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

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EXECUTIVE SUMMARY

General Electric 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 the GE Power Systems.

Achieving the advanced turbine system goals of 60% efficiency, 8 ppmvd 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 efficiency and cost goals. However, higher temperatures move in the direction of increased NO_x emission. Improved coating and materials technologies along with creative combustor design can result in solutions to 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 encompasses 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 70MW class industrial gas turbine based on the GE90 core technology utilizing an innovative air cooling methodology.
2. A 200MW 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 Advanced Turbine System (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 upon innovative cycle design and low emission combustion. The emphasis for the utility 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 emissions combustion. Significant overlap in the development programs will allow common technologies to be applied to both products. GE's 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.

INDUSTRIAL ATS – STATUS OF TASK 3 – TASK 8

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 has been completed. The cycle selected is based on the GE90 aero engine, and meets the ATS goals for overall cycle efficiency and NO_x. The third program goal (-10% cost of electricity) will be evaluated in Task 5. Details are given in the Yearly Technical Progress Report.

Task 4: Conversion to a Coal Fueled ATS (FATS)

Definition of needed fuel properties for coal derived fuels has been completed and engine cycle and component studies are continuing.

Task 5: Market Study

The Market Study work effort was concentrated on the initialization of the North America Electricity Reliability Council (NERC) region models required for the FASTPLAN capacity expansion model. Electricity demands as reported in the NERC's "Electricity Supply and Demand" database (June 1994) are used to define long term capacity needs. A preliminary report is included in Tab 3. A detailed report will be available for the next Monthly Report.

Task 6: System Definition and Analysis

Overall plant layout studies have been completed. Thermodynamic studies to evaluate engine performance as a function of ambient temperature have been completed for both simple cycle and combined cycle configurations. Component analysis for the intercooled engine configuration has been completed. Component analysis have been completed for the following sub-systems:

- Engine Cycle System
- Low Pressure Booster
- Combustor/Emissions & Cooling
- Turbocooler System
- High Pressure Turbine
- Low Pressure Turbine
- Thermal Barrier Coating Applications
- Material Applications
- Engine Packaging
- Power Plant Layout

Figure 1 shows the overall engine package for the gas turbine engine only.

Task 7: Integrated Program Plan

No progress on this Task during reporting period. Task will be performed with cycle information developed in Task 3.

Task 8: Design and Test of Critical Components

The overall objective of this Task is to perform experimental evaluations that will enable implementation of advances in several areas critical to the Industrial and Utility ATS. Seven sub-tasks comprise this Task, and are reported individually in Tab 5.

Task 8.5: (Enhanced Impingement Heat Transfer) deals directly with the Industrial ATS

Texas A&M University has finished heat transfer testing of different impingement configurations for the high pressure nozzle and has finished the final report for the testing that was done.

GE90 ATS BASED MACHINE

CONFIG=BOOSTED,TURBOCOOLED,
INTERCOOLED,CORE,LPT

NET POWER OUTPUT(SC/CC)=132/159MW

EFF.(SC/CC)=50/60.4

Figure 1

TASK 5 MARKET STUDY RESULTS

The economic potential of gas-fired advanced turbine systems was determined using GE's FASTPLAN capacity expansion model. To account for regional differences in existing generation mix and fuel prices, detailed simulations were performed for regions as defined by the North American Electric Reliability Council (NERC).

Regional capacity needs for the NERC regions are summarized in Table 1. The capacity needs, reserve margins and capacity margins reflect utility plans as reported in NERC's Electricity Supply and Demand Database (ES&D). The 1995 ES&D Database was made available about a month ago. It is important to note that both reserve margins and capacity margins are decreasing over the 1995-2004 study period. In the past, most utility systems were designed with a reserve margin of 18-22%. Reserve planning criteria in most regions are decreasing to 11% levels or lower according to the NERC data.

According to the NERC ES&D Database, total capacity needs over the 1995-2004 period are 80,190MW. The FASTPLAN capacity expansion analysis for six NERC regions shows that the economic potential market for gas turbines is 64,000MW. The distribution of additions by region and time is summarized in Table 2.

The FASTPLAN results reflect gas turbine performance and cost data summarized in Table 3 and DRI fuel cost projections summarized in Figure 1. The coal-fired option in the FASTPLAN capacity expansion analysis was assumed to be a coal-fired integrated gasification combined cycle (IGCC). The IGCC option was priced very competitively at \$1,100/kw (1995\$) with an 8100 Btu/kwh (HHV) heat rate.

Figures 2-10 show cost of electricity for a variety of current and advanced technology gas turbine configurations for operation in 1999, 2023, and a composite value over 25 years. Also included is a map of the NERC.

Table 1**Regional Capacity Needs and Reserve Margins**

<u>Nerc Region</u>	Capacity Need 1995 through 2004 <u>(MW)</u>	Reserve Margin % of Peak Demand		Capacity Margin % of Firm Demand	
		<u>1995</u>	<u>2004</u>	<u>1995</u>	<u>2004</u>
SERC	33,300	12.4	11.1	16.0	15.2
ECAR	11,940	16.5	13.5	16.4	14.8
WSCC	10,670	22.8	13.4	21.8	15.6
MAAC	5,690	20.9	17.2	20.8	19.2
ERCOT	6,730	19.3	11.5	19.5	13.9
SPP	5,730	17.3	9.8	18.5	13.4
MAIN	4,030	15.9	12.0	16.4	16.7
MAPP	1,100	17.3	-0.5	16.8	7.6
NPCC	<u>1,000</u>	30.2	18.3	23.3	15.6
TOTAL	80,190				

Source: North American Electric Reliability Council (NERC)
Electricity Supply & Demand (ES&D) Database, May 1995

$$\text{RESERVE MARGIN} = \frac{C - P}{P}$$

$$\text{CAPACITY MARGIN} = \frac{C - P'}{C}$$

Table 2**Economic Potential Market For Gas Turbines (MW)**

<u>Region</u>	<u>1996</u>	<u>1997</u>	<u>1998</u>	<u>1999</u>	<u>2000</u>	<u>2001</u>	<u>2002</u>	<u>2003</u>	<u>2004</u>	<u>Total 1996-2004</u>
SERC		1771	3795	3850	3500	3850	3360	3850	3850	27,826
ECAR		1008	1008	2016	1200	1512	1680	1920	1750	12,094
WSCC				700	2100	0	2100	2100	2100	9,100
MAAC		759	759	700	1050	700	1050	1050	350	6,418
ERCOT				350	1400	1050	0	1050	1050	4,900
SPP			506	1050		700	1400			3,656
TOTAL		3538	6068	8666	9250	7812	9590	9970	9100	63,994

Table 3

Gas Turbine Performance & Cost Data

<u>Current Technology</u>	Net Output (MW)	Efficiency η LHV (%)	Heat Rate LHV (Btu/kWh)	Total Installed Cost (\$/kw)	<u>O&M</u>	
					Fixed (\$/kw/yr)	Variable (\$/MWH)
Utility Current Technology (SC)	167.8	36.2	9,420	321	1.7	2.5
Industrial Current Technology (SC)	78.8	38.3	8,910	460	2.0	2.9
Utility Current Technology (CC)	253.4	55.0	6,200	535	13	1.6
Industrial Current Technology (CC)	230	52.4	6,510	754	17	2.0

Advanced Technology

Utility Advanced Technology (SC)	240	39.5	8,640	302	1.7	2.5
Utility Advanced Technology (CC)	350	58	5,883	500	11	1.3
Industrial ATS (SC)	131.9	50.3	6,790	450	1.8	2.6
Industrial ATS (CC)	158.6	60.4	5,647	680	15	1.8
Utility ATS (CC)	400	60	5,687	480	11	1.3

Note: Except where indicated, all performance data reflects ISO conditions and natural gas fuel.
All cost data in 1995\$.

Figure 1

UTILITY FUEL PRICES (NOMINAL) IN CURRENT YEAR \$

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

COMBINED CYCLE COST OF ELECTRICITY

1999 INSTALLATION, 50 % CAPACITY FACTOR

DRI PROJECTED GAS PRICES, 1999-2023

Cents/kWh
(Current Year \$)

10
9
8
7
6
5
4
3
2
1
0

9.4

O&M

Fuel

Capital Costs

2023

STAG 107G

5.3

O&M

Fuel

Capital Costs

25 Year Levelized

4.2

O&M

Fuel

Capital Costs

1999

Figure 8

Figure 9

Figure 1D

COMBINED CYCLE COST OF ELECTRICITY

1999 INSTALLATION , 50 % CAPACITY FACTOR
DRI PROJECTED GAS PRICES ,1999 - 2023

UTILITY ATS – STATUS OF TASK 3 – TASK 8

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

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

The Utility GFATS cycle selection has been completed. The cycle selected is a growth version of the current MS7001F machine, and meets the ATS goals for overall cycle efficiency and NOx. The third program goal (-10% cost of electricity) will be evaluated in Task 5. Details are given in the Yearly Technical Progress Report.

Task 4: Conversion to a Coal Fueled ATS (FATS)

No progress on this Task during reporting period. Task will be performed with cycle information developed in Task 3.

Task 5: Market Study

The Market Study work effort was concentrated on the initialization of the North America Electricity Reliability Council (NERC) region models required for the FASTPLAN capacity expansion model. Electricity demands as reported in the NERC's "Electricity Supply and Demand" database (June 1994) are used to define long term capacity needs. A preliminary report is included in Tab 3.

Task 6: System Definition and Analysis

Work was begun on the Utility ATS System Definition and Analysis report. Topics covered include descriptions of GFATS conceptual design, components, accessories, bottoming cycle and component life and maintainability.

Task 7: Integrated Program Plan

No progress on this Task during reporting period. Task will be performed with cycle information developed in Task 3.

Task 8: Design and Test of Critical Components

The overall objective of this Task is to perform experimental evaluations that will enable implementation of advances in several areas critical to the Industrial and Utility ATS. Seven sub-tasks comprise this Task, and are reported individually in Tab 5.

Task 8.1: Particulate Flow Deposition

Task 8.2: Particulate 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: Heat Transfer and Combustion Instability

Task 8.7.1: Turbine Inlet Nozzle Heat Transfer

Task 8.7.2: Turbulent Heat Transfer

Task 8.7.3: Nozzle End Wall Impingement

Task 8.7.4: Nozzle Airfoil Impingement

Task 8.7.5: 1st Stage Bucket Heat Transfer

Task 8.7.6: Combustion Instability

During the reporting period, the Phase 2 work scope was modified to include the following subtasks. Work has begun on several of the tasks.

<u>Task Title</u>	<u>Related Task</u>
7G Preliminary Design	6
Coolant Purity	8.1
Advanced Seals	8.4
Rotational Heat Transfer	8.6
Effect of Hot Fuel on Combustion Dynamics	8.7
Rotor Materials Coolant Compatibility	8.2
Nozzle Cascade Prel. Test & Facility Qualification	8.7
TBC Testing & Analysis	8.3
LCF Life and Crack Propagation	8.3
Turbulence Intensity Probes	8.7
Bond Coats for Improved TBC Thermal Cycle Life	8.3
Rotational Heat Transfer-Wheel-space Cooling	8.6
Short Liner	8.7
Turbulent Heat Transfer-Static Components	8.7
Critical TBC Properties	8.3
Increased Mach Number Diffuser Design	8.7
Transition Piece Design Tools	8.7

QUARTERLY PROGRESS REPORT BY SUBTASK

Task 8.1 - Particulate Flow Deposition

Objective

The primary objective of Task 8.1 is to characterize the particulate generated in an operating gas turbine combined cycle (GTCC) power plant whose configuration approximates that proposed for an Advanced Turbine System (ATS) power plant. In addition, the task is to evaluate the use of full-flow filtering to reduce the stream 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.

Progress Since Last Reporting Period

The coolant filtration system has remained on-line, and more coolant characterization samples have been taken. The coolant continues to be isokinetically sampled, condensed, and run through 47-mm cellulose acetate filter disks of either 0.1- or 0.45-micron porosity. With the second condenser and filter now on-line, these measurements are being made simultaneously on the same coolant flow. Three-hour samples clearly showed oxide particles of up to 20 microns in the upstream sampled coolant while the downstream filter showed oxide chips smaller than 0.5 micron. In Figure 8.1-1, there are very few crystals in the upstream sample (top), and the oxide particles are seen clearly. In the downstream sample (bottom), particulates in the cellulose acetate mesh are visible on the top of the filter as white spots that are collections of 0.1- to 0.2-micron particulates. These results indicate that the 2-micron filter cartridge is working well. Electron microprobe analyses of the particles in Figure 8.1-1 report the presence of Fe, Cr, and Mo, all of which are elements in the superheater T22 alloy, which is considered the primary source for the coolant particulates.

More has been learned about the crystal structures seen on condensate filters exposed for a number of days. Rod-like crystals about 0.5 micron in diameter and between 8 and 10 microns in length grow on the filter at long exposures. Electron microprobe analyses this quarter have shown that they contain only iron and oxygen and no alloying elements. These crystal structures dominate the scanning electron micrograph (SEM) images in some cases. They grow out of the fine particulate oxides collected on the filter. Their number and size increase with the amount of deposit collected. They appear to grow from agglomerates of small particles (less than 0.3 micron) as opposed to growing on the oxide chips larger than 1 micron. Figure 8.1-2, downstream sampling over a seven-week period on a lower porosity 0.1-micron filter shows "mud-cracking" of the very fine cake and crystallites growing from the cake, giving it a "hairy" appearance. No chips of oxide are visible in this specimen. The cake structures result from the filter support hole pattern (large circles) and the bubbling up of the cake as it is exposed to the hard vacuum of the SEM and the possible dislodging of cake agglomerates during filter handling.

Water chemistry experts who have examined similar filters from BWR reactor water observed that the crystal structures shown in the lower image of Figure 8.1-2 are familiar and are referred to as "star critters" and "fern critters." The crystal structures are not present in the coolant stream itself. Over long periods of time at the 90 F condensate

temperature, the fine oxide particles collected on the filter cake are dissolved and grow crystallites.

Since the very fine particulates (under 0.5 micron) collected on these condensate filters over long time periods can result in deceptively large (tens of microns) structures unrelated to the size of particulates in the sampled flow, future samples will be taken over shorter periods of time (a few hours). The resulting images will then be dominated by the captured particulates and not the crystals that grow from them. This change will also eliminate the build-up of filter cakes that capture particles much smaller than the nominal filter porosity.

All chemical analyses of metals collected to-date on the 0.45-micron filters indicate that iron oxide, which is present at 1 ppbw or less, is the major contaminant.

Upstream and downstream sampling was conducted simultaneously in two separate systems. Long-term exposures (3-4 days) again revealed the recrystallization of oxide material to form needle-like structures. Shorter term exposures (1-2 hours) showed more chip-like oxide structures on the cellulose acetate filters with very few needles. This result suggests the use of shorter sampling periods in the future to minimize the opportunity for recrystallization of the collected oxide material. In addition, the downstream filters were much cleaner than the upstream filters (operated at the same steam condensate filtration rate), demonstrating that the screen filter was working. However, the downstream filters still contained a very few 4-micron agglomerates of smaller materials. These are thought to represent fine material that had been deposited in the steam sampling system and then released to the filter. Almost all these larger chips on the downstream sample filter were clearly agglomerates.

The filtration apparatus was shut down to recover the filter and allow plumbing work to begin for installation of the centrifuge for Task 8.2. The filter looked very good after a total of about 2500 hours of exposure. The surface color had darkened to a dark brown over the screen, but the surface looked intact and was still strong. Attempts were made to brush any filtered debris off the outer surface, but none was visible to the naked eye, and no material could be collected. A fine wire screen on top of the powdered metal surface was still very clean, and no material was visible in its interstices.

Tab 6 contains ASME Paper 95-GT-281, entitled "Ensuring Adequate Coolant Purity for Advanced Gas Turbines," was presented on June 5 at the ASME Turbo Expo Meeting in Houston by D.E. Woodmansee. The paper described the importance of cleaning the steam in the high-G fields encountered in closed cycle cooling and showed how the critical size of about 0.5 micron was predicted by both settling- and 3D-CFD calculations. Photographs of the filtration apparatus, filters, and the centrifuge (Task 8.2) were shown without specifying locations, vendors, part numbers, etc., since the work is not yet complete.

Plans for Next Reporting Period

The system will continue to remain on-line with the condensate samples being taken over shorter periods of time. When the centrifuge reaches the plant and is put on-line, the coolant system will be shut down and the filter cartridge inspected again.

Task 8.2 - Coolant Particle Centrifugal Sedimentation

Objective

The primary objective of Task 8.2 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 Advanced Gas Turbine (ATS) engine. 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.

Progress Since Last Reporting Period

The centrifuge has been assembled without the coolant seals in place and successfully turned at 1000 rpm at the subcontractor shop with no problems or vibrations. The assembled centrifuge system was shipped to Building 263 (Aero Development Lab) in the GE Main Plant and plumbed for a cold spinup trial to 5000 rpm, which is 200 rpm

over the design value of 4800 rpm. All systems are mounted on the 6 foot $\times$ 10 foot skid; the unit is about 7 feet high and weighs 13000 lbm.

A cold spinup test to demonstrate satisfactory mechanical performance of the centrifuge without steam flows but at speeds up to its design point of 4800 rpm was successfully accomplished in Building 263 of the GE Main Plant. This design point would provide a 15,600G acceleration field, matching the field in the ATS second-stage bucket cooling passage, where the formation of insulating deposits would be critical in reducing the target 24000-hour Time Between Outages for bucket cleanup.

The test reached 4300 rpm smoothly before becoming limited by the inability of the steam ejector facility to hold a rotor chamber pressure of 2 psia. This is 90% of design speed and 80% of design G-loading, which was considered to be a successful demonstration of mechanical performance of the system during this cold run. Electrically, the system also worked well, operating at 105% of design load (40 hp) and 77% of design torque. In continuous hot operation at the power plant, we expect to utilize less than half this power.

Plans for Next Reporting Period

The system has been shipped to the vendor for installation of the steam seals that could not be in place during cold spinup. Heaters are also to be mounted on the system. The system will then be shipped to the power plant for installation. The insulation on the rotor housing will be made removable since any large steam leakage through the rotor housing seals may require heat dissipation from the case instead of insulation. Only the on-site test will enable us to make a decision as to how much insulation will be needed.

Task 8.2.1 - Materials Coolant Compatibility

Objective

In Task 8.2.1 the effects of the operation of gas path materials and structural materials in the coolant environment expected for advanced gas turbine operating conditions will be evaluated. Potential barrier problems and their solutions will be identified. While emphasis will be on development of techniques for testing, some testing will be performed on early material and process trials to begin to gain an understanding of the behavior of the materials. Testing will include fatigue crack propagation, low cycle fatigue, creep, and slow strain rate tensile testing. Comparisons will be made to air environments.

Progress Since Last Reporting Period

Enhancement of the SPLCF (sustained peak load low cycle fatigue) test stations to include crack length monitoring by dc electrical potential drop has continued. One shake-down test and two real tests have now been run with this new instrumentation. The results are encouraging. Data will be accumulated on subsequent tests to establish trends to allow real-time estimates of remaining specimen life.

The calibration of specimen geometries is complete. The current hollow LCF specimen geometry used with an internal and external air environment shows the same strain range versus life dependence as the more conventional solid geometry used in LCF testing done in air.

We have completed the enhancement of one of our new, deadweight-loaded screening test stations by modifying it to include crack length monitoring by dc electrical potential

drop. Data from the first test using this instrumentation show excellent agreement with tests run under full instrumentation in a servo-hydraulic machine.

Enhancement of the second SPLCF has continued. One additional deadweight-loaded, screening test station has been modified to include crack length monitoring by dc electric potential drop. There are now two stations with this capability. The quality of crack length data from these two stations is excellent.

Design of instrumentation and a data collection system to instrument six additional screening test stations with dc electrical potential drop crack length monitoring capability has been completed. Preparation of improved, multichannel data collection software has been completed and beta tested with sample data. The new system will allow for simultaneous monitoring of deadweight-loaded crack propagation tests in eight stations, six of which will have the capability for testing in the coolant environment expected for advanced gas turbine operation.

Plans for Next Reporting Period

Instrumentation and a data collection system will be installed to provide six additional screen test stations with dc electric potential drop crack length monitoring capability. This effort should begin in the next reporting period. Two sustained-load, screen test stations will be instrumented with stepping motors to provide the capability to run extremely low frequency cyclic loading tests. Parts have been ordered.

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. The first 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.

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 developed further include thin-film thermocouples, thin-film strain gauges, IR pyrometers, surface profile monitors, and laser fluorescence of the thermally grown alumina layer.

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 near-critical 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.

Progress Since Last Reporting Period

Four "tophat" specimens with various bond coat/TBC interface stress states (-30, -60, -60, -90 kpsi) have been fabricated to map and confirm the numerical modeling of the sample strain state during thermal test and are ready for testing. Calculations, machining, TBC coating, and instrumentation (13 backside thermocouples and 8 strain gauges) are complete. After final checkout and debugging of the E-beam, these samples will be tested to measure/verify the TBC conditions (strain state, surface temperature levels, temperature distribution, and through thickness thermal gradient) for a given tophat sample geometry and compare them with the numerically modeled values.

Numerical Modeling

The 3D thermal and stress analysis of the tophat specimen is in progress. A 3D model, that includes material orthotropy, has been created in ANSYS to allow analysis of specimens of various dimensions and loading conditions. This model has been validated against experimental results from tests of isotropic substrates. After further validation, predictions and post-test analyses will be performed on tophat specimens under various conditions. Sensitivity studies have been completed to determine the required mesh refinement for accurate results and minimum CPU time and disk space. It was found that a combination of linear elements (for the thermal analysis) and quadratic elements (for the structural analysis) minimize the resource requirements for these calculations.

The role of the present analyses is to design valid experiments for measuring specimen life and to help interpret experimental test results. Because of the anisotropic material properties of the substrate, 3D thermomechanical stress analysis is necessary to capture the effect of the orientation of the crystallographic axes. The actual material orientations measured in the test samples are being used as inputs to the numerical model.

Further validation of the 3D model is continuing: 3D results compare well with previous 2D ANSYS calculations for the axisymmetric analysis and isotropic substrates, and comparisons with experimental data are underway. The current focus is on refining the thermal and structural boundary conditions. Many uncertainties exist in the values of the experimental heat fluxes and heat transfer coefficients, some of which may significantly influence the analysis results. Sensitivity studies are being performed to determine the best set of boundary conditions to use for subsequent analyses.

When compared with test data, the current thermal results can be made to compare with the thermocouple readings. However, stress predictions currently exceed test data obtained from strain gauge readings by a factor of approximately 2. We are studying the effect of the boundary conditions on the stress predictions to determine which ones are most representative of the test conditions.

The effect of using ReneN5 (anisotropic material) as the specimen substrate has also been examined. The predicted bondline stresses for N5 can either increase or decrease, by approximately 20%, when compared with GTD-111 (isotropic) calculated stresses. The actual stress level in N5 specimens depends on the orientation of the crystallographic axes.

Plans for Next Reporting Period

The first set of samples will be tested to measure/verify the TBC conditions (strain state, surface temperature levels, temperature distribution, and through thickness thermal gradient) for a given tophat sample geometry and compare them with the numerically modeled values.

The first numerical modeling will be started. Design of the mechanical test samples will be initiated. Casting requirements for the E-beam fillet specimen will be discussed with Howmet, the casting vendor.

Task 8.3.2 - LCF Life and Crack Propagation

Objective

In Task 8.3.2 Low Cycle Fatigue (LCF) life of the most critical regions of the ATS turbine inlet nozzle will be evaluated 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 Since Last Reporting Period

This is the first reporting period for this task. Planning efforts are underway to scope out the requirements for testing, such as dynamic crack detection methods, safety precautions, and specimen geometry.

Plans for Next Reporting Period

Analyses will be initiated on specimen models to determine the effects of initial cracks, pre-formed cracks, and crack strain relief on a variety of geometries.

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 0.015"-thick, dense, vertically microcracked, 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 Since Last Reporting Period

Preparation of Samples for Experimental Matrix and Choice of Bond Coat Parameters

Over 200 N5 single crystal buttons have been machined and numbered and have been mounted on metal foil for application of APS NiCrAlY and APS Co129 bond coats and APS 8YSZ top coat. A test specimen matrix has been established that will emphasize

materials and processes critical to the Advanced Turbine Systems. The matrix will cover temperature trials from 1800 F to 2200 F and two different thermal cycling rates. These substrates will be coated and subsequently separated according to bond coat type and coating parameters.

During this reporting period experiments were conducted to assess the effect of variations in bond coat parameters on bond coat microstructure prior to committing the entire matrix to a set of bond coat spray parameters. To conserve the N5 substrates, IN718 substrates were used for the bond coat trials. Test specimens were sprayed using both APS NiCrAlY and APS Co129 bond coats. A baseline set was sprayed using standard conditions with N₂ as the carrier gas and a 5-inch gun-to-substrate distance. Additional sets were sprayed using air as the carrier gas and gun-to-substrate distances of 5, 7, and 9 inches. The sprayed samples have been submitted for metallographic examination.

Plans for Next Reporting Period

Bond coat microstructures will be evaluated. Thick bond coats will be prepared for evaluation of Young's modulus. A decision will be made regarding the bond coat parameters required to produce significant changes in bond coat mechanical properties. The selected bond coat parameters will be utilized in spraying the test matrix for furnace cycle and furnace exposure testing of specimens.

Task 8.3.4 - Critical TBC Properties

Objective

TBC thermal conductivity is clearly important for thermal analysis and design of coated turbine components. Current practice uses conductivities that are measured using laser flash techniques that directly evaluate the thermal diffusivity. 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 exposed to a short-duration, high-temperature impingement jet to provide a uniform heat flux over the test region of interest. Instrumentation data and known heat flux will be used with finite element modeling to determine the effective thermal conductivity and the TBC thermal conductivity.

Progress Since Last Reporting Period

This is the first reporting period for this task, which is in the planning and scheduling stage.

Plans for Next Reporting Period

Design of the thermal conductivity test rig will begin.

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 crossflow 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 crossflow mixes and raises the temperature of the cold air jet before it strikes the hot wall.

Progress Since Last Reporting Period

Texas A&M University has finished heat transfer testing of different impingement configurations for the high pressure nozzle, and has finished the final report for the testing that was done.

Task 8.6 - ROTATIONAL HEAT TRANSFER

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 power gas turbines being designed today, 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.

The rotating test facility installed at CRD in 1993 is now obtaining data in smooth rectangular full-scale blade cooling passages. Electrical heat addition is employed on each of the few passage walls that are instrumented with thermocouples to determine the local heat transfer coefficients. The coolant pressure is varied over a broad range to achieve the required ranges of Reynolds number and Rotation number.

Progress Since Last Reporting Period

A review of the blade tip and aspect ratio test section data taken at speeds of up to 900 rpm showed that no further data are needed at the blade tip, but several added data points are desirable for the rectangular duct. The turbine tip data showed the same increase with Buoyancy number at the maximum rpm as measured previously at up to 650 rpm. The potting compound used to hold the thin film heater instrumentation in place failed at 800 rpm. Inspection showed an inadequate bond to the steel enclosure.

The improved formulation of the bonding agent was successfully tested up to 900 rpm. The data for the turbulated aspect ratio duct required at 900 rpm was then completed. The aspect ratio test section has been removed to allow installation of the aspect ratio duct.

For lead and trail side heating, only the minimum heat transfer coefficient as a function of Buoyancy number was about the same as with four side heating; but it was significantly less than that with four side heating at high Buoyancy numbers. The measured radial location of the minimum heat transfer coefficient on the lead side in radial outflow was in reasonable agreement with the location predicted by a CFD analysis of the velocity fields in the aspect ratio duct.

The summary report covering the performance of the turbulated aspect ratio test duct is being prepared for publication. The Buoyancy number range over which sufficient

enhancement was obtained with this turbulated duct is clearly identified in the report. The minimum enhancement measured for this rectangular duct was much lower than that reported in the literature for turbulated square ducts at low Reynolds numbers. Modification of the experimental technique and data reduction method has been initiated to take into account the various lead and trail side heater and instrumentation designs incorporated for this test duct.

Plans for Next Reporting Period

Modification of the experimental technique and data reduction method will be completed. Conduction analyses will be used to differentiate between local data at the turbulator locations and data averaged over the radial distance between turbulators.

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 Since Last Reporting Period

This effort was initiated in May. It was determined that, in addition to the new stator configuration required to geometrically scale the first-stage rotor-stator cavity of the ATS gas turbine, the existing support for the motor-shaft assembly also needs to be redesigned. The existing rotor disc can be employed with a backing plate and seal ring designed to scale the new seal configuration. The preliminary engineering design is about half completed. Drafting has begun on the key components. The goal is to complete all machined components, including the new test stand and test rig manifolds, by the time the small-scale duct tests that use the same test rig are finished in September. CFD analyses of the seal configuration are in progress to allow the design of the variable area orifice needed to achieve the desired variation of the circumferential static pressure at the rotor-stator gap.

Plans for Next Reporting Period

The engineering design of the scaled rotor-stator cavity, including the required CFD analyses, will be completed and the drafting work should be about eighty percent complete by the end of June. The changes needed in the test rig manifolding will be defined. Initial fabrication work should begin by the end of June.

Task 8.7 - HEAT TRANSFER AND COMBUSTION INSTABILITY

Task 8.7.2 - Turbulent Heat Transfer

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 GEPS combustor test stands, including the ATS Full Scale Nozzle Cascade Test Stand. Data from the nozzle cascade test stand will be compared to CFD analysis of the flow path and to numerical thermal analysis of the nozzle airfoils to calibrate the design methods and machine design assumptions.

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

Progress Since Last Reporting Period

The probe manufacturer, Vatec Corporation, has determined that they cannot produce a reliable probe of the intended design, nor can they duplicate the result obtained with the prototype probe. A new design for the probe has therefore been deemed necessary. The redesigned probe will retain the essential outward characteristics of a 1.27-cm diameter tube, but will utilize the more reliable HFM-6 sensor. The miniature plug-type sensor will be imbedded into the tip of the probe, encased in nickel. The sensor area will actually be slightly smaller than the earlier design. The instrument leads will run inside a tube that is internal to the cooling tube of the probe and sealed against coolant leakage. This design is far more durable but has reduced cooling capacity and reduced cooling predictability. Because the probe uses a tested heat flux microsensor design in the HFM-6, it can be constructed more quickly. The first two of three such replacement probes (replacing the original design) were received by CRD on March 31. These heat flux sensors have been calibrated only to the extent allowed by use of traceable thermal radiation lamps in a room environment, about 220 C. The resistance temperature sensors have been calibrated to 350 C. The probes were cycled to high temperature several times prior to calibration in order to ensure settling of the sensitivities. The final replacement probe was received early in April. During this period, one probe was installed in the 9G Full Scale Nozzle Cascade, nozzle box test rig, at GE Aircraft Engines, Evendale, Ohio. This rig is not expected to go on-line for testing until June or July. A second probe was installed in a combustor test stand at GE Power Systems for 9G combustor testing at sub-scale flow conditions. Both probes will be water cooled. The second probe was also pressure tested with 17 atm water differential pressure, and experienced only minor leakage. Operating pressure differentials in fired tests will be very much lower. A third probe was planned for testing in CRD's Transient Cascade but, due to the redesign of the probe, the total probe length was found to be too much for pressurized cascade testing. Fired combustor tests were run during May in GEPS's Combustor Test Stand #6. Two days of testing were run on the combustor system, with the water-cooled probe installed for the entire duration. After initial lite-off of the combustor on the first day of testing, the probe survived for about 1.5 hours of hot flow, during which time the main flow temperature was increased from 780°C to 1300°C. The probe resistance temperature sensor (RTS) indicated an increase in maximum probe surface temperature from 440°C to 625°C during this time. These probe temperatures are well within the expected survival limits for continuous operation of the probe (800°C), and as expected for the cooled

Progress Since Last Reporting Period

The impingement heat transfer coefficients measured for Modules 1 and 2 were previously compared with Metzger's correlation existing in the open literature (Florschuetz, Truman and Metzger, *ASME J. of Heat Transfer*, 103, 337-342, 1981).

Plans for Next Reporting Period

Comparison of the impingement heat transfer coefficient distributions data reported earlier with correlations reported in the literature completed the activities in this task.

Task 8.7.4 - Nozzle Airfoil Impingement

Objective

The objective of Task 8.7.4 is to investigate and determine the pressure drop and heat transfer coefficient distributions for first-stage nozzle airfoil span-wise impingement passages and compare the results with the expected values from the design methods.

The airfoil body cooling system is composed of several impingement modules connected in series and/or in parallel between the cooling circuits of the tip and root end wall cooling supplies. The test rig will model cavities 4, 5, and 6 as representative elements of the cooling system. Cavities 4 and 5 will have typical impingement inserts, while cavity 6 will act mainly as a flow by-pass element to simulate the 180-degree turn. Cavity 4 will have the pressure and suction side impingement walls instrumented with thin foil heaters

configuration. The heat flux sensor (HFS) began to show signs of failure when the probe temperature exceeded about 600°C, but this was not due to over-temperature. The HFS indicated a range of heat fluxes through the sensor element from 70 to 170 W/cm².

After tests were completed, the probe was removed for inspection. The probe housing was entirely secure, indicating the success of the cooling method. The probe sensors and body were covered with carbon deposits from the combustion products; both natural gas and oil were used as fuels at various times during the tests. The probe was then returned to the manufacturer, Vatec Corp. of Blacksburg, VA, for disassembly and destructive evaluation. The sensors appear to have failed in three distinct regions: (1) the lead-wire connections at the termination block were dislodged due to vibration; (2) the weld connections of the lead-wires to the sensor backside were also severed, apparently also due to vibration; (3) the thin-film sensor array had lost continuity of electrical path in one or more locations, probably due to contamination from the carbon deposits. The vendor has agreed to improve the termination block connections on the remaining probes. The other two items are more problematic. Vibration levels depend on many factors and are not necessarily predictable, especially in new or developing systems. The same can be said of deposits, depending on the severity of start-ups, the type of fuel used, and any other problems that may arise in development.

Data from this test is being reduced, although only single point information was available at each operating condition, i.e., no dynamic information was obtained due to the limitations of the data acquisition system used.

Plans for Next Reporting Period

Data from the first test will be reduced and conclusions / lessons summarized to aid further testing. The failed probe will be returned to CRD for examination of the deposits covering the sensor. Another probe will be set-up to run in a more controlled fired environment in a CRD combustor rig, with only natural gas. More will be learned about the probe's behavior in this controlled testing. The probe which had been installed in the ATS Full Scale Nozzle Cascade at GEAE in Evendale, OH, will be returned to CRD for modification. Modifications will include strengthening of the termination connections, and possibly allowing for coolant bleed through the tip of the probe for more effective cooling very near the sensor.

Task 8.7.3 - Nozzle End Wall Impingement

Objective

The objective of Task 8.7.3 is to investigate and determine the pressure drop and heat transfer coefficient distributions for typical first-stage nozzle airfoil end wall impingement modules and compare the results with the expected values from the design methods.

The first-stage nozzle end wall cooling system is composed of several impingement modules connected in series and/or in parallel to cover the various regions of the airfoil end wall. The impingement hole patterns in each module are tailored to accommodate the hot gas side thermal loads and maintain wall temperatures at acceptable levels. A test rig simulating two consecutive end wall impingement modules was designed and manufactured prior to the initiation of the present Task.

The impingement wall surface was covered with a liquid crystal sheet and a thin foil heater to measure the local heat transfer coefficient distributions. The test section was also equipped with static pressure taps to characterize the pressure distributions as a function of flowrate and geometries.

and a liquid crystal sheet to measure the local heat transfer coefficient distributions all along the cooled surface. The test rig will also be equipped with several static pressure taps to measure the pressure distributions through cavity 4, the 180-degree turn, and through cavities 5 and 6, which are fed by the coolant flow from cavity 4 and additional flow inserted through the side walls of the 180-degree turn at the inlet regions of cavities 5 and 6. The shell of the test rig with the air inlet and exit sections was designed and manufactured prior to the initiation of this Task.

Progress Since Last Reporting Period

Ten typical impingement module parts were manufactured by electro-discharge machining (edm). The impingement jet holes were drilled at specific locations at various radial distances. The impingement hole geometries were tailored to the cooling requirements at each radial location whether it impinges on the pressure or suction side of the airfoil.

The pieces of the impingement insert were assembled. The parts were epoxied together, and the regions between the sections were reinforced with thin stainless steel shims that were spot welded at discrete points. The insert was then epoxied to the flange that brings the coolant into the impingement insert. The insert was checked for leakage in the interconnection regions. Several static pressure taps were drilled on the side walls of the test section to measure the static pressure distributions along the impingement cross-flow region. Three static pressure probes were positioned at three distinct positions along the insert in the impingement supply chamber.

Plans for Next Reporting Period

Flow and pressure distribution tests will be conducted with the assembled test section. The next step will involve gluing the liquid crystal sheets and thin foil heaters onto the Plexiglas test walls and conducting the heat transfer tests.

Task 8.7.5 - 1st Stage Bucket

Objective

The objective of Task 8.7.5 is to perform non-rotating heat transfer tests with scaled models of the first-stage bucket serpentine cooling circuit to measure the local heat transfer coefficient distributions by using thin foil heaters and liquid crystal sheets.

The test rig consists of two Plexiglas models: one represents the leading edge passage, and the other represents the remaining passages of the serpentine turbulated cooling circuit. The models were designed and constructed before this Task was initiated, while keeping the cooling passage geometrical parameters as close as possible to a typical design geometry. The test rigs are also instrumented with static pressure taps to provide information on the related pressure drops as a function of coolant flowrates.

Progress Since Last Reporting Period

Using the new acrylic window for the serpentine passage, baseline (smooth wall) heat transfer data have been repeated to compare with the old heater. Further tests at higher flow rates have also been completed.

Analysis of the smooth wall data with the new window/heater assembly shows good agreement with data taken with the previous heater. The new window/heater allows superior optical access, significantly improving the quality of data and the testing rate.

Turbulators have been installed in the passages, and tests have been completed with two turbulator configurations and several coolant flow rates for each configuration.

Analysis of all serpentine passage data has been completed. Tests were run with smooth, fully turbulated (45-degree turbulators) and partially turbulated passages. Heat transfer coefficient distributions were measured at 3 different coolant flowrates: $\dot{m} = 0.1, 0.2$, and 0.3 lb/sec. The fully turbulated case was the only one tested at the highest flowrate. The results for $\dot{m} = 0.2$ are reported here as they are representative of all $\dot{m}$ tested.

The Dittus-Boelter correlation was used to generate the predicted fully developed smooth wall pipe flow heat transfer coefficient distributions:

$$Nu_{db} = 0.023 \cdot Re_{Dh}^{0.8} \cdot Pr^{0.4} \quad (1)$$

This image was used to normalize the measured heat transfer coefficient distributions to produce the heat transfer enhancement images.

Heat transfer tests of the (turbulated) serpentine passage tip regions (180-degree turns) were completed. Analysis of all heat transfer data from the serpentine passage model was completed.

Plans for Next Reporting Period

The leading edge passage will be altered to accommodate turbulator ribs, which are at 45 degrees to the flow and positioned in a staggered mode along the cooling passage. Pressure drop and heat transfer tests will be conducted with this new cooling enhancement geometry.

Task 8.7.6 - Combustion Instability

Objective

The objectives of Task 8.7.6 are to understand the physical mechanisms responsible for the onset and sustenance of dynamics in lean premixed combustion systems, 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 to enhance computational capabilities in the form of improved sub-models to better quantify upstream and downstream acoustic boundary conditions and fuel delivery system impedances and their effects on dynamics.

Progress Since Last Reporting Period

(1) The exhaust nozzle treatment to simulate the first-stage nozzle at the combustor exit in the form of water-cooled tubes was installed and run in the 3 atm, 900 F inlet DLN2 dual burner rig along with a split liner. This rig has two full-scale DLN2 burners installed at the head-end with full length (52") reverse flow cooled liner in a manner similar to that used in GEPG full scale combustors. The exhaust nozzle simulates the first stage nozzle and represents the same area blockage. Liner hardware with air-cooled splitter plate (the splitter plate extends throughout the combustor liner and effectively splits the burner into two independent DLN2 combustors) has been installed and run during this period. Ten tests have been conducted with four hardware configurations in the dual-burner DLN2 rig to determine the effect of transition piece gap (if any) on the mode of instability and to

determine how the "push/pull" mode (observed in DLN machines in the field) is set up. The following four configurations have been run:

1. No splitter plate + no nozzle (baseline configuration)
2. No splitter plate + nozzle
3. Splitter plate + no nozzle
4. Splitter plate + nozzle

Additional tests were conducted with the configuration consisting of the splitter and the nozzle bars. In an attempt to decouple the two burners, the nozzle exit open area was decreased to ensure choked operation. Detailed simultaneous dynamic data were obtained to determine the exact mode shape.

Additional tests were conducted in the 3-atm, 900 F DLN2 dual burner rig with water-cooled exhaust nozzle treatment and air-cooled splitter plate to study the effect of transition piece gap on dynamics mode and frequency. Ten more tests were conducted with the configuration consisting of the splitter and the nozzle bars. More tests are underway and the splitter will be removed completely for final tests. Quantitative values will be provided in the next reporting period after all tests have been completed.

(2) In the task related to obtaining detailed understanding of the physical mechanism, the design of the spinning blast-gate valve to generate large, periodic pressure fluctuations to simulate combustion dynamics has been completed. Appropriate ball-bearings and a high-speed electric motor and controller have been procured. Fabrication of the valve body in the shop is nearly complete and design modifications of the fuel nozzle to accept the miniature pressure transducers for internal injector dynamics measurements have been initiated.

(3) A series of numerical tests using CombDyn-1D were performed to determine the factors that affect the amplitude and frequency of acoustic pressure in the simple 1D combustion flow configuration described previously.

The effect of chemical reaction rate (flame length) on the acoustic amplitude and frequency was also examined using the same boundary conditions. Three different reaction rates were used to generate three different flame lengths of 0.5, 1.5, and 3.7 feet.

Plans for Next Reporting Period

Further tests in the dual-burner rig will be conducted with much reduced splitter gap and eventually zero gap. Tests will be used to obtain boundaries of transition between the two modes. For fundamental dynamics studies tests will be conducted in a piggy-back manner along with other on-going high pressure tests to maximize system utilization. For the 1D CFD code the plan is to further investigate the mechanism of the flame and acoustic pressure interaction. The question that will be addressed is the effect of steady and unsteady reaction rate on the predicted dynamic frequency.

Task 8.7.7 - Effect of Hot Fuel on Combustion Dynamics

Objective

The objective of Task 8.7.7 is to determine the influence of fuel heating on the fuel delivery system and on combustion.

Progress Since Last Reporting Period

This is the first reporting period for this task. A kick-off meeting was held at GEPG to review the work scope for this task. In light of combustion testing at GEPG with fuel heated to 350 F, it was decided to increase the focus on the fuel delivery system and reduce the effort on combustion testing. Design of the experimental conditions for hot fuel exposure testing has begun with a review of contaminants in natural gas. A literature search was initiated. A meeting was held with EGT engineers to discuss the design of a lower temperature (350 F) fuel heating system.

Plans for Next Reporting Period

We plan to complete the design of the bench-scale exposure experiments and order the necessary items. Assembly of the experiment will begin during this period. We plan to meet with GEPG engineers to review the system issues of hot fuel such as control valves and pipe volumes. We expect to get more detailed design information from EGT engineers on the currently installed fuel heating systems.

Issues, Problems, Changes

Based on feedback from GEPG engineers during the kick-off meeting, the workscope of this task will increase the effort on heat exchanger fouling tests and decrease the effort on combustion testing.

Task 8.7.9 - Turbulent Heat Transfer - Static Components

Objective

The objective of Task 8.7.9 is to predict the metal temperatures and gradients of the first stage nozzle airfoils represented in the Full Scale Nozzle Cascade test. The solution of the conjugate heat transfer problem will be accomplished by imposing known convective thermal boundary conditions to the external surface of the airfoils and solving a conduction heat transfer model that includes the internal passage thermal boundary conditions. Internal boundary conditions will be supplied by two experimental models: one determining the impingement heat transfer characteristics within the several internal airfoil cavities, the other determining the high Reynolds number turbulated heat transfer within the aftmost convective channel of the airfoil. Both experimental models will utilize the thermochromic liquid crystal technique. External airfoil boundary conditions will be provided by the ATS Turbine Inlet Nozzle Cascade, in conjunction with information from the Full Scale Nozzle Cascade test and analysis.

Progress Since Last Reporting Period

This is the first reporting period for this task. The analytic modeling effort was begun by obtaining the airfoil geometry files from GEPS and creating the initial mesh structure for the model.

The airfoil internal impingement model was begun earlier this year under GE funding. Much effort has gone into the machining of segmented versions of the contoured impingement inserts for the separate cavities. The acrylic body of the model had also been fabricated. The impingement inserts have been completed, and the model is now being assembled.

The trailing edge turbulated channel model is in the initial planning and sizing stage.

Plans for Next Reporting Period

An initial trial run of the analytic model will be performed with "slave" representative boundary conditions. The airfoil impingement model assembly will be completed and checkout tests started. Fabrication of the trailing edge channel model will be initiated.

Task 8.7.10 - Transition Piece Design Tools

Objective

The methods used for developing and designing transition pieces could be made more accurate through the application of CFD and supportive testing, such that final designs can be arrived at with lower cost, lower risk, and shorter cycles.

With any CFD calculation for complex geometries, most of the elapsed time is consumed by the generation of the computational mesh. Recent advances within GE in the area of unstructured mesh generation have led to significant reductions in elapsed time. The purpose of the proposed work at MIT is to formalize and extend these advances.

The resulting mesh generation code would be state of the art and enable the novice user to mesh and analyze complex geometries efficiently.

The various pieces of the design process will be integrated for transition piece design so that the output of one design code easily becomes the input for another. Empirical data will be obtained for establishment of boundary conditions and calibration of results.

Progress Since Last Reporting Period

A statement of work has been negotiated with MIT for the software work in this Task.

Plans for Next Reporting Period

The subcontract with MIT will be finished and work initiated on this Task.