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

**Quarterly Report
March 1 - May 31, 1994**

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REPORTING PERIOD: 3/1/94 - 5/31/94

TABLE OF CONTENTS

EXECUTIVE SUMMARY	TAB 1
STATUS OF TASK 3 THROUGH TASK 8	TAB 2
DETAILS OF TASK 3A	TAB 3
DETAILS OF TASK 8	TAB 4

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 NOx 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 NOx 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: 3/1/94 - 5/31/94

STATUS OF TASK THROUGH TASK 8

Task 3 - Gas Fired ATS Selection

Work continued on GFATS cycle selection. Task 3A (Industrial GFATS) progress is described in the Tab 3 section. Task 3B Utility GFATS) - cycle has been defined, and will be used in the subsequent Tasks.

Task 4 - Conversion to Coal

No progress in this reporting period.

Task 5 - GFATS Market Study

No progress in this reporting period.

Task 6 - System Definition and Analysis

No progress this reporting period.

Task 7 - Integrated Program Plan

No progress this reporting period.

Task 8 - Component Design and Test

Task 8 subtask progress is described in the Tab 4 section.

3.0 TECHNICAL PROGRESS

3.1 HIGH PRESSURE TURBINE HEAT TRANSFER

Preliminary turbine cooling designs for the high pressure turbine vane and blade were developed in the previous reporting period to support the evolution of the ATS cycle and establish the design constraints necessary for a successful detailed design. In this reporting period, technical challenges were addressed pertaining reduction of cooling for the HPT Stage 1 vane.

Technical effort was initiated to reduce the amount of cooling flow needed for all components but particularly for the stage 1 nozzle vane. The approach taken to reduce the component cooling air was to lower the temperature of the cooling air via external heat exchangers. The lowering the cooling air temperature results in the reduction of cooling for several components, hence reducing cycle losses. The resulting cooling flow distribution is shown in Table 1.

Table 1

	<u>Wc (%W25)</u>	<u>Wc(%W25)</u>
	Original Flows	Reduced Flows
	(Tcoolant=700°F)	(Tcoolant=300°F)
Combustor Aft Seal Leakage	0.0	1.8
Combustor Inner Liner	1.5*	1.5*
Combustor Outer Liner	1.5	1.5
HPT Vane Inner Band & Leakage	1.0*	1.0*
HPT Vane Outer Band & Leakage	1.5	1.5
HPT Vane Film	3.7*	2.8*
HPT Shroud	0.5	0.5
HPT Stage 1 Blade	2.2*	1.4*
Forward Combustor	<u>0.4*</u>	<u>0.6*</u>
Total	12.3	12.6

Note: All flows noted with a * pass through the HPT vane, which is captured and used to cool the combustor inner liner, vane inner band, HPT stage 1 blade, and forward combustor seal.

Vane thermal studies are in progress to evaluate the effect reducing the cooling flow temperatures as noted. Figure 1 shows the resulting vane temperatures for the new cooling flows and reduced temperatures.

METAL TEMPERATURES

T BULK=	1456
SEGMENT=	5
RADIUS=	17.67885

Figure 1

3.2 TURBOCOOLER SYSTEM

The revised pressure loss for new cooling flow of 12.6%w25 is shown in Figure 2. With the reduced pressure loss, less airflow is needed to power the turbocooler turbine which reduces the cycle losses.

ESTIMATED PRESSURE DISTRIBUTION
IN ATS TURBOCOOLER
AT FULL POWER

Figure 2.

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

This quarter saw the first exposure of the two micron filter element cartridge in the powerplant flow system shown in Figure 1. The system worked as designed with the computer controlling the upstream valve, CV101, to control flowrate at 1 lb/sec (as metered by the orifice) and the downstream valve, CV401, to control filter system pressure. The 30"x2-1/2" filter cartridge tested was fabricated from a 304SS double-screen with a powder metal coating to provide a 98% capture of particles 2microns or greater. The filter was mistakenly crushed axially because of a 1/4" interference fit error in its housing design, but, except for a slight bulge in the diameter near the tip, the filter appeared to remain intact, giving an encouraging sign of robustness for powerplant use. Both the housings and the filter cartridge have been returned to the vendor for a housing modification and to check the bubble point and gas permeability of the filter. No increase in pressure drop across the filter was observed during the exposure, and an upstream coolant condensate silver filter is being analyzed for total iron, the primary contaminant observed in prior coolant sample filtering experiments, both in the gas- and condensed- phases. SEM photographs of the filter show a few particles as large as 400 microns, but most on the filter are in the 4-10 micron range. The particle Fe/Cr ratio indicates they are from the superheater, as expected. The particles are very friable and do not stick to any filter as a cake but seem to fall off if given the chance. This is encouraging for maintaining low pressure drops in the practical system. Earlier measurements indicated only 2ppbw of Fe as Fe_3O_4 in the steady coolant flows, so it was not surprising that there was no pressure drop increase during the first test. The next test will be left online for longer run time.

Progress was also made on developing a filtration system for practical powerplant use. The initial concept of the filtration system was to employ four, 50 lb/sec coolant flow canisters of cartridges in parallel with appropriate valving to enable three online while one was being cleaned. With the small mass of particulate found in these studies, with the high cost of

double-valving each isolation point, and with the pressure loss projected for the complex header system, it was decided to focus on a single, 150 lb/sec filter unit which would be serviced when the plant is off-line. The design concept currently developed for the application is to mount the cartridges into headers mounted into each end of a vessel whose axis is horizontal. The feed would come into the vessel in a space between the two cartridge banks and then be directed through the cartridges and out the ends. This arrangement was decided to be the easiest to service, provide the least pressure drop, and avoid the need for multiple vessels and closures.

The system will be reassembled as quickly as possible with the 2 micron cartridge when the modified housings are received from the vendor. The host site has also requested that a second manual feed isolation valve be inserted just ahead of the CV101 control valve to allow operator shutdown without having to operate the main extraction valve which is in a difficult position to reach under the turbine. The plan will be to allow the system to run continuously for over 1000 hours. Earlier runs have been interrupted by plant upsets and shutdowns, but the computer system has been modified to try to keep the filtration system online as much as possible. That means that the effect of load changes will be integrated into the overall result, but a record of large changes will be kept as part of the filtration dataset.

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

The purpose of this test is to subject a coolant return bend to the same acceleration conditions that would be seen in the cooled bucket having the highest G-field in the machine to determine if deposition rates are indeed as low as estimated from particle size and concentration measurements. During this quarter, the system design by the vendor, MTI, has proceeded from preliminary design through final design for the system. Figure 8.2.1. shows the views of the apparatus itself, and Figure 8.2.2. shows the control and instrumentation system which is connected to the same computer now online in Task 8.1.

A Detail Design Review was held. Issues coming from the review were mainly focused on missile containment and creep strength of the yoke, both of which have been subsequently addressed satisfactorily.

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

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. Delamination mechanisms are especially critical because they are capable of catastrophically removing the thermal protection provided by the TBC. Analyses of many examples of coating loss have shown that delamination crack growth often occurs at low temperatures due to high in-plane residual stresses in the coating. There is also evidence that damage may occur at high temperature due to thermal stress caused by high thermal gradients and/or rapid thermal transients.

Methods are available and numerous measurements have been made in this laboratory of the residual stress states of TBC's at room temperature. Comparable methods and measurements, however, are not available for thermal conditions representative of advanced gas turbine operation which include high temperatures, large thermal gradients and high, externally-imposed states of strain. In this task calculations will be made of the stress state of coated substrates in isothermal, gradient and transient conditions. In addition, the actual stress state will be measured versus temperature in isothermal conditions. Comparisons of calculated versus measured stresses will be used to assess the ability to predict stress states in actual turbine operation.

Also, in order to directly evaluate the durability of TBC's in steep thermal gradients and under transient conditions, an improved thermal gradient exposure facility will be developed and constructed. The facility will be capable of exposing TBC coated specimens to thermal conditions representative of advanced gas turbine components and will be demonstrated on coated substrates.

The following two sub-sections describe the progress and plans related to the two objectives of this task.

Analysis and Measurement of Coating Stress

The accurate prediction of TBC stress states requires advances in both stress analysis techniques and measurement of important physical properties. This subtask includes effort directed towards both needs.

Specimens of dense zirconia have been prepared for evaluation of Young's modulus versus temperature and of shear modulus at room temperature. The temperature dependence of Young's modulus will be needed to correct the results of an experiment to measure elastic modulus versus stress that is described later in this report. The high damping nature of microcracked TBC's precludes direct measurement of resonant frequency versus temperature of free-standing TBC specimens in the impulse excitation equipment available. The intrinsic behavior of elastic modulus versus temperature is expected to be independent of density and microcracking. Therefore, dense specimens are being used for this measurement. The specimens were fabricated at CRD using Tosoh 4Y powder which is a 4 mole % (7 wt %) yttria partially stabilized zirconia of virtually the same composition as the TBC's of interest. The powder was uniaxially pressed in a 3.5 in. diameter cylindrical die at 8300 psi at room temperature; bagged and isopressed at 40,000 psi; and sintered in air at 1450 C for four hours with 100°C/ hour heating and cooling rates. The resulting disks measured approximately 79 mm diameter and 3.8 mm in thickness with a density of approximately 6.02 g/cc (from geometric measurement and mass). This density is very close to the theoretical density for this composition.

A metallographic specimen was cut and polished from one disk of zirconia. Inspection of the microstructure revealed very little porosity. Quantitative image analysis was performed on ten randomly chosen fields of view within this same sectioned specimen. The total area analyzed was approximately 0.4 mm². The resulting average porosity was found to be 0.609 percent of the image area, indicating a density of greater than 99 percent of theoretical.

Specimens of dense zirconia were cut and diamond ground from one disk and used to evaluate shear modulus and Poisson's ratio at room temperature and Young's modulus versus temperature up to 700°C. Care was taken to define parallel opposite surfaces and sharp edges to minimize errors in data reduction and analysis of the elastic moduli. The specimens were found to exhibit clean, sharp resonance using an impulse excitation technique. The acoustic impulse technique was based on the upcoming ASTM standard C-1259-94 entitled "Elastic Modulus by Impulse Excitation of Vibration."

Dynamic Young's modulus was measured on a specimen with approximate dimensions of 0.14 x 0.25 x 2.0 inches. The specimen support and impulse excitation geometry encourage longitudinal out-of-plane flexural vibrations. FFT analysis of the signal sampled by a digital oscilloscope showed a strong fundamental vibration of this mode along with detectable signals for the next three higher harmonics of longitudinal out-of-plane flexure. The fundamental mode is used for modulus determination because published geometric corrections are most mature for the fundamental mode. Harmonics analysis, however, showed that the higher order modes are in agreement (result in approximately the same Young's modulus) thus confirming the assignment of vibrational modes to observed resonant frequencies. The room temperature Young's modulus was 30.5 Mpsi (210 GPa).

The Young's modulus was evaluated versus temperature by hanging the same specimen from the fundamental node positions for flexure using Pt wires and heating the specimen assembly in a resistance heated, vertical tube furnace. The specimen was excited by the impact of a small zirconia sphere dropped through a guide tube positioned to define the point of impact at the center of the beam length. The acoustic response was sensed by a microphone located below the bottom of the furnace. The signal was sensed at the specimen midspan and carried out the bottom of the furnace using a 0.5 inch diameter tubular waveguide.

The results of Young's modulus versus temperature are included in Figure 8.3.1. The modulus was determined at temperatures of room temperature, 200, 400, 550 and 700°C. Temperature was equilibrated in each case before the acoustic measurements were made. Specimen dimensions at temperature were adjusted according to the growth expected from thermal expansion. To confirm that the heating cycle did not modify the elastic properties, the entire thermal cycle and associated measurements were repeated a second time. Figure 8.3.1 shows results from both heating cycles and shows that there is no significant difference in moduli in the second cycle.

A beam-shaped specimen measuring approximately 0.14 x 0.5 x 2.0 in. was used for measurement of dynamic shear modulus. The shear modulus was only measured at room temperature. The specimen supports, microphone location and excitation location were positioned as recommended in the ASTM standard to encourage torsional modes of vibration. The resulting shear modulus was 11.6 Mpsi (80.1 GPa).

The room temperature longitudinal and torsional resonant frequencies were used in an iterative fashion as also described in the ASTM standard to determine a value of Poisson's ratio at room temperature of 0.312.

Specimens have been prepared and measurements have begun for determination of TBC residual stress and attached Young's modulus versus temperature from room temperature to 700°C. Information from these measurements will, in turn, allow deduction of elastic modulus versus stress and any non-linearities in the elastic behavior over the range of stresses observed in the experiment.

The specimens were prepared as coupons of IN-718 substrate measuring approximately 1 x 2 x 0.125 inch that were coated on one side with approximately 0.005 inch of a NiCrAlY bondcoat and approximately 0.055 inch of 8 w/o yttria partially stabilized zirconia. The coatings were applied by air plasma spraying using deposition conditions that create TBC microstructures similar to those thought to be desirable for advanced turbine applications. The relatively large thickness of TBC was chosen to allow greater sensitivity in measurement of stress and modulus. It is hoped that the technique will have sufficient sensitivity to allow future measurements on thinner TBC layers.

From one coupon, three beam specimens have been prepared, each measuring approximately 2 x 0.25 x 0.185 inch. The specimens will be carried together through the measurements of stress and modulus. One edge of each beam was polished to allow optical measurement of the layer thickness versus position along the specimen length. The back side of the substrate was

polished to provide a smooth surface for profilometer traces that are taken repeatedly through the course of the experiment.

The experiment consists of measuring: specimen curvature at room temperature using profilometry; specimen curvature versus temperature up to 700°C using a three-point probe in a dilatometer (bimaterial dilatometry); and resonant frequency versus temperature up to 700°C using an impulse excitation technique described in earlier reports. These measurements are made before and after a portion of the TBC thickness is removed by diamond lapping. The experiment is planned to lap approximately one-third of the coating in each of three thinning operations. This will allow the properties of stress and modulus to be measured for individual sublayers through the TBC thickness as well as for the entire coating thickness.

The three specimens are carried through the experiment together except that one specimen is never heated above room temperature, the second is never heated above 400°C, and the third is heated to the full 700°C. The purpose of this experimental design is to allow a degree of redundancy in the measurements while providing a means to detect if any irreversible effects occur as a result of the heating cycles.

Specimen preparation is complete and curvature/resonance measurements are now in progress prior to the first thinning.

Initial screening of non-linear models in the ABAQUS finite element analysis code has begun. Using a one element structure, various material models were compared. Through this process, the choices of material models for use in describing the non-linear nature of TBC stress/strain behavior have been narrowed down.

A procedure was established for deriving a stress-strain curve when Young's modulus is measured at a number of residual stress levels. The procedure consists first of fitting the measured Young's modulus vs. stress points with a polynomial. The second step is to perform a numerical integration of a differential equation to derive the stress-strain curve. Stress-strain curves were created for APS and PVD TBC's based on preliminary data available at the present time.

Based on the preliminary nonlinear stress-strain relationships for the TBC, a stress analysis procedure has been established. As a first step, from the measured residual stress state in the coating a zero-stress reference temperature is calculated to serve as a reference state for subsequent predictions of stresses at elevated temperatures. Work is in progress to establish the effect of different degrees of nonlinearity on the stress levels.

Various axisymmetric TBC'd test specimen geometries were analyzed in an effort to design an appropriate test specimen for high thermal gradient testing. The effect of different mechanical constraints and fixture boundary conditions were compared. Analytical closed-form relationships were derived to obtain the TBC stress state at the TBC/metal interface in terms of the metal stresses. The goal of this analysis is to estimate the test conditions and specimen geometry which will simulate the TBC stress state of components in an advanced gas turbine. It was shown that if the interface metal stress and interface temperature in the test specimen are matched to those of the engine component, then the TBC stress state is very similar to that of the component and is quite insensitive to the actual boundary conditions of

the test specimen used to generate that interfacial stress. The analysis of effects of boundary conditions and constraints has been extended to 16 different cases.

Assuming a given value of compressive metal stress at the metal/ceramic interface (obtained from design analysis), a parametric study was conducted covering 20 different cases of variations in TBC and metal moduli, Poisson's ratios and interface temperatures. The results of these studies have been summarized in terms of simple design curves, including a curve describing the TBC stress as a function of metal stress at the interface.

Thermal Gradient Exposure Facility

In order to evaluate TBC performance, a laboratory scale thermal gradient exposure facility is being developed and constructed. The objective of the facility is to closely simulate the extreme thermal conditions anticipated in an advanced gas turbine TBC. The primary heat source being investigated for this facility is an atmospheric electron-beam (E-beam) gun.

E-beam experiments have been performed on TBC specimens mounted on a finned copper heat sink. The TBC samples were 0.015 in. thick and deposited on 0.125 in. thick Inconel 718 substrate. The specimens were 1 by 1 in. in area. The fins of the copper heat sink were water cooled. The specimens were exposed to the e-beam operating at 175 Kev with a current of 30 or 35 milliamps. The distance of the sample from the e-beam focus and the settings of the e-beam were chosen so as to deliver about 1.6 kilowatts per square inch onto the sample. Type K thermocouples were used to monitor the temperatures of the Inconel and the copper block. A Land infrared pyrometer was used to measure the temperature of the TBC layer. Thermal gradients through the TBC of up to 108 F/mil were recorded, along with surface TBC temperatures of around 2200-2300°F. These experiments demonstrate that the e-beam can successfully impose sufficient thermal flux on the TBC to generate the thermal gradients required for the development of TBC's for the ATS application.

Experiments have been performed to investigate the flux distribution that can be obtained from the atmosphere-capable e-beam. In normal use, the device is focused to a spot some 0.5 inches into the air, measured from the final differentially pumped aperture. In our application, we allow the beam to expand beyond this focus and use the large spot size to heat our sample. The electron beam expands in diameter both because of the geometrical optics that were defined by the parameters of the electron gun and also because of scattering of the electrons by the gas molecules upon which the beam impinges once it leaves the vacuum. The scattering effect of the gas depends upon the electron density that it presents to the e-beam. Thus it will depend on both number density and atomic number. An atmosphere of helium gas will scatter the beam considerably less than an atmosphere of nitrogen or argon.

Our experiments consisted of traversing a tungsten rod over a plane normal to the e-beam and at a known distance from the e-beam aperture. The tungsten rod was 0.25 inch in diameter and 2 inches long. Several thermocouples were embedded in the rod along its length. One end of the rod was water cooled while the other was exposed to the e-beam. The sides of the rod were insulated with zirconia balloons. At each position of the rod a temperature gradient was set up. This gradient was proportional to the e-beam flux into the exposed end of the rod. By moving the rod in a raster pattern normal to the e-beam direction, a profile of the e-

beam flux was developed. Preliminary analysis of the data shows that we can expect a 10% variation of the flux over a 1 inch diameter TBC sample. This would be achieved, in air, at a distance of 4-5 inches from the e-beam final aperture and with e-beam conditions of 50 milliamps and 150 keV. The nominal flux delivered by the e-beam was about 300 watts per square centimeter.

In this first series of tests, the absolute e-beam flux distribution was examined by traversing a tungsten probe through the beam. In a second type of experiment the e-beam was allowed to fall upon a disc of pure zirconia and video images were taken of the thermal state of the zirconia surface. The images were recorded through a narrow band filter centered at 0.6232 microns (red). The images were corrected for optical distortion and converted into relative temperatures. These relative temperatures were compared with the values obtained (on a much coarser grid) from the tungsten flux probe. The two experiment were in reasonable agreement.

In addition to a thermal profile of the TBC sample under test we also expect to need a measure of the sample strain. In order to become familiar with the latest mechanical and optical measurement techniques for strain at high temperature we visited the Strain Gage Laboratory at NASA Lewis. Several techniques were demonstrated to us that could be applicable to our testing geometries and conditions.

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

Three advanced sealing concepts of TP-FSN applications were developed. These include hooked cloth concept, Wedge Seal Concept #1; and Wedge Concept #2. Straight, 12-inch "standard" seals of the first two concepts have been tested. They show effective gaps of 8.8 mils and 5.5 mils respectively. The leakage is expressed as equivalent gaps in mils. A straight, 12-inch sample of the existing rigid seal design was tested for back-to-back comparison. It showed an equivalent gap of 13.6 mils. The new seals show approximately 3:1 improvement in the leakage efficiency. Curved (120-inch Radius), 12-inch samples of all three concepts will be tested in the next quarter. Figure 8.4.1 shows the test setup. The curved seal samples are

being ordered. The third concept involving a wedge seal will also be tested in the next quarter. This will be done only on the curved sample.

Two cloth seal concepts have been developed for the Nozzle-Shroud Sealing application. Twelve-inch, straight seal samples were fabricated and tested under different pressures. Additionally, relative positions of the mating parts were varied to represent growth and misalignment. Large offsets showed a tendency for a sudden drop in sealing effectiveness: this was discovered to be due to large deflections of the cloth seals causing the high-pressure air to "lift" the seal off the mating surface. New seal designs have been developed to circumvent this problem. These will be fabricated and tested in the next quarter. Following that, curved samples of the best design(s) will be fabricated and tested to evaluate the effect of curvature.

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 been selected to perform this task. A contract will be placed with Texas A&M once subcontract approval has been granted by DOE.

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 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

The data for the smooth rectangular duct (0.3" x 1.0" x 7" long) were completed and the results reported. The data cover the effect of high Reynolds and Rotation number for both radial outflow and inflow conditions as well as the effect of inlet conditions. The results clearly indicate the significant change in the local heat transfer coefficients that take place at the operating conditions of interest to power generation gas turbines compared to the data available at lower Reynolds and Rotation numbers in square ducts. It also shows the region over which inlet effects can control local heat transfer.

The construction of the turbulated rectangular test section was completed during this reporting period together with its installation and instrumentation. This test section includes inlet and discharge 180° bends similar to those found in turbine blade passages to insure realistic inlet conditions. The turbulators were shaped similarly to those in the application using the EDM process. Calibration and balance testing is now in progress with initial data expected in mid June. At stationary conditions the data in the literature for similar turbulated rectangular ducts varies by at least 30%. For this reason, and to obtain a comparison base, initial data will be taken at stationary conditions.

Task 8.7

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

Cascade fabrication is complete, including all auxiliary flow preparation components. Airfoils receiving static pressure holes and tubing for the measurement of passage Mach number distributions have been completed. All inlet and exit piping, flanges, and valves for the cascade have been assembled, welded, and received the necessary instrumentation ports. Thrust supports for both the cascade and the associated piping reaction loads have been fabricated and secured in-place. All wiring and cable routing has been completed, including thermocouple leads, pressure transducer lines, readout meters, remote control lines, video monitor transmission line, and computer front end communication. The data acquisition system and programming are also complete.

The cascade housing and upstream flow preparation vessel were hydrostatically pressure tested to a level approximately 2.7 times the anticipated operating pressure to be used during testing with air flow. This higher pressure level is equal to the rupture pressure of the safety rupture disk installed on the vessel after hydro testing was completed. Only minor leakage was noted, primarily in the region of the cascade-to-vessel interface. This region has since been sealed more effectively with thicker, more compliant gasket material, and slightly greater bolt torque.

The cascade was reassembled with airfoils in the middle three positions which contain static pressure instrumentation for flow through the center two air passages. All test rig pressure transducers were calibrated at this time. Air flow was initiated through the cascade, initially at low flow and low pressure. During this time, the instrumentation was verified to be displaying correct information. Those readings which were found to be incorrect due to improper or faulty wiring were corrected. Minor modifications to the computer data acquisition and display system were also performed. Mainstream air supply was brought to the cascade in separate tests using each of the two supply lines. When the cascade is operated at full conditions, these two lines shall be flowing in parallel. Operation through the larger of the two lines allowed verification of the total flow orifice station for the cascade via comparison with another orifice located farther upstream in this supply line.

Static pressure distribution measurements made during the flow tests showed Mach number distributions appropriate for the cascade pressure ratio used. The suction side of the central airfoil showed static pressures which were inconsistent with the other surrounding measurements. After eliminating other flow effect possibilities, this airfoil was removed for inspection. Signs of pressure tube crimping were evident for the measurement locations in question, apparently as a result of installation. These pressure lines have been repaired.

The repaired airfoil will be installed in the cascade, and flow tests performed to verify the correct Mach number distribution. The remote system for the traversing and/or rotation of probes, such as a hot-wire anemometer, will be installed prior to flow characterization testing. Flow testing will proceed to establish the baseline conditions of inlet flow distribution, temperature uniformity, and turbulence intensity levels, as well as the exit turbulence intensity. Using recently received airfoil thin-foil surface heaters, trials will be made to assure the proper

adhesion of the heaters to the airfoils, and the correct attachment of leads to the heaters. Heat transfer testing will progress to determine the external coefficient distributions for various baseline configurations, as well as conditions with varying turbulence intensity and airfoil surface roughness.

Figure 8.2.1 Centrifugal Test Apparatus

Figure 8.2.2 Control and Instrumentation System

CENTRIFUGAL DEPOSITION INSTRUMENTATION & CONTROL

Figure 8.3.1 Young's Modulus versus Temperature

Figure 8.4.1 Seal Test Facility

REPORTING PERIOD: 3/1/94 - 5/31/94

TABLE OF CONTENTS

EXECUTIVE SUMMARY	TAB 1
STATUS OF TASK 3 THROUGH TASK 8	TAB 2
DETAILS OF TASK 3A	TAB 3
DETAILS OF TASK 8	TAB 4

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: 3/1/94 - 5/31/94

STATUS OF TASK THROUGH TASK 8

Task 3 - Gas Fired ATS Selection

Work continued on GFATS cycle selection. Task 3A (Industrial GFATS) progress is described in the Tab 3 section. Task 3B Utility GFATS) - cycle has been defined, and will be used in the subsequent Tasks.

Task 4 - Conversion to Coal

No progress in this reporting period.

Task 5 - GFATS Market Study

No progress in this reporting period.

Task 6 - System Definition and Analysis

No progress this reporting period.

Task 7 - Integrated Program Plan

No progress this reporting period.

Task 8 - Component Design and Test

Task 8 subtask progress is described in the Tab 4 section.

3.0 TECHNICAL PROGRESS

3.1 HIGH PRESSURE TURBINE HEAT TRANSFER

Preliminary turbine cooling designs for the high pressure turbine vane and blade were developed in the previous reporting period to support the evolution of the ATS cycle and establish the design constraints necessary for a successful detailed design. In this reporting period, technical challenges were addressed pertaining reduction of cooling for the HPT Stage 1 vane.

Technical effort was initiated to reduce the amount of cooling flow needed for all components but particularly for the stage 1 nozzle vane. The approach taken to reduce the component cooling air was to lower the temperature of the cooling air via external heat exchangers. The lowering the cooling air temperature results in the reduction of cooling for several components, hence reducing cycle losses. The resulting cooling flow distribution is shown in Table 1.

Table 1

	<u>Wc (%W25)</u>	<u>Wc(%W25)</u>
	Original Flows	Reduced Flows
	(Tcoolant=700°F)	(Tcoolant=300°F)
Combustor Aft Seal Leakage	0.0	1.8
Combustor Inner Liner	1.5*	1.5*
Combustor Outer Liner	1.5	1.5
HPT Vane Inner Band & Leakage	1.0*	1.0*
HPT Vane Outer Band & Leakage	1.5	1.5
HPT Vane Film	3.7*	2.8*
HPT Shroud	0.5	0.5
HPT Stage 1 Blade	2.2*	1.4*
Forward Combustor	<u>0.4*</u>	<u>0.6*</u>
Total	12.3	12.6

Note: All flows noted with a * pass through the HPT vane, which is captured and used to cool the combustor inner liner, vane inner band, HPT stage 1 blade, and forward combustor seal.

Vane thermal studies are in progress to evaluate the effect reducing the cooling flow temperatures as noted. Figure 1 shows the resulting vane temperatures for the new cooling flows and reduced temperatures.

Tgas=3075 (LM6000 PF) Case 16F 10&15 mils TBC Tc=300

METAL TEMPERATURES

T BULK= 1456
 SEGMENT= 5
 RADIUS= 17.67885

07:49 05/02/94 mE02074912bdl c0031 PLOT 1
 EGS LIB 4.4.3.D 17-MAY-1991 (EGSREP.XPOST 4.4.4.6 10/15/92 on ss15)
 (NO PROG. VER. SPECIFIED)

3.2 TURBOCOOLER SYSTEM

The revised pressure loss for new cooling flow of 12.6%w25 is shown in Figure 2. With the reduced pressure loss, less airflow is needed to power the turbocooler turbine which reduces the cycle losses.

**ESTIMATED PRESSURE DISTRIBUTION
IN ATS TURBOCOOLER
AT FULL POWER**

Figure 2.

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

This quarter saw the first exposure of the two micron filter element cartridge in the powerplant flow system shown in Figure 1. The system worked as designed with the computer controlling the upstream valve, CV101, to control flowrate at 1 lb/sec (as metered by the orifice) and the downstream valve, CV401, to control filter system pressure. The 30"x2-1/2" filter cartridge tested was fabricated from a 304SS double-screen with a powder metal coating to provide a 98% capture of particles 2microns or greater. The filter was mistakenly crushed axially because of a 1/4" interference fit error in its housing design, but, except for a slight bulge in the diameter near the tip, the filter appeared to remain intact, giving an encouraging sign of robustness for powerplant use. Both the housings and the filter cartridge have been returned to the vendor for a housing modification and to check the bubble point and gas permeability of the filter. No increase in pressure drop across the filter was observed during the exposure, and an upstream coolant condensate silver filter is being analyzed for total iron, the primary contaminant observed in prior coolant sample filtering experiments, both in the gas- and condensed- phases. SEM photographs of the filter show a few particles as large as 400 microns, but most on the filter are in the 4-10 micron range. The particle Fe/Cr ratio indicates they are from the superheater, as expected. The particles are very friable and do not stick to any filter as a cake but seem to fall off if given the chance. This is encouraging for maintaining low pressure drops in the practical system. Earlier measurements indicated only 2ppbw of Fe as Fe_3O_4 in the steady coolant flows, so it was not surprising that there was no pressure drop increase during the first test. The next test will be left online for longer run time.

Progress was also made on developing a filtration system for practical powerplant use. The initial concept of the filtration system was to employ four, 50 lb/sec coolant flow canisters of cartridges in parallel with appropriate valving to enable three online while one was being cleaned. With the small mass of particulate found in these studies, with the high cost of

double-valving each isolation point, and with the pressure loss projected for the complex header system, it was decided to focus on a single, 150 lb/sec filter unit which would be serviced when the plant is off-line. The design concept currently developed for the application is to mount the cartridges into headers mounted into each end of a vessel whose axis is horizontal. The feed would come into the vessel in a space between the two cartridge banks and then be directed through the cartridges and out the ends. This arrangement was decided to be the easiest to service, provide the least pressure drop, and avoid the need for multiple vessels and closures.

The system will be reassembled as quickly as possible with the 2 micron cartridge when the modified housings are received from the vendor. The host site has also requested that a second manual feed isolation valve be inserted just ahead of the CV101 control valve to allow operator shutdown without having to operate the main extraction valve which is in a difficult position to reach under the turbine. The plan will be to allow the system to run continuously for over 1000 hours. Earlier runs have been interrupted by plant upsets and shutdowns, but the computer system has been modified to try to keep the filtration system online as much as possible. That means that the effect of load changes will be integrated into the overall result, but a record of large changes will be kept as part of the filtration dataset.

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

The purpose of this test is to subject a coolant return bend to the same acceleration conditions that would be seen in the cooled bucket having the highest G-field in the machine to determine if deposition rates are indeed as low as estimated from particle size and concentration measurements. During this quarter, the system design by the vendor, MTI, has proceeded from preliminary design through final design for the system. Figure 8.2.1. shows the views of the apparatus itself, and Figure 8.2.2. shows the control and instrumentation system which is connected to the same computer now online in Task 8.1.

A Detail Design Review was held. Issues coming from the review were mainly focused on missile containment and creep strength of the yoke, both of which have been subsequently addressed satisfactorily.

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

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. Delamination mechanisms are especially critical because they are capable of catastrophically removing the thermal protection provided by the TBC. Analyses of many examples of coating loss have shown that delamination crack growth often occurs at low temperatures due to high in-plane residual stresses in the coating. There is also evidence that damage may occur at high temperature due to thermal stress caused by high thermal gradients and/or rapid thermal transients.

Methods are available and numerous measurements have been made in this laboratory of the residual stress states of TBC's at room temperature. Comparable methods and measurements, however, are not available for thermal conditions representative of advanced gas turbine operation which include high temperatures, large thermal gradients and high, externally-imposed states of strain. In this task calculations will be made of the stress state of coated substrates in isothermal, gradient and transient conditions. In addition, the actual stress state will be measured versus temperature in isothermal conditions. Comparisons of calculated versus measured stresses will be used to assess the ability to predict stress states in actual turbine operation.

Also, in order to directly evaluate the durability of TBC's in steep thermal gradients and under transient conditions, an improved thermal gradient exposure facility will be developed and constructed. The facility will be capable of exposing TBC coated specimens to thermal conditions representative of advanced gas turbine components and will be demonstrated on coated substrates.

The following two sub-sections describe the progress and plans related to the two objectives of this task.

Analysis and Measurement of Coating Stress

The accurate prediction of TBC stress states requires advances in both stress analysis techniques and measurement of important physical properties. This subtask includes effort directed towards both needs.

Specimens of dense zirconia have been prepared for evaluation of Young's modulus versus temperature and of shear modulus at room temperature. The temperature dependence of Young's modulus will be needed to correct the results of an experiment to measure elastic modulus versus stress that is described later in this report. The high damping nature of microcracked TBC's precludes direct measurement of resonant frequency versus temperature of free-standing TBC specimens in the impulse excitation equipment available. The intrinsic behavior of elastic modulus versus temperature is expected to be independent of density and microcracking. Therefore, dense specimens are being used for this measurement. The specimens were fabricated at CRD using Tosoh 4Y powder which is a 4 mole % (7 wt %) yttria partially stabilized zirconia of virtually the same composition as the TBC's of interest. The powder was uniaxially pressed in a 3.5 in. diameter cylindrical die at 8300 psi at room temperature; bagged and isopressed at 40,000 psi; and sintered in air at 1450 C for four hours with 100°C/ hour heating and cooling rates. The resulting disks measured approximately 79 mm diameter and 3.8 mm in thickness with a density of approximately 6.02 g/cc (from geometric measurement and mass). This density is very close to the theoretical density for this composition.

A metallographic specimen was cut and polished from one disk of zirconia. Inspection of the microstructure revealed very little porosity. Quantitative image analysis was performed on ten randomly chosen fields of view within this same sectioned specimen. The total area analyzed was approximately 0.4 mm². The resulting average porosity was found to be 0.609 percent of the image area, indicating a density of greater than 99 percent of theoretical.

Specimens of dense zirconia were cut and diamond ground from one disk and used to evaluate shear modulus and Poisson's ratio at room temperature and Young's modulus versus temperature up to 700°C. Care was taken to define parallel opposite surfaces and sharp edges to minimize errors in data reduction and analysis of the elastic moduli. The specimens were found to exhibit clean, sharp resonance using an impulse excitation technique. The acoustic impulse technique was based on the upcoming ASTM standard C-1259-94 entitled "Elastic Modulus by Impulse Excitation of Vibration."

Dynamic Young's modulus was measured on a specimen with approximate dimensions of 0.14 x 0.25 x 2.0 inches. The specimen support and impulse excitation geometry encourage longitudinal out-of-plane flexural vibrations. FFT analysis of the signal sampled by a digital oscilloscope showed a strong fundamental vibration of this mode along with detectable signals for the next three higher harmonics of longitudinal out-of-plane flexure. The fundamental mode is used for modulus determination because published geometric corrections are most mature for the fundamental mode. Harmonics analysis, however, showed that the higher order modes are in agreement (result in approximately the same Young's modulus) thus confirming the assignment of vibrational modes to observed resonant frequencies. The room temperature Young's modulus was 30.5 Mpsi (210 GPa).

The Young's modulus was evaluated versus temperature by hanging the same specimen from the fundamental node positions for flexure using Pt wires and heating the specimen assembly in a resistance heated, vertical tube furnace. The specimen was excited by the impact of a small zirconia sphere dropped through a guide tube positioned to define the point of impact at the center of the beam length. The acoustic response was sensed by a microphone located below the bottom of the furnace. The signal was sensed at the specimen midspan and carried out the bottom of the furnace using a 0.5 inch diameter tubular waveguide.

The results of Young's modulus versus temperature are included in Figure 8.3.1. The modulus was determined at temperatures of room temperature, 200, 400, 550 and 700°C. Temperature was equilibrated in each case before the acoustic measurements were made. Specimen dimensions at temperature were adjusted according to the growth expected from thermal expansion. To confirm that the heating cycle did not modify the elastic properties, the entire thermal cycle and associated measurements were repeated a second time. Figure 8.3.1 shows results from both heating cycles and shows that there is no significant difference in moduli in the second cycle.

A beam-shaped specimen measuring approximately 0.14 x 0.5 x 2.0 in. was used for measurement of dynamic shear modulus. The shear modulus was only measured at room temperature. The specimen supports, microphone location and excitation location were positioned as recommended in the ASTM standard to encourage torsional modes of vibration. The resulting shear modulus was 11.6 Mpsi (80.1 GPa).

The room temperature longitudinal and torsional resonant frequencies were used in an iterative fashion as also described in the ASTM standard to determine a value of Poisson's ratio at room temperature of 0.312.

Specimens have been prepared and measurements have begun for determination of TBC residual stress and attached Young's modulus versus temperature from room temperature to 700°C. Information from these measurements will, in turn, allow deduction of elastic modulus versus stress and any non-linearities in the elastic behavior over the range of stresses observed in the experiment.

The specimens were prepared as coupons of IN-718 substrate measuring approximately 1 x 2 x 0.125 inch that were coated on one side with approximately 0.005 inch of a NiCrAlY bondcoat and approximately 0.055 inch of 8 w/o yttria partially stabilized zirconia. The coatings were applied by air plasma spraying using deposition conditions that create TBC microstructures similar to those thought to be desirable for advanced turbine applications. The relatively large thickness of TBC was chosen to allow greater sensitivity in measurement of stress and modulus. It is hoped that the technique will have sufficient sensitivity to allow future measurements on thinner TBC layers.

From one coupon, three beam specimens have been prepared, each measuring approximately 2 x 0.25 x 0.185 inch. The specimens will be carried together through the measurements of stress and modulus. One edge of each beam was polished to allow optical measurement of the layer thickness versus position along the specimen length. The back side of the substrate was

polished to provide a smooth surface for profilometer traces that are taken repeatedly through the course of the experiment.

The experiment consists of measuring: specimen curvature at room temperature using profilometry; specimen curvature versus temperature up to 700°C using a three-point probe in a dilatometer (bimaterial dilatometry); and resonant frequency versus temperature up to 700°C using an impulse excitation technique described in earlier reports. These measurements are made before and after a portion of the TBC thickness is removed by diamond lapping. The experiment is planned to lap approximately one-third of the coating in each of three thinning operations. This will allow the properties of stress and modulus to be measured for individual sublayers through the TBC thickness as well as for the entire coating thickness.

The three specimens are carried through the experiment together except that one specimen is never heated above room temperature, the second is never heated above 400°C, and the third is heated to the full 700°C. The purpose of this experimental design is to allow a degree of redundancy in the measurements while providing a means to detect if any irreversible effects occur as a result of the heating cycles.

Specimen preparation is complete and curvature/resonance measurements are now in progress prior to the first thinning.

Initial screening of non-linear models in the ABAQUS finite element analysis code has begun. Using a one element structure, various material models were compared. Through this process, the choices of material models for use in describing the non-linear nature of TBC stress/strain behavior have been narrowed down.

A procedure was established for deriving a stress-strain curve when Young's modulus is measured at a number of residual stress levels. The procedure consists first of fitting the measured Young's modulus vs. stress points with a polynomial. The second step is to perform a numerical integration of a differential equation to derive the stress-strain curve. Stress-strain curves were created for APS and PVD TBC's based on preliminary data available at the present time.

Based on the preliminary nonlinear stress-strain relationships for the TBC, a stress analysis procedure has been established. As a first step, from the measured residual stress state in the coating a zero-stress reference temperature is calculated to serve as a reference state for subsequent predictions of stresses at elevated temperatures. Work is in progress to establish the effect of different degrees of nonlinearity on the stress levels.

Various axisymmetric TBC'd test specimen geometries were analyzed in an effort to design an appropriate test specimen for high thermal gradient testing. The effect of different mechanical constraints and fixture boundary conditions were compared. Analytical closed-form relationships were derived to obtain the TBC stress state at the TBC/metal interface in terms of the metal stresses. The goal of this analysis is to estimate the test conditions and specimen geometry which will simulate the TBC stress state of components in an advanced gas turbine. It was shown that if the interface metal stress and interface temperature in the test specimen are matched to those of the engine component, then the TBC stress state is very similar to that of the component and is quite insensitive to the actual boundary conditions of

the test specimen used to generate that interfacial stress. The analysis of effects of boundary conditions and constraints has been extended to 16 different cases.

Assuming a given value of compressive metal stress at the metal/ceramic interface (obtained from design analysis), a parametric study was conducted covering 20 different cases of variations in TBC and metal moduli, Poisson's ratios and interface temperatures. The results of these studies have been summarized in terms of simple design curves, including a curve describing the TBC stress as a function of metal stress at the interface.

Thermal Gradient Exposure Facility

In order to evaluate TBC performance, a laboratory scale thermal gradient exposure facility is being developed and constructed. The objective of the facility is to closely simulate the extreme thermal conditions anticipated in an advanced gas turbine TBC. The primary heat source being investigated for this facility is an atmospheric electron-beam (E-beam) gun.

E-beam experiments have been performed on TBC specimens mounted on a finned copper heat sink. The TBC samples were 0.015 in. thick and deposited on 0.125 in. thick Inconel 718 substrate. The specimens were 1 by 1 in. in area. The fins of the copper heat sink were water cooled. The specimens were exposed to the e-beam operating at 175 Kev with a current of 30 or 35 milliamps. The distance of the sample from the e-beam focus and the settings of the e-beam were chosen so as to deliver about 1.6 kilowatts per square inch onto the sample. Type K thermocouples were used to monitor the temperatures of the Inconel and the copper block. A Land infrared pyrometer was used to measure the temperature of the TBC layer. Thermal gradients through the TBC of up to 108 F/mil were recorded, along with surface TBC temperatures of around 2200-2300°F. These experiments demonstrate that the e-beam can successfully impose sufficient thermal flux on the TBC to generate the thermal gradients required for the development of TBC's for the ATS application.

Experiments have been performed to investigate the flux distribution that can be obtained from the atmosphere-capable e-beam. In normal use, the device is focused to a spot some 0.5 inches into the air, measured from the final differentially pumped aperture. In our application, we allow the beam to expand beyond this focus and use the large spot size to heat our sample. The electron beam expands in diameter both because of the geometrical optics that were defined by the parameters of the electron gun and also because of scattering of the electrons by the gas molecules upon which the beam impinges once it leaves the vacuum. The scattering effect of the gas depends upon the electron density that it presents to the e-beam. Thus it will depend on both number density and atomic number. An atmosphere of helium gas will scatter the beam considerably less than an atmosphere of nitrogen or argon.

Our experiments consisted of traversing a tungsten rod over a plane normal to the e-beam and at a known distance from the e-beam aperture. The tungsten rod was 0.25 inch in diameter and 2 inches long. Several thermocouples were embedded in the rod along its length. One end of the rod was water cooled while the other was exposed to the e-beam. The sides of the rod were insulated with zirconia balloons. At each position of the rod a temperature gradient was set up. This gradient was proportional to the e-beam flux into the exposed end of the rod. By moving the rod in a raster pattern normal to the e-beam direction, a profile of the e-

beam flux was developed. Preliminary analysis of the data shows that we can expect a 10% variation of the flux over a 1 inch diameter TBC sample. This would be achieved, in air, at a distance of 4-5 inches from the e-beam final aperture and with e-beam conditions of 50 milliamps and 150 keV. The nominal flux delivered by the e-beam was about 300 watts per square centimeter.

In this first series of tests, the absolute e-beam flux distribution was examined by traversing a tungsten probe through the beam. In a second type of experiment the e-beam was allowed to fall upon a disc of pure zirconia and video images were taken of the thermal state of the zirconia surface. The images were recorded through a narrow band filter centered at 0.6232 microns (red). The images were corrected for optical distortion and converted into relative temperatures. These relative temperatures were compared with the values obtained (on a much coarser grid) from the tungsten flux probe. The two experiment were in reasonable agreement.

In addition to a thermal profile of the TBC sample under test we also expect to need a measure of the sample strain. In order to become familiar with the latest mechanical and optical measurement techniques for strain at high temperature we visited the Strain Gage Laboratory at NASA Lewis. Several techniques were demonstrated to us that could be applicable to our testing geometries and conditions.

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

Three advanced sealing concepts of TP-FSN applications were developed. These include hooked cloth concept, Wedge Seal Concept #1; and Wedge Concept #2. Straight, 12-inch "standard" seals of the first two concepts have been tested. They show effective gaps of 8.8 mils and 5.5 mils respectively. The leakage is expressed as equivalent gaps in mils. A straight, 12-inch sample of the existing rigid seal design was tested for back-to-back comparison. It showed an equivalent gap of 13.6 mils. The new seals show approximately 3:1 improvement in the leakage efficiency. Curved (120-inch Radius), 12-inch samples of all three concepts will be tested in the next quarter. Figure 8.4.1 shows the test setup. The curved seal samples are

being ordered. The third concept involving a wedge seal will also be tested in the next quarter. This will be done only on the curved sample.

Two cloth seal concepts have been developed for the Nozzle-Shroud Sealing application. Twelve-inch, straight seal samples were fabricated and tested under different pressures. Additionally, relative positions of the mating parts were varied to represent growth and misalignment. Large offsets showed a tendency for a sudden drop in sealing effectiveness: this was discovered to be due to large deflections of the cloth seals causing the high-pressure air to "lift" the seal off the mating surface. New seal designs have been developed to circumvent this problem. These will be fabricated and tested in the next quarter. Following that, curved samples of the best design(s) will be fabricated and tested to evaluate the effect of curvature.

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 been selected to perform this task. A contract will be placed with Texas A&M once subcontract approval has been granted by DOE.

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 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

The data for the smooth rectangular duct (0.3" x 1.0" x 7" long) were completed and the results reported. The data cover the effect of high Reynolds and Rotation number for both radial outflow and inflow conditions as well as the effect of inlet conditions. The results clearly indicate the significant change in the local heat transfer coefficients that take place at the operating conditions of interest to power generation gas turbines compared to the data available at lower Reynolds and Rotation numbers in square ducts. It also shows the region over which inlet effects can control local heat transfer.

The construction of the turbulated rectangular test section was completed during this reporting period together with its installation and instrumentation. This test section includes inlet and discharge 180° bends similar to those found in turbine blade passages to insure realistic inlet conditions. The turbulators were shaped similarly to those in the application using the EDM process. Calibration and balance testing is now in progress with initial data expected in mid June. At stationary conditions the data in the literature for similar turbulated rectangular ducts varies by at least 30%. For this reason, and to obtain a comparison base, initial data will be taken at stationary conditions.

Task 8.7

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

Cascade fabrication is complete, including all auxiliary flow preparation components. Airfoils receiving static pressure holes and tubing for the measurement of passage Mach number distributions have been completed. All inlet and exit piping, flanges, and valves for the cascade have been assembled, welded, and received the necessary instrumentation ports. Thrust supports for both the cascade and the associated piping reaction loads have been fabricated and secured in-place. All wiring and cable routing has been completed, including thermocouple leads, pressure transducer lines, readout meters, remote control lines, video monitor transmission line, and computer front end communication. The data acquisition system and programming are also complete.

The cascade housing and upstream flow preparation vessel were hydrostatically pressure tested to a level approximately 2.7 times the anticipated operating pressure to be used during testing with air flow. This higher pressure level is equal to the rupture pressure of the safety rupture disk installed on the vessel after hydro testing was completed. Only minor leakage was noted, primarily in the region of the cascade-to-vessel interface. This region has since been sealed more effectively with thicker, more compliant gasket material, and slightly greater bolt torque.

The cascade was reassembled with airfoils in the middle three positions which contain static pressure instrumentation for flow through the center two air passages. All test rig pressure transducers were calibrated at this time. Air flow was initiated through the cascade, initially at low flow and low pressure. During this time, the instrumentation was verified to be displaying correct information. Those readings which were found to be incorrect due to improper or faulty wiring were corrected. Minor modifications to the computer data acquisition and display system were also performed. Mainstream air supply was brought to the cascade in separate tests using each of the two supply lines. When the cascade is operated at full conditions, these two lines shall be flowing in parallel. Operation through the larger of the two lines allowed verification of the total flow orifice station for the cascade via comparison with another orifice located farther upstream in this supply line.

Static pressure distribution measurements made during the flow tests showed Mach number distributions appropriate for the cascade pressure ratio used. The suction side of the central airfoil showed static pressures which were inconsistent with the other surrounding measurements. After eliminating other flow effect possibilities, this airfoil was removed for inspection. Signs of pressure tube crimping were evident for the measurement locations in question, apparently as a result of installation. These pressure lines have been repaired.

The repaired airfoil will be installed in the cascade, and flow tests performed to verify the correct Mach number distribution. The remote system for the traversing and/or rotation of probes, such as a hot-wire anemometer, will be installed prior to flow characterization testing. Flow testing will proceed to establish the baseline conditions of inlet flow distribution, temperature uniformity, and turbulence intensity levels, as well as the exit turbulence intensity. Using recently received airfoil thin-foil surface heaters, trials will be made to assure the proper

adhesion of the heaters to the airfoils, and the correct attachment of leads to the heaters. Heat transfer testing will progress to determine the external coefficient distributions for various baseline configurations, as well as conditions with varying turbulence intensity and airfoil surface roughness.

Figure 8.2.1 Centrifugal Test Apparatus

Figure 8.2.2 Control and Instrumentation System

CENTRIFUGAL DEPOSITION INSTRUMENTATION & CONTROL

Figure 8.3.1 Young's Modulus versus Temperature

Figure 8.4.1 Seal Test Facility