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

Quarterly Report

September 1 - November 30, 1994

RECEIVED

MAR 04 1997

OSTI

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

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26507-0880

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

By
General Electric Company
Power Generation Engineering
1 River Road
Schenectady, New York 12345

ph

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

REPORTING PERIOD: 9/1/94 - 11/30/94

TABLE OF CONTENTS

EXECUTIVE SUMMARY	TAB 1
INDUSTRIAL ATS - STATUS OF TASK 3 THROUGH TASK 8	TAB 2
DETAILS OF TASK 8.5	TAB 3
UTILITY ATS - STATUS OF TASK 3 THROUGH TASK 8	TAB 4
DETAILS OF TASK 8	TAB 5

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.

REPORTING PERIOD: 9/1/94 - 11/30/94

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 on the Yearly Technical Progress Report.

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

Definition of needed fuel properties for coal derived fuels are being continued.

Task 5: Market Study

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

Task 6: System Definition and Analysis

Studies were continued to reduce line pressure drop for the turbocooler circuit with the goal of reducing the amount of turbocooler turbine air used in the cycle. Flow design requirements have been transmitted to Allied Signal for the preliminary design of the turbocooler. Allied Signal has started the preliminary design of the turbocooler.

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 8.5 (Enhanced Impingement Heat Transfer) deals directly with the Industrial ATS high pressure nozzle. Texas A&M University has begun heat transfer testing of different impingement configurations. Details are given in the TAB 3 Section.

REPORTING PERIOD: 9/1/94 - 11/30/94

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.

Technical Progress

Texas A&M University has begun heat transfer testing of different impingement configurations for the high pressure nozzle. Figure 8.5.1 shows the different exit flow configurations to assess the effects of crossflow on the impingement jets. Figure 8.5.2 shows the impingement plate hole pattern. Figure 8.5.3 shows the modification of the impingement surface using dimples in the surface which will be used to assess the interaction of the dimples with the impingement jets.

Figure 8.5.1 Sketch of the three flow orientations

Figure 8.5.2 Impingement Jet Plate

Figure 8.5.3 Sketch of studied four impingement surfaces

REPORTING PERIOD: 9/1/94 - 11/30/94

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 on 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

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

Task 6: System Definition and Analysis

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

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 Particle 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

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 8.1.1 The remaining work involves completing assembly and checkout of the system, and then conducting measurements to meet the above-mentioned objectives.

Technical Progress

During this Quarter, the coolant filtration system operated for another month (through October) before it was brought down to effect changes and repairs. This added another 500 hours of operation on the two-micron SS filter cartridge at an average 0.6 lb/sec of coolant. Upon inspection of the metal filter cartridge during the outage, it was found to have darkened somewhat in color, but there was no evidence at all of particulates on the element and the housing itself was clean. This lack of buildup of oxide material is encouraging and is in agreement with earlier hot coolant filtering studies which found the oxide deposit friable and easily removable from the filter screen. It is conjectured that any oxide particles were lost from the filter during condensate blowdown from the filter housing upon shutdown. Quantitative- and SEM- analysis of a 0.1 micron coolant filter downstream of the metal filter included only particulates under 1 micron or so, demonstrating the filtering ability of the metal filter. Moreover, the iron concentration continued to be in the 1 ppb level in the coolant, providing additional encouragement that the ATS could achieve 20000 hour time between outage goals if sedimentation predictions are subsequently confirmed.

Only one operational issue gave rise to a concern for the filter performance in the ATS cycle, though it did not appear at the filter itself. A leaking heat exchanger in the power system allowed volatile contaminants to make their way into the coolant vapor stream. These contaminants came overhead with the coolant and appeared as condensed solids (largely organic) on the cold coolant sample filters. However, the vapor condensate did not appear in the hot coolant filter cartridge itself, so must have only condensed in the cooled sample filter. This in itself is encouraging, but, in addition, the ATS system has been specified to have a full-flow cleanup system which would prevent such organic carryover as was seen here.

In addition to replacement and backup of key coolant extraction systems in the filtration apparatus, a second coolant sample filter has just been added to the installation so that coolant

particulate measurements can be made both upstream and downstream of the coolant filter cartridge.

Issues

During this Quarter, operations were curtailed not only for repairs but also because of personnel changes at the power plant site and unusually warm weather leading to the plant being dispatched offline for short periods. The personnel changes make the usual shift data-taking less continuous and reduce the ability of the operators to change coolant sample filters on the desired schedule. Nevertheless, the onsite crew is interested in the project and continues to try to be helpful in running this remote experiment.

Plans

The coolant filtration experiments are planned to continue for the duration of the ATS research activity since characterization of the coolant particulates is required for downstream experiments. Several plant staff are being trained to operate the computer-controlled experiment, including the installation and recovery of coolant particulate filters.

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.

Technical Progress

Parts for the centrifuge for conducting the sedimentation experiment is being constructed at the vendor site. The flow specimens themselves have been manufactured and E-beam welded together. The rotor arm has been received, but it arrived with a key misplaced coolant duct which currently prohibits connection of one specimen to the arm. A rework plan is being prepared to attempt to resolve this issue without requiring a new rotor arm be built. The rotary shaft seals have been received, but shipment of the shaft itself and base have been delayed till February.

Instrumentation details have been completed and instrumentation ordered. This includes accelerometers for the shaft bearings as well as temperature and pressure instrumentation. A procedure for operating the shaft seals has been developed so as to preclude the need for an

initially planned vacuum pump system. Vacuum will be provided by another plant system, improving the projected reliability of the system operation.

A procedure for startup, shutdown, and emergency shutdown has been developed for the experimental apparatus.

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. Finally, the delays in the acquisition of hardware continue to postpone getting the system on-line. These have been due to three specialty fabricators going out of business, necessitating finding replacements to continue the fabrication work efforts.

Plans

If the current fabrication issue can be solved quickly, the plan is to continue to assemble the apparatus at the vendor site and take it to GE's spin pit facilities for balancing confirmation and first spin up to design speed. After that, the system will be shipped to the plant site about April, 1995, for installation and onsite checkout before putting it on-line.

A paper describing the theoretical predictions of particulate settling in coolants has been prepared and accepted for presentation at the International Gas Turbine Conference in June, 1995.

Task 8.3 TBC Mechanical Test and Analysis

Objective

Development of thermal barrier coatings (TBC's) 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 TBC's in an advanced gas turbine.

Technical Progress

a) Non-Linear Stress-Strain Characterization of TBC's:

As mentioned in the previous quarterly progress report, the non-linear stress-strain behavior characterization of TBC's is being extended to include a more compressive stress range. By

deforming the metal substrate plastically in compression, the TBC compressive residual stress can be increased. The TBC stress state and the elastic modulus are measured as described before, and from this data the stress-strain relationship can be obtained.

For the non-linear stress-strain characterization of TBC's in high compressive stress range, cylindrical test specimens were coated with TBC in October at GECRD. The test specimens had an IN718 substrate, a nominally 10 mil thick NiCrAlY bondcoat and a nominally 20 mil thick APS TBC coating. After the coating deposition, the specimens were given a heat treatment of 2 hours at 2050 F. The samples were submitted to a mechanical testing service organization for strain gage application and compression testing.

In November, the cylindrical test specimens were loaded in compression to different plastic strain levels to induce different compressive stress states in the TBC coatings. Strain was measured from two strain gages that were bonded to the metal cylindrical substrate on the inside of a hole that runs through the center of the specimens. The plastic strain at failure was determined by loading Specimen 1 until the TBC spalled due to buckling and delamination of the coating. The total failure strain was -1.75% and the plastic strain at failure was -1.40%. Specimens 2-6 were loaded compressively to induce plastic strains in the specimens ranging between -0.22% to -1.09% (corresponding to 0.16 - 0.78 times the plastic strain to failure). Specimen 7 was loaded and unloaded elastically with no plastic deformation, and Specimen 8 was not loaded at all.

Rectangular specimens for substrate curvature and resonant frequency measurements are being fabricated from the cylindrical test specimens. The residual stress induced in the coatings from the plastic deformation of the substrates will be measured directly by substrate curvature measurements, and the moduli of TBC's with the compressive stress states will be determined from the resonant frequency measurements.

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

The high-thermal-gradient test development and the instrumentation of the "Tophat" test specimens are in progress. In September, the single crystal N5 "Tophat" specimens have been received from Howmet Corporation. A total of 22 specimens were made from three different molds. Each mold used a different process to evaluate the most viable process for future castings. Of the 22 specimens, 17 have no grain defects inside the center 1-inch diameter of the primary test region, and 9 of these meet the crystalline orientation specifications. The castings also meet the required chemistry specification. One process mold produced no fully acceptable specimens and were not continued in subsequent castings. The other two processes performed about equally well. Those specimens made from the least desirable process, 7 in number, are still single crystal N5 and will be used for initial trials and checkout tests, most likely with conventional instrumentation under less severe conditions. The compressors for the E-beam testing have been received at CRD, the large unit for the CRD E-beam facility, as well as the smaller unit for the portable Helium cooling system. The portable system is approximately 60% completed in assembly.

Instrumentation developments were continued along several fronts. Having completed a trial with diamond coating of an Inconel substrate, GE Super Abrasives will be attempting to coat diamond into the cavity of a GTD-111 tophat specimen (Nickel-based superalloy). CRD's diamond coating facility has been made operational this period, and will be used to coat diamond layers onto Inconel samples which have first been coated with a thin layer of Molybdenum. The tension test specimen made for the purpose of high temperature testing of a new PdCr thin-wire strain gage has received installation of both a conventional gage and the PdCr gage. The possibility of using Excimer laser ablation techniques for the application of thin-film strain gage patterns is also being investigated. The initial specimen for thermocouple sputtering trials with multiple masks has been prepared for thermocouple lead deposition.

Installation of the supporting facilities for the CRD E-beam rig is currently underway. In October, the main compressor for delivery of coolant to the test specimens, a modified Ingersoll-Rand capable of 2.1 m³/min. at rated conditions, has been installed in the facility. Much of the electrical, water, and high pressure air supplies have been placed within the facility for hook-up to the rig equipment. Facility logistics and structure are currently in progress to receive the E-beam and its associated containing room and equipment. The E-beam generator vendor has informed CRD that refurbishment of the device will take longer than initially anticipated. Whereas the vendor's initial delivery date was scheduled for mid-November, they indicated a slip of approximately one month due to the need for much more extensive re-wiring.

In the interim period prior to operation of the CRD facility, a portable Helium cooling rig will be used with the E-beam at Precision Technologies (PTR) in Connecticut. This portable cooling rig has been completed and received a safety review in preparation for shipment. The initial subset of N5 tophat specimens, those of lowest overall quality, has been machined to common dimensions. Some of these specimens will be used in the early testing with the portable system.

In October, instrumentation development efforts continued in the application of high temperature sputtered thermocouples and strain gages within tophat specimens. The superalloy tension test specimen having one conventional strain gage and one high temperature thin-wire strain gage has been prepared for testing. GE Super Abrasives continued to work on the coating of thin diamond films onto the instrumentation face of a tophat, and started working in conjunction with CRD to accomplish the most feasible method for this task. Masking trials for the sputtering patterns of instrumentation have focused first on the consistent application of masks within the tophat geometry such that the required pattern integrity may be achieved from part-to-part. An initial trial with the sputtering of PdCr has begun, prior to the use of an Excimer laser process to ablate the undesired material away, leaving a strain gage of the desired dimensions and form. NASA Lewis Research Center has set up their Laser Optic Speckle Strain Measurement system for testing on CRD supplied TBC coated samples. A cooling pump failure has forced NASA to delay testing until November.

In November, the preparation of the CRD facility has been completed pending delivery and installation of the Electron beam generator. The vendor providing the E-beam generator, Advanced Vacuum Resources, has postponed acceptance testing and delivery until early January 1995. In the interim period, testing has been initiated at Precision Technologies, using the portable Helium-cooled test rig. The first set of tests focused on characterizing the rig operation and assuring that the desired thermal conditions could be reached. As a result, some minor rig modifications were made to achieve lower coolant loop pressure losses, as well as to make the interchange of specimens a less time consuming task.

Thin-film instrumentation trials continued in two areas. A tophat specimen of GE material GTD-111 has been polished to a mirror finish on the "cold" side of the specimen. This surface has been coated with a thin sputtered layer of alumina in preparation for putting down thin-film thermocouples of Pt/Pt-Rh. Trials at both GE Super Abrasives and at CRD continue in the effort to deposit thin films of diamond on prepared metal surfaces, as highly thermally conductive but electrically insulating layers for instrumentation.

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

It was expected that rigid spline seals would be used for the First Stage Nozzle inter segment junctions, both in production and in the planned Nozzle Cascade Tests. However, prototype castings will be used in the Cascade Tests, and these have significant radial misalignments at the sealing locations. As a result, rigid seals cannot be used.

The locations of the sealing junctions are shown in Figure 8.4.1. Cold gaps will be machined to be 0.120"; hot gaps range from 0.020" to 0.070". Radial misalignments exceed 0.180" in a shroud which is 0.375" thick. In some locations, the direction of radial misalignment reverses direction.

The designs of the slots and seals are still in progress. The castings will be matched to limit the radial misalignments to 0.130". The designs for the First Stage Nozzle inter segment seals have been finalized. Samples and jaws were made and tested in the two can rig. Sealing

performance will be determined and assembly issues will be addressed in the interpretation and analysis of the data collected.

Figure 8.4.1 Inter segment sealing junctions for First Stage Nozzle

Plans for Next Reporting Period

Further progress in this task will await allocation of additional funds.

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.

Technical Progress

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 currently being designed, 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 is now obtaining data in smooth rectangular full scale blade cooling passages. 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.

Technical Progress

Prior to obtaining data on the turbulated aspect ratio rectangular duct at the maximum rotational speed, thin film heaters and thermocouples were installed on the outlet manifold, in radial outward flow, in order to obtain turbine tip heat transfer data with and without rotation. An added objective of this step is to evaluate the operation of cemented thin film heaters at high rotational speed to qualify these heaters for use on larger aspect ratio ducts. Their application will permit the largest aspect ratio duct within the configuration of the test arm.

During this quarter, which involved a low level of activity, the serpentine pattern thin film heater attached to the outer manifold surface, together with thin film thermocouples, were

further tested with and without heat addition to the test duct. The measured tip heat transfer coefficients in the initial data were insensitive to heat addition in the test duct and varied significantly with rotational speed. There was also a large variation of the local coefficients over the outer manifold surface with the ratio of the maximum local-to-average heat transfer coefficient being about two-to-one.

The absence of heaters on the manifold side walls required a significant conduction error correction that would be eliminated if guard heaters were employed on the side walls. Secondly the serpentine heater conductor pattern limits the heater to a lower maximum heat flux due to conductor hot spots. For this reason a continuous film heater is being added to the manifold side wall to both evaluate its adhesion at high rotational speed and its maximum heat flux capability. After these tests are completed, the turbulated duct data will be completed at the maximum rotational speed in the first quarter of 1995.

Since it has been decided to subsequently test a larger aspect ratio rectangular duct, in view of the large difference between square duct and rectangular duct heat transfer coefficients at increasing Buoyancy numbers, further evaluation of the continuous film heaters and thermocouples will be required. Both the thermal conductivity of the thermocouple heater sandwich will be measured and duct wall conduction error analysis will be carried out to insure that a sufficient range of operation can be obtained. The use of these thin film components will allow twice the aspect ratio to be installed in the rotating test facility, a step that would not be possible using the present heater design.

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 the Stage 1 Nozzle airfoil of the Advanced Machine, 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 NO_x 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.

Technical Progress

The cascade was re-assembled with a mechanically fixed exit boundary modifying piece, that of the 2.5-degree wedge. The cascade was flow tested using the combined output of all three facility compressors. Flow testing showed an apparent choked condition in the flow path, since the pressure ratio of the cascade could not exceed about 1.65. Upon removal of the exit piping, the exit flange gasket was found to be slightly extended into the flow path on one side. This condition was corrected and the cascade again flow tested. The maximum flow of the combined compressors reached 8.4 kg/sec, with cascade inlet total pressure of 5 atm and total temperature of 293 K. The cascade pressure ratio reached 1.93, with slightly supersonic flow on the suction side of the airfoils. Also of importance, the cascade measurements show the cascade to be nearly periodic in flow amongst the passages. Previous tests which did not indicate periodicity, apparently were affected by the de-adhering insert wedge.

Subsequent flow tests were conducted at conditions yielding a similar inlet Reynolds number to that of the turbine. Tests were run with about 7.5 kg/sec flow, at 5.5 atm and 294 K, giving an inlet Reynolds number of about $1.07 \cdot 10^6$. Airfoil static pressure measurements were recorded for the two central airflow passages at cascade pressure ratios of 1.46, 1.55, 1.67, 1.78, 1.86, and 1.93, providing Mach number distributions over this range of conditions. At the highest pressure ratio, the cascade is slightly transonic, providing turbine representative local flow Mach numbers for heat transfer testing.

Upon completion of the preliminary flow testing, the cascade was partially disassembled, and the center airfoil removed. In preparing the thin-walled, thermocouple instrumented airfoil for placement into the cascade, the adhesion method for application of the thin-foil surface heater was found to be unsatisfactory. Alternative adhesive methods were then sought, including a Scotch-Weld epoxy and a very thin photographic mounting film. The photographic mounting film was chosen as the best overall adhesion method, providing uniform thickness without voids, and capability up to 94°C.

The heat transfer airfoil was wrapped with a thin-foil surface heater, and all power leads attached and routed. Work was begun on re-assembly of the test airfoil within the cascade. The heater power supply unit was set up within the test cell. The remote instrumentation traversing control device was tested for proper function.

Plans for Next Quarter

After proper functioning of the power supply and airfoil surface heater have been verified, airfoil heat transfer tests will be conducted beginning with a smooth surface airfoil and low

freestream turbulence intensity level. No flow swirl will be used initially. Testing will then proceed to two higher levels of freestream turbulence. This series of tests will then be repeated first for an airfoil of higher, uniform surface roughness, and then for an airfoil with distributed surface roughness modelling the expected engine conditions.

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

GE Power Systems funding has been used during the first three quarters of 1994 to design and fabricate three turbulence intensity probes. These probes are all of a similar construction. The prototype development and probe fabrication have been carried out by Vatec Corporation of Blacksburg, Virginia.

Each probe consists of an outer stainless steel cylinder of 1.27 cm diameter and an inner cylinder of smaller diameter. The probe is cooled by air entering the inner tube and returning via the outer flow annulus. The external surface of the outer cylinder has two pieces of instrumentation deposited in thin-film form via vacuum sputtering techniques. A Heat Flux Microsensor (HEM) is located on the surface in a region roughly 25 mm by 50 mm. A Resistance Temperature Sensor (RTS) is located immediately adjacent to the HFM element.

The HFM is a relatively new instrument, having been under development at Virginia Tech and Vatec for the past several years. The HFM is a multi-layer, vacuum deposited device, which forms a thermopile element on the surface of the metal. An initial layer of electrically insulating material, such as Al_2O_3 is sputtered onto the surface first. The voltage signal of the thermopile is directly proportional to the surface heat flux through the element, while the RTS element provides knowledge of the local surface temperature. These devices, including insulating and protective layers, have a total thickness of about 2 microns, making them virtually invisible to the external flow field. The HFM delivers a signal of typically 20 μV per W/cm^2 . The device response is as high as 100 kHz, with capability at least to 500 W/cm^2 heat flux.

The probes will be operated in warm or hot flow streams such that the HFM detects the cylinder stagnation point heat flux. Using information gathered on the gas temperature, the stagnation point heat transfer coefficient will be determined. The gas turbulence intensity level is then deduced from the established relationship between cylinder heat transfer and free stream turbulence.

The prototype probe was received in July 1994. This probe was subsequently returned to the manufacturer for calibration to higher temperature levels. The second probe was received in September 1994. This probe has been calibrated to 400°C and shows a linear response character.

Installation requirements have been identified for eventual testing with these probes in a combustor test stand operated by GEPS. Preliminary testing methods and apparatus have been setup for comparison tests with hot-wire anemometry in a CRD test rig. Efforts planned for the "calibration" of the turbulence probes in CRD test rigs, comparisons to hot-wire anemometry, were postponed due to requirements on other ATS program tasks.

The vendor for the turbulence probes, Vatel Corporation, informed CRD that they will not be supplying the third of three ordered probes via the same manufacturing process as the first two probes. The vendor has stated that they do not feel the current probes will be durable in the test environment for which they were intended. The specific problem involves the possible lack of adhesion of the insulating layer between the thin-film sensors and the base metal of the probe. This layer is plasma sprayed Alumina and may de-adhere from the stainless steel metal when heated to test conditions. The vendor has begun investigations into two alternate processes. The vendor has also stated the intention to supply CRD with replacement probes in 1995, at no additional charge.

Plans for Next Quarter

The prototype probe will be installed in CRD's Transient Heat Transfer Cascade and tested in comparison against a hot-wire anemometry probe. The turbulence probe vendor has committed to supplying improved probes during this period. Plans will be made for the introduction of a probe in a full-scale combustor test stand.

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 presented in Figure 8.7.3.1 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 which correspond to impingement jet Reynolds numbers ranging from 8,000 to 72,000.

Module 1 presented in Figure 8.7.3.1 consisted in an impingement supply chamber of 10.16x16.25x5.08 cm (4x6.4x2 inches). The air entered the supply chamber through three 2.54 cm (one inch) holes machined on the side wall. The impingement holes distributed over a plate of 10.16 cm (4 inches) by 17.02 cm (6.7 inches) consisted of twelve rows of holes with each row having eight holes. The diameters of the impingement holes for this first module ranged from 0.193 to 0.244 cm (0.076 to 0.096 inches). The details of the geometry of the impingement holes are presented in Figure 8.7.3.2a and given in Table 8.7.3.1. In addition to the hole pattern, Table 8.7.3.1 also presents the stream wise (X/D) and span wise (Y/D) dimensionless distances for the hole configuration as well as the dimensionless distance between the impingement hole plate and the impingement surface (Z/D). 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 2.54 cm (one inch) holes. These passages connecting the first and second module should have had the shape of race track holes but for the first series of tests the 2.54 cm (one inch) holes were left as manufactured. 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 presented in Figure 8.7.3.1 consisted in an impingement supply chamber of 11.43x15.24x5.08 cm (4.5x6x2 inches). The air entered the supply chamber through three 2.54 cm (one inch) holes machined on the side wall. The impingement holes distributed over a plate of 11.43 cm (4.5 inches) by 13.97 cm (5.5 inches) consisted of ten rows of holes with each row having different number of holes ranging from 7 to 5 depending on the respective row. The diameters of the impingement holes for this second module ranged from 0.193 to 0.498 cm (0.076 to 0.196 inches). The details of the geometry of the impingement holes are presented in Figure 8.7.3.2b and given in Table 8.7.3.2. In addition to the hole pattern, Table 8.7.3.2 also presents the stream wise (X/D) and span wise (Y/D) dimensionless distances for the hole configuration as well as the dimensionless distance between the impingement hole plate and the impingement surface (Z/D). 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 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 2.54 cm (one inch) 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

Figure 8.7.3.3 presents typical temperature (heat transfer coefficient) distributions recorded photographically with module 1 at an air flow rate of 0.136 kg/s (0.3 lb/s). The figures are posted in ascending heat flux levels for a constant air flow rate. The first figures show the first appearance of the green color in the field. 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 super imposed onto each other in order to calculate an average heat transfer coefficient for a typical jet of each row. The photographic temperature (heat transfer coefficient) distributions presented in Figure 8.7.3.3 show three important facts. First of all, although the impingement hole module had twelve rows, the photographs show only eleven rows. The last twelfth row located at the 90 degree turn does not impinge on the bottom plate. The strong cross flow generated by the

turn appears to have entrained the jets issuing from this last row. The heat transfer in this region is mainly controlled by the cross flow and not by the last impingement row and thus have a lower value than expected. Since this turn region is a critical one further tests will be conducted to find means of insuring that the impingement heat transfer levels are obtained. The second fact involves the entrainment of the impingement jets by the strong cross flows. The jet impingement cooling patterns are not directly underneath the jet hole center but have moved downstream due to the entrainment by the cross flow. This displacement increases from the first to the last impingement row. These displacements of the cooling region are not accounted for by the correlations existing in the literature. The third fact observed consists in the plugging off of one of the impingement holes during the tests due to some impurity. The second jet from the right on the fifth row show that the hole is plugged, and a reduction in the local heat transfer coefficient is recorded. The reduction is almost fifty percent of the impingement value which is important if the region of interest has high gas side heat transfer coefficients. Although the metal wall thickness will smear some of this cooling inefficiency by conduction, the results may still depend on the local thermal loads.

Figure 8.7.3.4 is a bar chart representation of the heat transfer results obtained with Module 1 at three main air flow rates for each film row. Each film row has six bars. The first two depict the values predicted by the Metzger correlation (Florschuetz, Truman and Metzger, ASME J. of Heat Transfer, 103, pp. 337-342, 1981) and measured heat transfer coefficients for the 0.045 kg/s (0.1 lb/s) flow tests (average jet Reynolds number 15,000). The third and fourth bars present the predicted and measured results for the test with a flow rate of 0.091 kg/s (0.2 lb/s) (average Reynolds number of 30,000), the last fifth and sixth bars present the same information for the last tests performed at an air flow rate of 0.136 kg/s (0.3 lb/s). The comparison of the results show that the measured values are lower than the correlation predictions. The difference becomes smaller as one proceeds from the first row of holes toward the last rows where the cross flow effects become important. The correlation used was derived from data with a maximum value of Z/D of 3. In the present tests the Z/D dimensionless distance is 6.8 in the first rows and becomes 5.8 in the last eleventh row.

Figure 8.7.3.5 presents typical temperature (heat transfer coefficient) distributions recorded photographically with module 2 at an air flow rate of 0.136 kg/s (0.3 lb/s). The figures are posted in ascending heat flux levels for a constant air flow rate. The first figures show the first appearance of the green color in the field. 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 super imposed onto each other in order to calculate an average heat transfer coefficient for a typical jet of each row. The photographic temperature (heat transfer coefficient) distributions presented in Figure 8.7.3.5 show that although the impingement hole module had ten rows, the photographs show only nine rows. The last tenth row located at the 90 degree turn does not impinge on the bottom plate. The strong cross flow generated by the turn appears to have entrained the jets issuing from this last row. The heat transfer in this region is once again

mainly controlled by the cross flow and not by the last impingement row and thus have a lower value than expected.

Figure 8.7.3.6 is a bar chart representation of the heat transfer results obtained with Module 2 at three main air flow rates for each film row. Each film row has six bars. The first two depict the predicted and measured heat transfer coefficients for the 0.045 kg/s (0.1 lb/s) flow tests (jet Reynolds numbers 8,000 to 22,000). The third and fourth bars present the predicted and measured results for the test with a flow rate of 0.091 kg/s (0.2 lb/s) (jet Reynolds numbers 17,000 to 45,000), the last fifth and sixth bars present the same information for the last tests performed at an air flow rate of 0.136 kg/s (0.3 lb/s). The comparison of the results show that the measured values are lower than the correlation predictions. The difference once again becomes smaller as one proceeds from the first row of holes toward the last rows where the cross flow effects become important. The correlation used was derived from data with a maximum value of Z/D of 3. In the present tests the Z/D dimensionless distance is 6.8 in the first rows and becomes 2.8 in the last ninth row.

Table 8.7.3.1 Geometrical Parameters for MODULE 1

Row #	Jet D (cm)	Jet D (inches)	No.jets	x/D stream	y/D span	z/D
1	0.193	0.076	8	7.9	6.6	6.8
2	0.193	0.076	8	7.9	6.6	6.8
3	0.193	0.076	8	7.9	6.6	6.8
4	0.193	0.076	8	7.9	6.6	6.8
5	0.193	0.076	8	7.9	6.6	6.8
6	0.193	0.076	8	7.9	6.6	6.8
7	0.198	0.078	8	7.7	6.4	6.6
8	0.198	0.078	8	7.7	6.4	6.6
9	0.206	0.081	8	7.4	6.2	6.4
10	0.218	0.086	8	7.0	5.8	6.0
11	0.226	0.089	8	6.7	5.6	5.8
12	0.244	0.096	8	6.2	5.2	5.4

Table 8.7.3.2 Geometrical Parameters for MODULE 2

Row #	Jet D (cm)	Jet D (inches)	No.jets	x/D stream	y/D span	z/D
1	0.193	0.076	7	7.9	8.9	6.8
2	0.193	0.076	7	7.9	8.4	6.8
3	0.264	0.104	6	5.8	6.6	5.0
4	0.264	0.104	7	5.8	6.5	5.0
5	0.297	0.117	6	5.1	6.3	4.4
6	0.345	0.136	5	4.4	6.4	3.8
7	0.391	0.154	5	3.9	5.5	3.4
8	0.462	0.182	5	3.3	5.3	2.8
9	0.462	0.182	5	3.3	4.9	2.8
10	0.498	0.196	5	3.1	5.0	2.6

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. Some of the preliminary tests did not have taps 4, 5, 9 and 10. In some tests only one of the modules was investigated and in some of the tests the pressure distributions of both modules were recorded during the same experiment. To calculate the discharge coefficients across the impingement holes in modules 1 and 2, we used the supply chamber pressure (p_1 for module 1, and p_6 for module 2), and the exit pressure downstream of the impingement holes (p_3 for module 1, and p_8 for module 2).

The overall discharge coefficient across the two 90 degree bends and the transition holes between Modules 1 and 2 and Module 2 and the ambient were also calculated by using the same isentropic equations. For these calculations the supply chamber pressures (p_3 for module 1, and p_8 for module 2), and the exit pressure downstream of the impingement holes (p_6 for module 1, and p_{atm} for module 2) were used for the overall discharge coefficients. The flow areas for each module were taken to be the total flow area for three one inch holes.

Some of the last series of tests performed had static pressure data before and after the 90 degree turns transitioning the flow from Module 1 to Module 2 and from module 2 to the ambient. The combined head losses for these two 90 degree turn transition regions were also calculated by using the pressures measured in taps 3, 4, and 5 for Module 1 and pressures 8, 9, and 10 for Module 2.

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 test rig will model cavities 4, 5 and 6 as representative elements of the cooling system (Figure 8.7.4.1). 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 and a liquid crystal 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 have been designed and manufactured prior to the initiation of this Task 8.7.4. The drawings of the impingement insert for cavity 4 and the Plexiglas insert which has to be glued onto one of the side walls, are complete. 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 Heat Transfer

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 180 degree turns, 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.

Figure 8.7.3.1 Schematic of the test section with two impingement modules and locations of pressure taps.

Figure 8.7.3.2a: Impingement Hole Patterns for
Module 1

MODULE 1

Figure 8.7.3.2b: Impingement Hole Patterns for
Module 2

MODULE 2

IMPINGEMENT HEAT TRANSFER - MODULE 1

Figure 8.7.3.4 Bar chart comparing the measured average jet impingement heat transfer coefficients with those calculated by Metzger's correlation for three air flow rates (Module 1).

Figure 8.7.3.5 Photographs of iso-h-lines with Module 2 at an air flow rate of 0.3 lb/s (Jet Reynolds numbers of 26,000 to 72,000) at increasing heat fluxes.

IMPINGEMENT HEAT TRANSFER - MODULE 2

Figure 8.7.3.6 Bar chart comparing the measured average jet impingement heat transfer coefficients with those calculated by Metzger's correlation for three air flow rates (Module 2).

Figure 8.7.4.1 Schematic of stage 1 nozzle airfoil impingement cooled cavities. Modeled cavities are 4, 5 and 6.