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

**Quarterly Report
December 1, 1994 - February 28, 1995**

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

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1.0 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 Industrial and 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 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 machines 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 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 Industrial and 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 THROUGH 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 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 (CFATS)

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" data base (June 1994) are used to define long term capacity needs.

Task 6: System Definition and Analysis

Overall plant layout studies have been started. Thermodynamic studies to evaluate engine performance as a function of ambient temperature have been completed for both simple cycle and combined cycle configurations, shown in Figures 1 and 2. Figure 3 shows the overall industrial engine configuration.

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 subtasks comprise this Task, and are reported individually in TAB 5.

Task 8.5 (Enhanced Impingement Heat Transfer) deals directly with the Industrial ATS high pressure nozzle. Texas A&M University has finished heat transfer testing of different impingement configurations for the high pressure nozzle, and is writing the Task 8.5 final report. An abstract of the final report is contained in the TAB 3 Section.

INTERCOOLED, TURBOCOOLED ATS

Figure 1

INTERCOOLED, TURBOCOOLED ATS

Figure 2

1019 01/17/95 m17101911.dwt c0149 X11 PLOT 1
EGS LIB 4.5L 08/30/94 (EGSREP XPOST 4.5L 08/30/94 on c0149)
HP 9000 V4 708

ATS ENGINE MECHANICAL CONFIGURATION

Figure 3

TECHNICAL REPORT TEES-44950

A HEAT TRANSFER EXPERIMENT OF IMPINGEMENT COOLING,

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General Electric-Aircraft Engines
Under Contract No. 200-1Q-14L22964

ATTACHMENT 1

March 1995

ABSTRACT

An experimental study on heat transfer by a series of jet impingement is presented. The results show that the orientation of the exit opening of the jet impingement channel is important and governs the heat transfer pattern. Higher heat transfer coefficient is observed near the closed end of the channel and lower heat transfer coefficient near the exit opening of the channel. The heat transfer pattern is found to be sufficiently independent of the surface roughness. Different surface roughnesses and crossflow obstructions with pins and dimples show similar heat transfer coefficients. However, the pressure drop gradient in the impingement channel is higher for the roughened surfaces.

The objective of this work is to determine influences of different configurations and flow conditions on heat transfer. The studied parameters are itemized below.

1. *Effect of exit opening orientation on heat transfer*

The cross flow developed in the impingement channel from the spent jets is dependent on the exit opening orientation. Whereas, the proximity of the exit with respect to the inlet to the pressure chamber determines the profile of pressure difference across the jet plate. Two open exit orientation weakens the crossflow effect.

2. *Effect of Plexiglass pins: Reduction of crossflow and jet interaction*

The cross flow from spent jets deflects the jet flow and reduces the impingement strength. The crossflow, as the name suggests, flows perpendicular to the direction of jets. Therefore the crossflow pushes the jet away from the target impingement surface and is not desired. Plexiglass pins are used to isolate jets from crossflow. Long Plexiglass pins are used to span the impingement channel depth. One upstream long pin is used for isolating each jet from

the upstream crossflow.

3. Effect of dimples on the impingement surface

The heat transfer area of the impingement surface is increased by dimples. The dimples increase the surface area by 25 percent from that of the smooth surface. Moreover, dimples increase the surface roughness.

4. Effect of dimples and long Plexiglass pins combined

The heat transfer pattern with the combined effects of dimples and long pins are studied. The long pins are used for jet isolation from crossflow, and dimples are used for enhancement of heat transfer surface area. Note that pins are of non-conductive material and reduce the amount of exposed area available for heat transfer.

5. Effect of short copper pins

This effect is similar to the dimples. In this case instead of depressions on the heat transfer surface, elevations are made with short copper pins. The enhancement in the heat transfer area is same as that of dimples, that is 25 percent increase in area from a smooth surface.

The results show that:

1. Two flow exits are better. Heat transfer with both the flow exits open shows a uniform and higher heat transfer performance.
2. Long Plexiglass pins do not have significant effect on heat transfer.
3. Dimples do not enhance heat transfer.
4. Dimples with Plexiglass pins perform similar to the case with dimples alone.
5. Short copper pins do not provide better heat transfer than the smooth wall impingement.

REPORTING PERIOD 12/1/94 - 2/28/95

UTILITY ATS STATUS OF TASK 3 THROUGH TASK 8

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

Task 3B: Selection of an 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 (CFATS)

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 American Electricity Reliability Council (NERC) region models required for the FAST PLAN capacity expansion model. Electricity demands as reported in the NERC's "Electricity Supply and Demand" data base (June, 1994) are used to define long term capacity needs.

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 evaluation that will enable implementation of advances in several areas critical to the Industrial and Utility ATS. Seven subtasks 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 (see TAB 3)

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

QUARTERLY PROGRESS REPORT BY SUBTASK

Task 8.1 - Particulate 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 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. General Electric had already negotiated an agreement with the candidate power plant, and 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 on GE funds, prior to the initiation of this Task 8.1. The remaining work involves completing assembly and checkout of the system, and then conducting measurements to meet the above-mentioned objectives.

Progress Since Last Reporting Period

During this Quarter, the coolant filtration system operated between 0.5 to 1.0 lb/sec of coolant flow with no indication of pressure drop increase from plant operators. The flows were not constant due to large load swings in the host plant. The system went back online with an additional coolant sample filter in place so that particulate loading measurements could be made upstream and downstream of the filter simultaneously. It has operated nearly continuously since the last Quarterly, and operators report no problems and they have recovered several more sample filters for analysis. Engineering activity has been very light on this Task during this Quarter while the system has been running.

Plans for Next Report Period

During the next Quarter, the system will be brought down so the filter cartridge can be inspected and the sample filters analyzed. An interim report will be issued to summarize the measurements to date. Then the flow system will be readjusted and plumbing added so that the coolant sedimentation apparatus can be installed and begin commissioning.

Issues

The trained operators on this remote experiment continue to be moved from one job to another, so it has been harder to effect filter changes on a timely basis. However, the plant continues to support the experimental activity.

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 Advanced Gas Turbine (ATS) engine. GE has identified a target power plant at which to site the experiment. GE had completed a proprietary computational code that was proposed to be useful in predicting particle trajectories prior to Task 8.2 start.

Progress Since Last Reporting Period

All major pieces of equipment are being assembled at the vendor shop, and a first slow rotation of the system there is now scheduled for early April. The rotor machining errors were corrected and the matching flow specimens have been mounted at the rotor tips, and the entire assembly has been static balanced. The base skid is serving as the assembly platform, and assembly of the equipment is going well. Figure 8.2.1a shows the bottom half of the rotor chamber mounted on the skid along with the instrumentation rack and the lubricating oil unit (at rear of skid in photo). Figure 8.2.1b shows the rotor on an assembly fixture. The identical flow turning specimens, which simulate the tip turn of the first cooling passage in the AGT, are seen mounted within each yoke at the rotor arm tips. These specimens are designed to be removable from the rotor arm by reaching through hand-holds in the rotor vacuum chamber.

Plans for Next Reporting Period

The plan is to complete the assembly of the apparatus at the vendor shop, including the addition of instrumentation and the conduct of a slow speed (100rpm) rotation (without flow of coolant through the rotor seals, shaft, arm, and specimens) to validate basic system operability. Then the unit would be taken to a facility where it could be spun to full speed and overspeed to validate its safety. For both the slow turn and full speed test operations, it has been decided to dismount the seal rings themselves since they require coolant flow for lubrication. Then the seal rings would be reinstalled prior to shipment to the test site. The successful operation of the seals remains perhaps the largest uncertainty in the experimental system. An additional orifice is now planned for the coolant flow system at the centrifuge discharge so that both entry- and exit- flows can be utilized to estimate seal leakage.

Issues

The rotary coolant seals remain the largest unknown until the system is put into operation. Other issues being worked out include interim, non-destructive inspection of any internal specimen deposits with fiber optics and remote sampling probes. The full speed spinup of the apparatus before shipment to the test site was complicated by the decision to use plant vacuum instead of the earlier planned vacuum pumps because the spin pit did not have such a vacuum source. However, two other spinup sites are being investigated which do have both power and vacuum.

(a) Centrifugal Base and Lower Housing

(b) Centrifuge Rotor with Flow Specimens Mounted

Figure 8.2.1: Centrifuge Being Assembled in Vendor's Shop

Task 8.3 - TBC Mechanical Test and Analysis

Objective

Development of thermal barrier coatings (TBCs) with improved life and reliability will require a comprehensive understanding of mechanisms of degradation that occur during gas turbine service. There are two complimentary objectives in this task. The first is to develop and confirm 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. The second objective is the 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.

Progress Since Last Report Period

a) Non-Linear Stress-Strain Characterization of TBCs:

The non-linear stress-strain behavior characterization of TBCs has been extended to include a more compressive stress range. By deforming the metal substrate plastically in compression, the TBC compressive residual stress was increased. The TBC stress state and the elastic modulus were measured and from this data the stress-strain relationship were obtained.

Rectangular specimens for substrate curvature and resonant frequency measurements were cut out of the cylindrical test specimens. The samples were lapped flat, and substrate curvature and resonant frequency measurements were initiated. The residual stress induced in the coatings from the plastic deformation of the substrates were measured directly by substrate curvature measurements, and the modulus of TBCs with the compressive stress states was determined from the resonant frequency measurements.

Seven TBC samples were produced with different levels of compressive stress in the TBC by deforming plastically the substrate in compression. Young's modulus and residual stress were measured for three of the specimens. The TBC modulus was measured from the change in resonant frequency of a TBC-substrate beam upon removal of the TBC layer, and the residual stress was measured from the change in substrate curvature upon TBC removal of the same specimen. The sample with 0% plastic strain had a residual stress of -10.7 ksi and an in-plane Young's modulus of 14.3 Mpsi. The sample with -0.38% strain had a stress of -17.5 ksi and a modulus of 15.6 Mpsi, and the sample with -0.92% strain had a stress of -36.5 ksi and a modulus of 18.1 Mpsi. The data followed the same trend observed earlier that the modulus increased with increasing compressive residual stress. However, these data allow for modulus determination at much larger compressive stresses than achieved before.

Using the data obtained in the compression tests, the non-linear stress-strain curve can be extended over a wider range of stress and strain. A procedure was previously established for deriving the stress-strain relationship when Young's modulus is measured

at a certain number of residual stress levels. The procedure consists of first fitting the measured Young's modulus vs. stress points with a polynomial (or any other function). The second step is to perform a numerical integration of a differential equation to derive the stress-strain curve.

Figure 8.3.1 shows Young's modulus data vs. stress from previous tests and the recent three test results. In this plot Young's modulus is plotted as function of the stress since this is the most convenient way of using the data for deriving the stress-strain curve. Also shown is a simple polynomial curve fit (Stress vs. Modulus) using least squares method. The polynomial chosen for the fit was of the form

$$Stress = a \cdot E^2 + b \quad (1)$$

The least square fit determined the constants a and b with the result that the relationship between Young's modulus and the residual stress can be written as

$$Stress = -92.96 \cdot E^2 + 1247 \quad (2)$$

with units of *Stress* are given in [psi], and Young's Modulus, *E* in [Mpsi].

It is seen that this second order polynomial gives a poor fit to the data. However, the functional form used for fitting the data is entirely arbitrary and any function that is convenient can be used for this purpose. To get a better fit to the data a function of the form

$$E = \frac{a}{Stress - b} + c \quad (3)$$

was used. The three constants a, b, and c, was determined using a least square fit and the resulting curve is shown in Figure 8.3.2. This resulted in the expression

$$E = \frac{125,000}{\text{Stress} - 6,460} + 21 \quad (4)$$

where Stress is expressed in psi and modulus, E in Mpsi. The above expression indicates that there is an asymptotic limit of E=21 Mpsi for high compressive stresses.

The expression in (4) was used to derive the TBC stress strain curve shown in Figure 8.3.2. The numerical integration which determines the stress-strain relationship leads to the nonlinear stress-strain curve shown in Fig. 8.3.3. The solid line indicates the part of the curve which is within the range of the experimental data. The dashed part of the curve indicates the extrapolated parts.

Figure 8.3.1: TBC Stress vs. Modulus & the Polynomial Curve Fit

Figure 8.3.2: TBC Stress vs. Modulus & the Improved Curve Fit

Figure 8.3.3: Nonlinear Stress-Strain Behavior of TBC

b) The E-Beam High-Thermal-Gradient Test ("Tophat" Specimen):

A series of E-beam tests were performed at Precision Technologies. Two instrumented test specimens were used. One tophat specimen of GTD-111 equiaxed material was instrumented with several thermocouples and several conventional strain gages on the cooled metal surface. This specimen was primarily exposed to steady-state energy flux conditions, with only a few cycles, to evaluate the strain gage responses and associated strain states. The other tophat specimen of single crystal N5 material was instrumented with thermocouples only, in a more numerous pattern than previously used. This specimen was tested under cyclic conditions. Both specimens were coated with CRD dense vertically cracked TBC. Neither specimen experienced any TBC failure.

Thin-film instrumentation efforts have continued with the preparation of two samples. One sample has been prepared to receive a detailed pattern of sputtered Pt/Pt-Rh thermocouples over a thin layer of alumina. The other sample has received thin-film pads of PdCr, intended as the basis for forming high temperature strain gages via laser ablation techniques.

Preliminary testing was performed at the NASA Lewis Strain Measurement Lab using their Speckle Measurement system on a TBC coated tension specimen. First results were encouraging for the application of this technology to surface strain of TBC. Data analysis on the existing test specimen runs were completed. Efforts under way at NASA Lewis for the use of optical TBC strain measurement have also continued. Efforts by Advanced Vacuum Resources to provide a fully operational and tested Electron beam generator and shielded enclosure have progressed at a slower pace than originally intended.

Task 8.4 - Advanced Seal Technology

Objective

Advanced turbine designs will produce more power with fewer stages and will be more efficient than the existing designs. This task will identify and specify critical sealing requirements in the advanced turbine system. Advanced seals will be developed and their performance evaluated through laboratory component testing for the following applications:

1. Transition-Piece to First-Stage-Nozzle (TP-FSN) inner, outer and side seals.
2. Nozzle-Shroud seals for FSN.
3. Nozzle-Shroud seals for second and third stages.

Technical Progress

Task 8.4 is complete. Details are given in the Yearly Technical Progress report.

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

Details are given in the TAB 3 Section.

Task 8.6 - Rotating Heat Transfer

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, that 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 excessive extrapolation of the existing data base is needed

This task will provide the required heat transfer data base over the range of dimensionless parameters. The rotating test facility installed at CRD in 1993 has obtained data in smooth rectangular full scale blade cooling passages and is now obtaining data in a turbulated rectangular passage. Electrical heat addition is employed on each of the few passage walls which 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

The installation of two added thin film heaters and several thin film thermocouples was carried out in order to evaluate these designs at high 'g' loading and to determine the maximum heat flux capability of these heaters prior to their selection for the high aspect ratio test duct to be constructed subsequently. The new heaters employ a continuous film rather than a serpentine circuit since early measurements indicated an excessive local temperature distortion with the serpentine heaters. These heaters were placed on the outer return bend manifold side faces with the original heater installation remaining on the outer return bend. The latter was instrumented with ten thin film thermocouples to allow measurement of the turbine blade tip heat transfer coefficients with and without rotation. The prior data taken up to 300 RPM were then extended up to 650 RPM. As the Buoyancy number increased, the relatively small increase in the turbine tip Nusselt number

The large variation of the local heat transfer coefficient measured at the turbine tip in the circumferential direction was similar at 650 RPM to that measured previously at 300 RPM. The decrease in the heat transfer coefficient with increasing Buoyancy number measured in the radial duct on the leading side in radial outflow did not take place at the turbine tip. The turbine tip heat transfer coefficient increases monotonically with increasing Buoyancy number. Measurements up to 900 RPM will be carried out on both the aspect ratio turbulated duct and the turbine tip to complete the planned data set with this test section.

Since the thin film heaters and thermocouples have demonstrated the capability to provide the required measurements at high rotational speed, a wall conduction analysis was carried out on the anticipated geometry of the large aspect ratio duct to determine the formulation required by a data reduction code that will correct for wall conduction. It was found that the smaller lateral wall conduction at the thin film heated walls can easily be accommodated by the same relations as those employed for the present aspect ratio duct. However, the greater sensitivity to radial conduction on the walls heated by thin film heaters renders the placement of thermocouples on the turbulated walls more critical than previously. Measurements of the local variation in heat transfer coefficient along turbulated walls in rotation, carried out in 1993 under a prior effort, will be used to locate the thermocouples in such a manner that the local maximum and minimum coefficients can be calculated using the wall conduction code.

Task 8.7 - Heat Transfer and Combustion Instability

Task 8.7.1 - Turbine Inlet Nozzle Heat Transfer

Objective

Program objectives include the investigation and determination of the external heat transfer coefficient distribution for a Stage 1 Nozzle airfoil, as well as the validation of computational heat transfer predictions. The program will include the characterization of external heat transfer due to the effects of inlet flow preparation including turbulence intensity level and swirl, airfoil surface roughness, and Reynolds number.

The test apparatus will have as its core a 1/2-scale linear airfoil cascade designed to model the appropriate nondimensional turbine nozzle parameters, including inlet flow Reynolds number, nozzle pressure ratio, and airfoil Mach number distribution. The cascade will be operated at an inlet total pressure of 5 atm, and temperature of 150°F. The cascade will consist of five airfoils, instrumented to obtain aerodynamic and heat transfer information. The central airfoil will be a thin-walled stainless steel unit with imbedded thermocouples, employing a thin-foil surface heater to determine local surface heat transfer coefficients. The airfoil surface will be variously coated with alumina particles to provide well characterized roughness distributions. The flow entering the cascade section will be conditioned to model the turbulence intensity level and swirl, which would be obtained with a Dry Low NOx combustor under cold flow conditions, including the actual swirler geometries and development sections. In addition, a range of axial turbulence intensities

without swirl will be available through the use of perforated plates at the cascade inlet. The effects of flow Reynolds number variation will also be investigated.

Progress Since Last Reporting Period

During this period the cascade was fully re-assembled with a smooth surface test airfoil. Some problems have been encountered in assembly with the thin-foil surface heater buss bar touching adjacent metal parts, resulting in short circuiting. Modifications were completed to the cascade endwalls to eliminate any possibility of electrical shorting. Repairs were also made to the instrumented airfoil to recover a broken thermocouple and replace the heater wire leads. The cascade was run with low flow to check out operation of all thermocouples and heater.

Smooth airfoil tests were performed during this period. The flow configuration consisted of three different inlet turbulence intensity levels.

Some problems were encountered in the hot-wire anemometry measurements of turbulence intensity. These measurements will be repeated under the next series of rough surface tests to verify the intensity levels obtained. Heat transfer coefficient results were of the form expected, and entirely consistent as Reynolds number and turbulence level were altered.

Plans for Next Reporting Period

Testing during the next period will focus on determining surface roughness effects on airfoil heat transfer under a Phase 3 task. Roughness tests will include two very different levels of average roughness, as well as a distributed roughness characteristic of that found in typical turbine inlet nozzles. In the course of these tests the mainstream flow Reynolds number will be varied, and three inlet turbulence intensity levels will be used. These tests will all be without mainstream flow swirl.

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 checkout of this probe in the External Heat Transfer test facility and for analysis of data collected during combustion testing. This data will be related to the ATS design requirements.

Progress Since Last Reporting Period

The Transient Heat Transfer Cascade has been prepared for testing with a wedge probe, a hot-wire anemometer, and the prototype turbulence probe. In the latest report from the probe vendor, Vatec Corporation, three new probes will be supplied during the first quarter of 1995. The base metal for these new probes will be Inconel rather than stainless

steel, to improve the sensor-to-metal adhesion characteristics for better probe durability and life.

Difficulties with the calibration of hot-wire anemometry probes have been encountered during this period. The entire calibration process is under careful examination to assure good comparison with the new turbulence probe. The Transient Heat Transfer Cascade has been run with a cylindrical pressure probe, a Kiel probe, and a wedge probe, all showing good comparison to the mass averaged flow velocity. The turbulence probe vendor, Vatec Corporation, has informed GE that due to subcontract delays the first of the replacement probes will not be ready by April 1 as expected. No firm date has been given.

Plans for Next Reporting Period

Due to the probe vendor's uncertainty in reliability of the probe construction, and to his inability to produce additional probes, the vendor has proposed a new design based upon the much more reliable HFM-6 probe. The vendor has committed to supplying two probes of this new design by April 1, 1995. One probe will be used in a CRD test rig for characterization, while the other will be used in the ATS Full Scale Nozzle Cascade. The latter test will occur in the combustor / nozzle box portion of this rig's test schedule during this period.

Task 8.7.3 Nozzle End wall Impingement

Objective

The objective is to investigate and determine the pressure drop and heat transfer coefficient distributions for typical stage 1 Nozzle airfoil end wall impingement modules and compare the results with the expected values from the design methods.

The stage 1 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.

Technical Progress

The test section consists of two impingement cooling modules connected in series where the cooling air exiting the first module is used to impingement cool the second module. The cooling air to the test rig is supplied by the Worthington compressor available in the ES Building. The coolant air flow rate was measured by means of instrumented venturi meters and controlled by flow control valves. The tests were performed at three air flow rates.

Module 1 consisted of an impingement supply chamber with the air entering the supply chamber through three holes machined on the side wall. The impingement holes distributed over a plate consisting of twelve rows of holes with each row having eight holes. The air after impinging on the bottom surface flowed along a channel which was

1.27 cm (0.5 inches) high and turned through a 90 degree bend at the end of the impingement surface. The last row of holes (Row 12) was inclined at an angle in order to impinge in a region close to the 90 degree bend and cool this critical region. The air then turned through a second 90 degree bend and fed the supply chamber of the second impingement module through three holes. The bottom impingement surface was covered with a liquid crystal sheet and a thin foil heater. The thin foil heater provided a uniform heat flux boundary condition on the heat transfer surface of interest and the color spectra of the liquid crystal allowed the visual measurements of the surface temperature contours and their photographic recordings for future data analysis.

Module 2 consisted of an impingement supply chamber of slightly different dimensions with the air entering the supply chamber through three holes machined on the side wall. The impingement holes distributed over a plate consisting of ten rows of holes with each row having different number of holes ranging from 7 to 5 depending on the respective row. The air after impinging on the bottom surface flowed along a channel and turned through a 90 degree bend at the end of the impingement surface. The last row of holes (Row 10) was once again inclined at an angle in order to impinge in a region close to the 90 degree bend and cool this critical region. The air then turned through a second 90 degree bend and discharge into the ambient through three holes. The bottom impingement surface was again covered with a liquid crystal sheet and a thin foil heater. The thin foil heater provided a uniform heat flux boundary condition on the heat transfer surface of interest and the color spectra of the liquid crystal allowed the visual measurements of the surface temperature contours and their photographic recordings for future data analysis.

The air supply temperatures were measured at each one of the supply chambers by means of two thermocouples. In additions to this instrumentation five static pressure taps were drilled for each one of the two modules. The first static pressure tap measured the air supply pressure. The second and third static pressure taps were located at the center of the 1.27 cm (0.5 inch) high impingement cross flow passage at the first and last impingement hole location. The fourth and fifth static pressure taps were located at the top wall of the two 90 degree bends to measure the pressure before the transition to the second module or discharge to the atmosphere. The forth hole was on the top of the center discharge hole, while the fifth was located on the top wall between two discharge holes.

TEST PROCEDURE

The test procedure consisted in setting up a given air flow rate through the given module, and then applying a given uniform heat flux to the thin foil heater. The dissipated heat in the heater was calculated from the measurements of the voltage drop across the heater and the current drawn. Once steady state conditions were reached the liquid crystal surface color distributions were recorded photographically for further analysis. The impingement supply chamber pressure and temperature were recorded as well as the static pressure distributions along the module. The heat flux was then increased and at the new steady

state conditions the same data were again recorded for analysis. Once the liquid crystal color spectra was exhausted, the system was cooled and the tests repeated at different flow rates. The liquid crystal color spectra was calibrated in a constant temperature water bath and the green color occurring at 35.5 C (95.9 F) was taken as the wall temperature in the calculation of the heat transfer coefficient contours.

HEAT TRANSFER RESULTS

Heat transfer coefficient distributions were recorded photographically. As the heat flux is increased, the temperature (color) distributions vary and at the highest heat flux, the liquid crystal has gone through the color spectrum. For each photograph the appropriate heat transfer coefficient was calculated from the dissipated heat flux, the measured inlet air temperature and the wall temperature corresponding to the green color. The various photographs were then superimposed onto each other in order to calculate an average heat transfer coefficient for a typical jet of each row.

DISCHARGE COEFFICIENTS

The test procedure for the pressure drop tests consisted in setting up a given air flow rate through the given module, and then measuring the pressure distributions across each module. The supply chamber pressure and the exit pressure downstream of the impingement was used.

Task 8.7.4 Nozzle Airfoil Impingement

Objective

The objective is to investigate and determine the pressure drop and heat transfer coefficient distributions for stage 1 Nozzle airfoil span wise impingement passages and compare the results with the expected values from the design methods.

Technical Progress

The airfoil body cooling system is composed several impingement modules connected in series and/or in parallel between the cooling circuits of the tip and root end wall cooling supplies. The files necessary to manufacture the pieces have been transmitted to the machine shop. The impingement insert design consists of ten pieces with eleven cross sections which model the flow area changes along the insert. The files containing the shape of the pieces have been generated and transmitted to the machine shop for electro-discharge machining of the pieces. The shape of the cross sections were being taken at eleven discrete location along the insert and connected with a linear variation in between the defined eleven sections.

Task 8.7.5 1st Stage Bucket

Objective

The objective 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.

Technical Progress

The test rig consists of two Plexiglas models, the first one represents the leading edge passage and the second one the remaining passages of the serpentine turbulated cooling circuit. The models were designed and constructed, 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 flow rates.

To analyze the heat transfer coefficient data obtained in the three instrumented samples, the photographs of the liquid crystal color fields were re-recorded with the LCVT (liquid crystal video thermography) camera. The liquid crystal color spectra versus temperature calibration was also performed with the LCVT camera. The final results will involve local heat transfer coefficient distributions and area averaged values as a function of the flow Reynolds numbers.

Baseline heat transfer experiments for the serpentine cooling circuit model have been completed for one mass flow rate with smooth walls (no turbulators). The liquid crystal color fields were recorded with the LCVT (liquid crystal video thermography) system. Analysis of data from the baseline serpentine circuit experiments and the 180° turn experiments is underway. The final results will involve local heat transfer coefficient distributions and area averaged values as a function of the flow Reynolds numbers. A modification to the serpentine cooling circuit test apparatus was designed which will improve the experiment. A Plexiglas window is currently being constructed which will allow the liquid crystal color field to be viewed from underneath the thin foil heater on the pressure surface of the bucket. This will minimize spatial distortion of the images, allow images from multiple passages to be acquired simultaneously, improve the uniformity of the lighting and eliminate the need for mylar film thermal resistance corrections. This modification is currently underway.

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. The modifications to the serpentine cooling circuit experiment will be completed and baseline smooth wall (no turbulator) heat transfer experiments will be finished to complete the baseline heat transfer data set. These data can be compared later

with the turbulated passage test results. The serpentine cooling circuit will then be altered by adding turbulator ribs at 45° to the flow.

Task 8.7.6 - Combustion Instability

Objective

The objectives of this sub task are to understand the physical mechanisms responsible for the onset and sustenance of dynamics in lean premixed combustion systems, (2) 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 fuel delivery system boundary conditions; and (3) enhance computational capabilities in the form of improved sub-models to better quantify upstream and downstream acoustic boundary conditions, 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 has been fabricated, installed and run in the 3 atm, 900 F inlet DLN-2 dual burner rig. This rig has two full-scale DLN-2 burners installed at the head-end with full length (52") reverse flow cooled liner in the manner similar to that used in GEPG full scale combustors. The area ratio for expansion 2:1 is close to that used in 7FA combustor with 5 DLN-2 premixers. The exhaust nozzle that has been installed simulates the first stage nozzle and has same area blockage. The baseline configuration was run with the exhaust nozzle (no splitter plate) at operating conditions corresponding to velocity in the annulus of two premixer tubes of 180 fps, pressure in combustor of 8 psi and preheat temperature of 400 F.

The exhaust nozzle assembly ran well with no hardware damage. Tests were also run without exhaust nozzle treatment and baseline liner.

Liner hardware with air-cooled splitter plate has been fabricated and is now available for installation in the pressure rig. The splitter plate extends throughout the combustor liner (in the center) and effectively splits the burner into two independent DLN-2 combustors.

(2) In the task related to obtaining detailed understanding of physical mechanism, a new high-speed valve system has been identified and ordered to allow for time-resolved fuel-air wave measurements with more control than the system used previously. Several suitable miniature pressure transducers have been identified for internal injector dynamics measurements. Additional penetration ports for the sample system have been installed. A new approach to obtaining detailed fuel injector dynamic response measurements is also being considered. The idea is to pulse the rig flow by modulation of the choked orifice with a spinning valve with no combustion. The pressure fluctuations so generated will simulate combustion-generated pressure fluctuations. We are currently analyzing a design of a spinning blast-gate valve to generate large, periodic pressure fluctuations to simulate combustion dynamics. This approach will allow much more precise and reliable

measurements to be made of the fuel injector dynamics since the problems associated with combustion tests, e.g., higher temperatures, unsteady dynamics, etc., will be avoided.

3) The 1-D combustion dynamics code (CombDyn-1D) was applied to compute single can combustor dynamics with a representative 17" long premixer and a 52" long downstream burner. The fuel injector was located mid-way in the premixer. The swirler has not been included in the current model. Different reaction models were initially examined with steady state calculations. With an Arrhenius reaction model, the flame temperature experienced a sharp increase, and the flame length was too short. To achieve a more realistic flame structure, as observed experimentally, an eddy break-up model was adopted. In this model, the reaction rate coefficient was taken as a constant which was derived from typical turbulent quantities for this flow configuration. The computed flame length using this model was about a foot. The dynamic response of the combustor was then tested for various exit boundary conditions: (i) constant pressure (open-end); (ii) constant velocity (closed-end); and (iii) choked flow condition. The inlet boundary conditions were held the same for all three cases: constant total pressure and total temperature. The fuel air ratio was also kept constant. The oscillation frequency for the open-end condition was found to be _____ whereas the frequency for the other two conditions was _____. Further analysis of the results and fine tuning of the model is being conducted based upon experimental data available.

Plans for Next Reporting Period

The dual-burner rig with splitter plate will be installed along with the exhaust nozzle and run with a varying splitter gap to study its effect on mode and frequency of oscillations. Two Kistler pressure transducers for dynamics pressure measurements will be installed in the two burners and recorded simultaneously to discriminate between normal "in-phase" axial mode and "push/pull" mode as a function of the splitter gap upstream of the nozzle. For fundamental dynamics studies hot-film anemometry probes along with miniature pressure transducers for injector pressure measurements will be obtained for velocity measurements. The phase-resolved sampling system and new valve will be bench-tested to establish system limits. Tests will be conducted in a piggy-back manner along with other on-going high pressure tests to maximize system utilization. In continuing development of the 1-D CFD code the length of the combustor will be adjusted to yield a reasonable frequency at the choked exit boundary condition. The dynamics of the fuel delivery system will be modeled next to study the impact of resulting fuel/air fluctuations on combustor pressure oscillations in detail. The code will be applied to the splitter plate experiment for further validation in terms of ability to predict frequency and amplitude of instability mode as a function of splitter gap and downstream boundary conditions.