ultrasound examination. LCF #4 and #5 specimens have received pre-test ultrasound examination.

Plans for Remaining Work

Specimens LCF #4 and 5 will be tested, destructively examined, and the results compared with analysis. Bond coat specimens DR1, DR2, and DR3 will be tested, destructively examined, and analyzed. Energy flux calibration specimens will also be run.

Task 8.3.3 - Bond Coats for Improved TBC Thermal Cycle Life

Objective

Recent experiments with alternate bond coat application techniques and alternate bond coat chemistries indicate that significant improvements in the thermal cycle life of a TBC system can be achieved through bond coat modification. An experimental matrix containing a bond coat chemistry other than the one proposed for use in the ATS TBC system will be established to assess the role of optimized bond coat processing on TBC thermal cycle life.

Bond coat process parameters and post-heat treatment sequences will be selected to alter bond coat mechanical properties. All bond coats will be coated with an approximately 0.038-cm-thick (0.015-inch-thick), dense vertically microcracked (DV μ C), air plasma sprayed (APS) TBC and evaluated in thermal exposure. Compressive shear resistance and other mechanical properties of the various TBC systems will be evaluated as a function of exposure time, exposure frequency, and exposure temperature in cyclic oxidation tests. The influence of bond coat properties on TBC life will be determined for the new system.

Progress for the Last Quarter

Experimental Matrix and Choice of Bond Coat Parameters

The test specimen matrix emphasizes materials and processes critical to strength, mechanical properties, and durability of Advanced Turbine System coatings. It was planned that the matrix would cover temperature trials from 982°C (1800°F) to 1204°C (2200°F) and two different thermal cycling rates at each temperature. Reassessment of time required for completion of the furnace cycle tests resulted in moving the base temperature from 982°C (1800°F) to 1093°C (2000°F). Coating strength and mechanical properties are being measured as a function of cycle time and temperature.

Two different thermal exposure cycles are being utilized. The first is a furnace cycle test (FCT) which heats up rapidly (around 75°C/min) from ambient room temperature to a 45-minute hold time at the selected maximum temperature with a forced air quench on each return to room temperature (cooling rate around 110°C/min).

The second thermal exposure cycle is designated as a furnace exposure test (FET) which utilizes a furnace power heat-up at around 40°C/min from room temperature to a 10-hour hold at the selected maximum temperature followed by a furnace-power-off cool-down at around 45°C/min. The different cycles are providing insight into the influence of cycle frequency and hold time at temperature on crack growth and failure in either the thermally grown oxide, the bond coat, or the ceramic layer.

FCTs are being conducted at four different durations for each temperature. The times were selected so that groups of specimens can be extracted at increasing times of exposure and, consequently, various degrees of thermal distress. The fourth time group is being cycled to failure. FETs are being cycled only to failure without extractions at intermediate times.

Sample groups extracted prior to failure are being evaluated metallographically to determine oxide growth rates and to determine length, location, and nature of propagating cracks. The scanning electron microscope will be used to evaluate microstructural changes in fracture surfaces of the TBC as a function of exposure time. Mechanical properties of the coatings at various stages of thermal cycling will be determined using tests for tensile pull strength, compressive shear strength of the attached coating, and Young's modulus of the detached coating. Arrhenius plots are being constructed from the failure time data and will be used as a guide in defining failure mechanisms.

Furnace Exposure Testing and Furnace Cycle Testing of Specimen Matrix

The test matrix covers temperature trials from 1093°C (2000°F) to 1204°C (2200°F) and two different thermal cycling rates at each temperature. Coating strength and mechanical properties have been measured as a function of cycle time and temperature. The experimental test matrix for studying the failure mechanisms focuses on N5 as the alloy of choice coated with either a NiCrAlY bond coat (Ni211) or a CoNiCrAlY bond coat (Co129), with each applied at a longer-than-standard gun-to-substrate distance to develop more entrained oxide in the deposited coating. A top coat consisting of a dense vertically microcracked TBC (APS 8YSZ) was applied on top of the bond coats. The thermal exposure cycles for the furnace cycle tests (FCT) and the furnace exposure tests (FET) are summarized in the September 1995 monthly report. Results will be compared with companion tests run on Ni211 sprayed under standard conditions

Evaluation of Effect of Furnace Cycle Frequency

The FCT matrix is being expanded to examine in more detail the relationship between the number of cycles to failure and furnace dwell time/cycle for the NiCrAlY bond coated samples. FCTs will be conducted using dwell times of 6 minutes, 45 minutes, 10 hours, and 20 hours, at temperatures of 1037°C (1900°F), 1093°C (2000°F), and 1149°C (2100°F). A test matrix for examining the role of pre-oxidation on the bond coat properties and FCT life has also been developed.

N5 substrates have been ordered and have been received in part. Six sheets of single crystal N5 have been coated with 10 mils of Ni211-2 bond coat and 20 mils of DV μ C TBC, and heat treated in vacuum after coating. The coated slabs will be water jet cut into 1-inch diameter test specimens.

Three new FCT furnaces ordered in December 1995 for conducting tests have been received and installed. The FCT furnaces are in the process of being calibrated prior to starting the furnace cycle tests.

Plans for Remaining Work

Furnace Cycle Testing of Specimen Matrix

Metallographic examination of failed specimens and of specimens withdrawn prior to failure will continue and mechanical testing of coated specimens will begin.

Furnace Dwell Time Testing of Specimen Matrix

A FCT matrix to examine in more detail the relationship between the number of cycles to failure and furnace dwell time/cycle for NiCrAlY bond coated samples will begin.

Task 8.3.4 - Critical TBC Properties - Thermal Conductivity

Objective

Accurate measurements of TBC thermal conductivity are important for thermal analysis and design of coated turbine components. Current practice uses conductivities that are measured with laser flash techniques that directly evaluate the thermal diffusivity. In this task, methodology and apparatus will be developed for measuring TBC thermal conductivity by an independent means. The effective thermal conductivity of various TBC systems including TBC, bond coat, and metal substrate will be determined by a transient technique employing convective heat flux. Instrumented test plates will be heated to a high temperature and subsequently cooled with large-diameter, air impingement jets at room temperature to provide a uniform heat transfer coefficient over the test article of interest. Instrumentation data and known heat flux will be used with finite element modeling to determine the effective thermal conductivity of the system and the TBC thermal conductivity.

Progress for the Last Quarter

Further analysis of the proposed experimental apparatus and techniques has shown that steady-state heat conduction tests offer significant advantages over transient testing methods for the TBC thicknesses of interest. The primary problem during transient testing is a relatively weak sensitivity of the thermal response of the TBC-coated specimen to the TBC thermal conductivity. Hence, since the TBC conductivity is the primary unknown in the experiments, measurements of the accuracy required would be very difficult to obtain. Also, the transient response of the specimen is a function of the bulk density and specific heat which introduces additional errors into the calculated thermal conductivity values.

Many of the experimental problems associated with the transient tests are alleviated by considering the steady-state conduction problem. In this case, the heat conduction (thermal conductivity) depends wholly on the effective thermal resistance of the conduction network, not on density or specific heat. The steady-state test methodology will entail matching the thermal resistance of the TBC-coated specimen with that of an uncoated reference material of known thermal conductivity and subsequently back-calculating the TBC thermal conductivity. The apparatus to conduct these experiments will use a natural gas torch for the heat source and backside cooling via a compressed air jet. The specimen will be embedded in a ceramic housing to minimize the introduction of radial conduction effects into the problem. A group of five specimens will be tested at identical conditions by utilizing a rotating wheel arrangement which will eliminate drift errors in the torch and cooling jet between tests.

The one-inch diameter sample specimens have been coated with APS TBC. Samples with two different TBC thicknesses (0.020 in and 0.040 in) were generated in order to study the thickness effect on TBC thermal conductivity that has been observed experimentally in previous investigations. The TBC surface was subsequently ground with a diamond-tip grinding wheel in order to reduce the roughness from the as-sprayed condition to that

more closely resembling the reference sample pieces. Direct measurements of the TBC surface roughness will be made in order to document the roughness of the test specimens.

Bench-top tests with a natural gas torch that will be used as the heat source in the upcoming experiments have shown it to have sufficient burning rates to attain the TBC surface temperatures required. The flame unsteadiness over long periods of time was monitored and found to be acceptable.

A design review of the test rig and experimental method was held, and many useful suggestions have been incorporated into the final rig design.

Final assembly of the TBC thermal conductivity rig has been completed. Flow meters to measure the gas and oxygen flowrates to the heating torch and to the cold side cooling jet have been installed on the rig. The initial tests to be conducted will focus on documenting the steadiness of the gas supplies which is critical for success of the experiment.

Final preparation of the TBC-coated samples is complete. In order to ensure negligible paint penetration into the TBC coating, a 2-micron-thick layer of platinum was sputtered onto the TBC surface to act as a barrier between the paint and the TBC. Finally, each surface of the specimen was painted to ensure a constant and consistent emissivity across the specimen. The last step in the specimen preparation involves curing the painted samples in an oven to form the emissive coating on each face of the specimen.

Plans for Remaining Work

Apparent thermal conductivities of several APS TBC-coated specimens will be measured. In addition, an error analysis of the measurement technique will be completed and the results compared to similar analyses conducted on the laser flash diffusivity method for determining thermal conductivity. Finally, the robustness of the current rig design will be investigated by systematically varying many of the design parameters in the specimen and rig assembly.

Task 8.4.1 - Advanced Machine Hot Gas Path Seals

Objective

The objective of this task is to design, fabricate, and install a high temperature static seal test rig capable of testing advanced seal concepts at 537°C (1000°F) and 2.412 Mpa (350 psi), providing 0.45 kg/sec (1 lb/sec) of air flow. The rig will be checked out for proper operation using some of the seals being developed for the ATS gas turbine.

Progress for the Last Quarter

The High Temperature Seal Test rig at CRD has been fabricated and installed. The final safety review was held, and the rig was approved.

The rig has been hydrotested to 1250 psi. The entire system, including piping has also been hydrotested to 1250 psi. The piping system welds have been X-rayed for flaws. The rig is fully instrumented with thermocouples and pressure gauges.

Checkout tests to evaluate the rig's thermal inertia (heat-up time) and bias leakage characteristics have been completed. It took about one hour to reach 800°F and 2.5 hours to reach 950°F. A rig pressure of 350 psig was attained. The bias leakage is about 0.00025 to 0.0003-inch equivalent gap. The rig is now ready for high temperature seal tests.

The project has been completed.

Plans for Remaining Work

The final report will be written.

Task 8.5 - Enhanced Impingement Heat Transfer

Objective

Tests will be performed to evaluate a new concept for backside impingement cooling aimed at lessening the adverse effect of cross-flow on air jet thermal dilution and to determine the upper limits for jet heat transfer at higher air supply pressures.

For long impingement channels, the spent jet impingement air represented as cross-flow mixes and raises the temperature of the cold air jet before it strikes the hot wall.

Progress Since Last Reporting Period

This task has been completed.

Task 8.6.1 - Rotational Heat Transfer - Bucket Cooling

Objective

Prediction of gas turbine blade life requires sufficient accuracy in the prediction of both the local hot gas side and coolant side heat transfer coefficients present at the relevant blade surfaces. While a considerable data base exists for the hot gas side coefficients, the data base for the rotating blade coolant passages is very limited. Only recently have measurements in rotating simulated blade passages become available that cover the conditions of interest to aircraft gas turbine blades. At the conditions present in the ATS turbine, extrapolation of the existing data base is needed. An effort is presently underway at CRD that will provide the required heat transfer data base over the range of dimensionless parameters of interest to the ATS turbine.

Progress for the Last Quarter

The outer manifold has been supplied with a heater and thermocouples to allow measurement of the rotational effect on bucket tip heat transfer. Reassembly is now in progress.

Plans for Remaining Work

The bucket tip heat transfer measurements will be completed and the final report will be prepared.

Task 8.6.2 - Rotational Heat Transfer - Wheelspace Cooling

Objective

The interstage turbine wheelspace, diaphragm, and outer seal design, as well as the operating conditions for the ATS turbine, are sufficiently different from existing gas turbine experience to render the use of normal purge flow criteria questionable for preventing hot gas ingestion and for providing sufficient cooling of this region. CFD computations have been used to select a design concept that will be verified in the proposed experiments. An existing GE Freon gas rotational test facility will be modified to simulate the ATS turbine wheelspace geometry. The Rotational and Radial Flow Reynolds numbers present in the ATS gas turbine design can be matched using a 3:1 reduced scale model operating with R-134A at about 21 psia in the cavity. Leakage across the nozzle stage and the effect of the circumferential pressure variation on ingestion will be measured. This testing will allow rapid evaluation of various design approaches.

Progress for the Last Quarter

Test rig construction was completed in December 1995. Test rig assembly was delayed by unexpected alignment problems that have now been resolved. The facility modifications needed to accommodate the test rig have been completed and the plumbing connections are 80% complete. Test rig assembly and instrumentation is 85% complete.

Plans for Remaining Work

Test rig assembly and instrumentation will be completed and the final report will be prepared. The wheelspace cooling test rig will then be ready for check-out and initial testing with the uniform area orifice installed to supply the data base in the absence of circumferential pressure gradients.

Task 8.7.6 - Combustion Instability

Objectives

The objectives of this task are (1) to understand the physical mechanisms responsible for the onset and sustenance of dynamics in lean premixed combustion systems, (2) to obtain detailed experimental data (consisting of frequency, amplitude, rms level, mode shape, and correlations) in the combustor for various upstream and downstream boundary conditions and various fuel delivery system boundary conditions, and (3) to enhance computational capabilities in the form of improved sub-models to better quantify upstream and down-

stream acoustic boundary conditions and fuel delivery system impedances and their effects on dynamics.

Progress for the Last Quarter

No progress was made in this quarter. The spinning valve system is ready for installation in the test rig; however, the test rig was not available in this quarter because of other test activity in the cell.

Plans for Remaining Work

The spinning valve will be installed in the test rig and tested for operability and oscillation strength with actual air flow and production hardware. Dynamic pressure in the combustion liner will be measured, and the excitation frequency will be varied to map the resonant frequencies of the rig.

Task 8.7.7 - Fuel Heating

Objective

Heated fuel can provide improved performance for the ATS gas turbine but must be investigated experimentally to evaluate the effects of hot fuel on system performance and combustion dynamics. One of the technical concerns in the use of fuel heating is carbon buildup in the fuel passages between the heat exchanger and the fuel injector. In this task, a series of exposure tests, using natural gas with various impurity loadings, will be run for conditions representing the operating range of the ATS gas turbine. In addition, techniques to coat large in-situ piping with coke barrier coatings (CBCs) will be developed and evaluated.

Systems issues that affect overall performance will also be considered. An analysis of the fuel delivery system, including the fuel injectors, will be performed to determine the sensitivity to parameters such as pressure drop that influence combustion dynamics. A fuel control strategy will then be developed to address these systems issues.

Progress for the Last Quarter

A process to coat long tubes was developed using an external furnace mounted to a traversing system. After experimenting with various process parameters (such as furnace traverse rate and reagent pressure), an acceptable SiO₂ coating was achieved along the 2-meter length of 25-mm diameter tubing. This work demonstrates that the barrier coatings can be applied to long lengths of large diameter piping such as that used to supply gas for gas turbine operation.

Plans for Remaining Work

The tasks will be completed by the end of March 1996. Activity will be focused on summarizing the results and writing a report.

Task 8.7.8 - Turbulence Intensity Probes

Objective

A turbulent heat transfer probe has been designed to allow measurement of free stream turbulence in a DLN combustion system under full fired operation. This effort will provide for testing of this probe in a combustion environment using one or more of CRD's combustor rigs. This task will also provide testing support in available GE Power Systems combustor test stands, including the ATS Full Scale Nozzle Cascade Test Stand.

The ATS Turbine Inlet Nozzle Cascade will be improved by replacing the aluminum flow-path frame with a stainless steel frame. Other modifications will be made to improve the durability and interchangeable nature of the instrumented airfoils.

Progress for the Last Quarter

Testing of thin-film microsensor probes in combustion-fed environments is sought in this task for the purpose of evaluating the ATS Turbine Inlet Nozzle freestream turbulence intensity level, which has a major and direct bearing on the heat load for the nozzle airfoil and endwall. Upgrade modification to the ATS Turbine Inlet Nozzle Cascade for the purpose of increased durability and flexibility is also included in this task.

Second Test in Full Scale Nozzle Cascade

In preparation for the second series of combustor and nozzle tests in the Full Scale Nozzle Cascade facility at GE Aircraft Engines, a new dynamic turbulence probe was fabricated and delivered to GE Aircraft Engines. At the time of delivery, GE Aircraft Engines indicated that the probe amplifier and shielded signal cable from the previous test could still be used in the current test. The new probe was installed in the nozzle box in December 1995.

On 15 January 1996, the combustor test was started up. A portable Toshiba 6600 PC, with a high-speed data acquisition system to record dynamic sensor information, was used to record the probe outputs. Upon system setup in the control room, it was apparent that the probe signals (at room temperature and zero heat flux) were not correct. The probe signal lines were checked, and the amplifier was found to have an open circuit on the resistance temperature sensor (RTS). The amplifier was apparently damaged.

Concurrent with the amplifier problem, the installed probe was checked and found to have the correct sensor resistances per specification. On 13 January, the probe was checked again and found to have an incorrect reading on the RTS sensor. These readings were verified on 15 January. No explanation could be given for the change, but it is clear that the sensor or the termination leads must have been damaged at some point between installation and final rig closing. After combustor testing was completed, the probe was removed and shipped back to CRD. The probe casing was found to be bent by about 20°, which may have caused breakage of the brazed sensor wires, and hence loss of sensor continuity.

As a result of these findings, GE will be unable to conduct further testing in the Full Scale Nozzle Cascade. The remaining effort will concentrate on probe tests within CRD's DLN combustor development rig (Cell 6). This rig is a single burner rather than the full set of six, and does not model actual liner lengths or transition piece geometry. Since turbulence intensity is not expected to decay much within the liner and transition piece, representative measurements should still be possible. The DLN rig offers the advantage of hands-on control over the flow rates, temperatures, and probe cooling, as well as a location for the probe lead connections in a non-aggressive environment.

Other Progress

Two new "ruggedized" static turbulence intensity probes were received from the manufacturer. One of these probes was calibrated against the response of a dynamic probe (i.e., the original design) using a propane torch as the external heat load and internal water cooling. As expected, the new probe has a slower response time, due to the added protection of the tube external wall, but still develops a comparable signal strength. The second probe was calibrated with a radiation spot heater while the probe was water cooled.

Testing anticipated for the Catalytic Combustion Rig at CRD was postponed for most of this period pending required modifications to the rig. A test was attempted in late February, but aborted due to a faulty soldering connection within the signal extension cable.

All work on the upgraded ATS Turbine Inlet Nozzle Cascade frame was completed.

A combustor liner for use in CRD's DLN combustion development rig has been slightly modified to allow insertion of a turbulence probe.

Plans for Remaining Work

Testing is planned for CRD's DLN combustion development rig using one or both types of turbulence probes, but is dependent on other test programs within this facility.

Task 8.7.9 - Turbulent Heat Transfer - Static Components

Objective

The objective of this task is to obtain the necessary heat transfer boundary conditions to predict the metal temperatures and gradients of the first-stage nozzle airfoils, as influenced by the cooling mechanisms used in the various portions of the nozzle airfoil. Although highly effective in keeping the airfoil cool, the innovative cooling approaches used in the nozzle may impose high thermal gradients through the airfoil walls, making accurate knowledge of and optimization of such cooling critical. Internal convective heat transfer distributions will be supplied by two experimental models, one determining the impingement heat transfer characteristics within the several internal airfoil cavities, the other determining the specific impingement heat transfer enhancements due to the addition of various internal surface features

such as miniature pin-fins. Both experimental models will utilize the thermochromic liquid crystal technique.

The first-stage nozzle endwall and airfoil cooling system is composed of several impingement modules connected in series and/or in parallel to cover the various regions of the endwalls and the airfoil. The impingement hole patterns in each module are tailored to accommodate the hot gas side thermal loads and maintain wall temperatures at acceptable levels. Calculations performed for the existing hot gas side thermal load levels have shown that in specific regions with very high gas side heat transfer coefficients, some enhancement techniques are needed on the impingement surfaces. The open literature has reported results with two-dimensional and axisymmetric jets impinging on surfaces with linear or concentric roughness elements (Miyake, Hirata, and Kasagi, *Exp. Heat Transfer*, 1994). Although they enhance the local heat transfer, these roughness elements also increase the pressure drop and are not independent of the impingement hole geometries.

An investigation and determination will be made of 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.

An investigation will also be made of the pressure drop and heat transfer coefficient distributions for first-stage nozzle airfoil spanwise impingement passages, and the results obtained will be compared with the values expected from the design methods.

The limited nozzle trailing edge air film cooling will be evaluated with warm rig testing to determine the most effective geometry for minimal coolant usage.

Progress Since the Last Reporting Period

Surface Enhanced Internal Heat Transfer

Heat Transfer Results

Heat transfer tests were conducted with twelve jet plates having different jet diameters and jet-to-jet spacings. The test plates used had either a plain surface or a nominal bump geometry for optimized heat transfer enhancements. The plain surface results agree with Metzger's correlation (Florshuetz, Truman, and Metzger, *ASME J. of Heat Transfer*, 103, pp. 337-342, 1981) and have a ± 15 percent variation from the correlation predictions. Impingement heat transfer tests were also conducted with the same jet plates and the specific enhanced test plate with the optimized bump geometries.

The data obtained with the enhanced bumpy surface were recorded at laboratory test conditions. The engine design conditions are not similar to the test conditions but have higher wall temperatures and higher heat transfer coefficient levels. To transfer the laboratory test results to the machine conditions, fin efficiency calculations were performed as a function of the specific bump geometry, metal thermal conductivity and coolant side heat transfer coefficients. The enhancement results presented above were corrected for the fin efficiencies at the laboratory conditions. The design calculations for enhanced surfaces using the bump geometries will use the same fin efficiency curve to scale the laboratory results to the machine conditions.

Nozzle Airfoil Impingement

First pressure distributions tests were conducted with both the pressure and suction sides flowing to generate information to build flow models. The results obtained showed a constant supply static pressure on the pressure side and a decreasing one along the suction side from inlet to discharge end.

To run the heat transfer tests, the flow rate was set to a specified value, the static pressure distributions were measured and the heat flux to the etched foil heaters was increased in specific increments. Once a steady state was reached and the temperature distributions of the liquid crystals were not changing with time, the color (temperature) field of the liquid crystal was recorded with the Liquid Crystal Video Thermography (LCVT) system developed at CRD.

Trailing Edge Film Cooling

The two objectives for this film testing are:

- (a) Determine the most advantageous film cooling geometry for use on the turbine inlet nozzle trailing edge region, where limited air film cooling will be employed. The geometry is subject to certain constraints, such as castability, limited axial space for the feature(s), and a common supply pressure for both pressure and suction side film.
- (b) Measure the adiabatic film effectiveness downstream of the film injection under conditions representative of the mainstream flow field, the coolant-to-gas density ratio, and the blowing ratio.

During this period, the suction side model was re-installed in the Warm Wind Tunnel rig at CRD. Two suction side film geometries were tested, those being the baseline radial holes case, and the best performing slot-like geometry from the pressure side results. Recall that previous suction side model results became suspect when two leaks were discovered in the upstream coolant supply lines, after the orifice metering station. These leaks were corrected prior to taking any pressure side data, and the entire line was checked at that time.

The present results are free from leaks. The suction side model is simply a constant area channel, without pressure gradient. The established Mach number at the location of coolant injection is 0.76. Two film geometries were tested:

- (1) Radial round holes, $P/D = 4$, $S/D = 0$, 30-degree angle to surface
- (2) Slot-like geometry of film

P is the hole pitch, and D is the hole diameter.

Four blowing ratios, M , were tested with the radial holes, with density ratios, DR , of 1.74 to 1.90. The results are a bit better than the same film on the pressure side model, but the effectiveness tends to come to the same value far downstream.

For the slot-like film geometry, the suction side film effectiveness is much higher in the near slot region than it was on the pressure side, but again they tend to the same level far

downstream. At the higher Mach number without pressure gradient, the slot film shows more spread of effectiveness magnitude with M .

Comparing the two film geometries, the slot-like film is the better only very near to the film injection location. After this region, the radial holes are better, and far downstream there is little difference (and higher uncertainty). Overall, the radial film holes appear to give the better performance, disregarding any effect on heat transfer coefficients.

Plans for Remaining Work

Prepare final report.

Task 8.7.10 - Transition Piece Design Tools

Objectives

Higher firing temperatures in the ATS gas turbine make the transition piece a crucial component. Flow separation in the transition piece must be avoided since it results in locally high heat transfer that could lead to liner burnout. Improved analytical prediction of flow separation in transition pieces will reduce the required amount of testing, and reduce design risk. Faster meshing capability will allow for increased use of CFD analyses on complex transition piece geometries, reducing cycle time. This project involves further development of a 3D unstructured meshing system to make it more automatic and robust for complex transition duct geometries, through a subcontract with MIT. Another aspect of the project is to improve our ability to predict flow separation in transition pieces through the use of adaptive meshing and advanced turbulence models.

Progress for the Last Quarter

MIT Subcontract

The initial implementation of the Geometry Viewer has been completed. The Geometry Viewer is an integral part of the unstructured meshing system being developed in this project, as it will allow the mesh to be viewed as it is being created, and allow the user to interact more effectively with the meshing procedure. All low-level 3D (and some 2D) drawing is done using the OpenGL standard. A freeware full emulation of OpenGL for X-Windows, MacOS, and Windows was located on the WEB. This emulation has been tested successfully using Visual3 (which has simpler drawing requirements) on all major UNIX workstations using 8-bit color.

The initial implementation of the new meshing software has been completed. The directional refinement seems to be working fine. This allows elements to be produced which are stretched along leading edges. An example of a mesh with this directional refinement is shown in Figure 8.7.10-1. The initial grid has been pre-refined along the leading and trailing edges of a wing geometry. The interface with the graphical front end is almost completed and was demonstrated to GE during our February visit.

The new meshing code has the ability to mix FELISA and PARASOLID geometry, which means that wakes can now be incorporated easily. An example of a mesh with wakes is shown in Figure 8.7.10-2, where the wake meshes behind the wing and behind the tail rudder of an airplane can be clearly seen.

A mesh for a typical transition piece geometry was successfully generated using the new meshing system, as shown in Figure 8.7.10-3. The success of the directional pre-refinement in creating stretched elements that are aligned along the walls of the duct and are capable of resolving the flow in the boundary layer is apparent.

Figure 8.7.10-1. Directional Pre-refinement of Mesh at Leading and Trailing Edges of Wing Geometry

Figure 8.7.10-2. Wake Meshes Behind Wing, Tail Rudder of Aircraft Geometry

Figure 8.7.10-3. Unstructured Mesh for Typical GE Transition Piece Generated with New MIT Meshing Software

Improved STAR-CD Meshes

Work has focused on improving the user interface. The major effort has been to eliminate the user inputs required by the meshing script, so that transition piece grids can be generated automatically. Most of the user input can be eliminated by hard-coding specific node numbers into the script as was done previously; unfortunately this was not a very

robust fix for this problem. The program that generates the initial node layout offers the option of using a different starting node number. If this option was chosen, the previously implemented fix would not work. To accommodate that option and to eliminate the rest of the required user input, the way in which the script locates inlet planes, outlet planes, planes of symmetry and other points was totally rewritten.

Additional work focused on improving the modeling of the boundary conditions at the exit of the transition piece. It has been suggested that moving the constant pressure boundary away from the physical end of the transition piece improves the ability of the code to predict separation.

Plans for Remaining Work

MIT Subcontract

The goal is to complete the coding and testing of the new meshing system and geometry viewer by the end of the contract (31 March), and deliver the code to CRD.

Improved STAR-CD Meshes

The improvements to the modeling of the boundary conditions will be completed in March. Time permitting, additional improvements to the user interface will be made in March, as will a refinement of the mesh in the boundary layer region.

Task 8.7.11 - Effects of High Mach Number Diffuser

Objectives

Proposed compressor exit designs for the ATS gas turbine give much higher exit Mach numbers than have previously been experienced. Potential difficulties include high combustion dynamics, a need for higher combustor system pressure losses to cool hardware, and flow field imbalances that increase the difficulty of obtaining low emissions. Studies are required to quantify risk and evaluate alternate designs. Three approaches are being followed. Laboratory testing in the GE Power Generation Laboratory test stand with modified inlet diffuser and pressure, dynamics and temperature measurement instrumentation will be carried out to evaluate the effects of increasing compressor exit velocities and the impact of split diffusers. At CRD, flow tests on existing multi-combustor models will be carried out for validation via flow visualization and pressure measurement of the impact of higher compressor exit velocities and split diffuser designs. CFD will also be used to model the flow field within the compressor diffuser/combustor wrapper volume to evaluate potential problems and likely solutions.

Progress for the Last Quarter

Progress in this quarter was in three areas: adding wall static taps to the Design 3 diffuser, modifying the test stand to achieve a wide range of inlet velocity profiles, and running trial tests with the Design 2 diffuser.

In order to adequately measure the aerodynamic pressure recover of the Design 3 diffuser, it was decided to install wall static pressure taps to all surfaces of the diffuser. To facilitate disassembly and reassembly while maintaining the diffuser geometry, aluminum alignment plates were imbedded into each of the end walls. All static taps have a diameter of 0.020 inch. On the two diffuser endwalls, metal tubes connect the backside of each of the static taps, which are then connected to pressure measurement instrumentation.

To ensure that the diffuser will work under all compressor operating conditions, four different diffuser inlet velocity profiles have been chosen. To achieve these inlet velocity profiles, the inlet to the test stand had to be modified. An annular sector inlet was constructed and attached to the front of the diffuser. A flow profiler, consisting of a perforated plate covering the inlet, is mounted to the inlet of the annular sector. Then sheet metal profiler shapes are fastened to the perforated plate. The sheet metal plates block the flow in such a way as to achieve the proper flow profile. There are different shapes of blockage for each of the profiles. After much trial and error, the four profiles were achieved.

Because the Design 3 diffuser was not available for use, the Design 2 diffuser was used to make trial runs to check out inlet velocity profiles and make limited measurements of pressure recovery in the diffuser.

The next phase of this program will be to carry out the diffuser pressure recovery measurements for Design 3. Due to the expansive nature of the original objective and the large body of work that has been done (4 diffusers have been built and tested), the Design 3 diffuser test will be done under Phase 3 of the ATS program.

Plans for Remaining Work

The final report will be prepared.