UNIVERSITY TURBINE SYSTEMS RESEARCH PROGRAM

ANNUAL REPORT

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ABSTRACT

In 2002, the U.S. Department of Energy established a cooperative agreement for a program now designated as the University Turbine Systems (UTSR) Program. As stated in the cooperative agreement, the objective of the program is to support and facilitate development of advanced energy systems incorporating turbines through a university research environment.

This document is the first annual, technical progress report for the UTSR Program. The Executive Summary describes activities for the year of the South Carolina Institute for Energy Studies (SCIES), which administers the UTSR Program. Included are descriptions of:

- Outline of program administrative activities
- Award of the first 10 university research projects resulting from a year 2001 RFP
- Year 2002 solicitation and proposal selection for awards in 2003
- Three UTSR Workshops in Combustion, Aero/Heat Transfer, and Materials
- SCIES participation in workshops and meetings to provide input on technical direction for the DOE HEET Program
- Eight Industrial Internships awarded to higher level university students
- Increased membership of Performing Member Universities to 105 institutions in 40 states
- Summary of outreach activities
- Summary table describing the ten newly awarded UTSR research projects

Attachment A gives more detail on SCIES activities by providing the monthly exceptions reports sent to the DOE during the year. Attachment B provides additional information on outreach activities for 2002.

The remainder of this report describes in detail the technical approach, results, and conclusions to date for the UTSR university projects.
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INTRODUCTION

Cooperative agreement DE-FC26-02NT41431 for the Advanced Gas Turbine Systems Research (AGTSR) program was established on March 20, 2002 between the U.S. Department of Energy/National Energy Technology Laboratory and the Clemson University Research Foundation/South Carolina Institute for Energy Studies (SCIES). This cooperative agreement established a five-year basic and fundamental research program that is a conduit for university support of the DOE’s Fossil Energy Turbine Program. To emphasize the university role, the program was renamed the University Turbine Systems Research Program (UTSR) in late 2002. Until April 2003, the Fossil Energy program supporting the UTSR was referred to as the High Efficiency Engines and Turbine Program (HEET) and that name is referenced numerous times in this report. In the future, the acronym HEET will be replaced by reference to The Turbine Program.

One of the requirements for the Cooperative Agreement is a yearly technical progress report. This document provides the technical progress report for the year 2002.

The major activities specified in the Scope of Work for the UTSR Program are related to the establishment of university research projects and the development of an outreach plan. The research is to be of high importance to long-term health of the U.S. energy (especially gas turbine) industry. The outreach plan is to aid in transfer of university research technology and entice growth of the number of industry and university participants in the program.

Major Program Plan elements identified in the Scope of Work to be implemented by SCIES for the UTSR Program are:

- Identification and selection of university research topics
- Request for proposals (RFP)
- Proposal selection
- Technology transfer
- Outreach

SCIES activities for 2002 in these areas are briefly described in the Executive Summary of this report and more detail is given in Attachment A – Monthly Exceptions Reports for Year 2002, which were submitted throughout the year to describe ongoing work. Details of outreach activities given in Attachment B – Outreach for Year 2002. The remainder of this report discusses the ongoing university research projects that are being administered by SCIES in the UTSR Program.
EXECUTIVE SUMMARY

The UTSR Program is similar in structure to previous Advanced Gas Turbine Systems Research (AGTSR) Program in that an Industrial Review Board (IRB) provides input to define needed energy systems (particularly gas turbine systems) research and Performing Member universities conduct the research. However, under DOE direction, new activities have been added to the UTSR Program beyond those of the previous AGTSR Program. These include:

- New Outreach activities
- Alternate fuel (esp. syngas) emphasis for turbines, rather than natural gas
- Broadened university research areas (e.g., RAM)
- Broadened research applications (e.g., distributed generation, hybrid systems)
- DOE product plans and technology roadmaps to guide research goals
- New and expanded reporting requirements for SCIES and the universities

UTSR ACTIVITIES FOR 2002

Research Related Activities

UNIVERSITY PROJECT AWARDS - From proposals in response to the year 2001 RFP, the first ten university projects of the UTSR program were awarded in 2002. Four of these projects are in the area of Aero/Heat Transfer, four are in the area of Materials, and two are in the area of Combustion. Telephone debriefings on their IRB proposal evaluations were also provided upon request to faculty that had unsuccessful proposals from the year 2001 RFP. The ten UTSR projects that were awarded in 2002 are described in detail in this report.

UNIVERSITY PROJECT ADMINISTRATION – SCIES administration activities for the UTSR university projects included:

- New project awards
- Administrative and technical oversight
- Processing requested subcontract modifications
- Sending semi-annual reports with evaluation forms to the IRB for review
- Informing university principle investigators of most significant IRB comments from review of their semi-annual reports
- Coordinating IRB reviews for sensitive information in university technical papers submitted for publication by the ASME and other technical societies
YEAR 2002 REQUESTS FOR PROPOSALS - SCIES obtained candidate research topics from DOE technical personnel and obtained industry research needs and candidate topics from presentations by IRB representatives at the most recent technical workshops sponsored under the AGTSR program. This extensive research topic list was compiled and sent to the IRB companies for ranking to determine the most important and appropriate topics for university research. SCIES then compiled the research topic rankings from all of the IRB organizations that choose to participate and identified those topics with the highest scores for the year 2002 RFP. The RFP was sent to point of contact persons from the over 100 Performing Member Universities with requests for distribution within their institutions. The RFP was also sent to principal investigators from previous AGTSR university projects.

Forty-nine university proposals were received in response to the RFP. The proposal numbers by technology area were 17 in Combustion, 15 in Aero/Heat Transfer, 11 in Materials, and 6 in RAM. All of the proposals were sent with ranking forms to each IRB organization for review and ranking. SCIES compiled the proposal ranking scores from all of the IRB organizations that choose to participate and determined an average score for each proposal within its technology area (i.e., Combustion, Materials, Aero/Heat Transfer, and RAM). The individual company scores and average scores within each technology area were then sent to the IRB companies for review prior to the IRB meeting in late September at Clemson. At that meeting, IRB representatives (with DOE input) final ranked the proposals across technology areas. A ranked short-list of nine proposals (three in Combustion and two each in the areas of Materials, Aero/Heat Transfer, and RAM) was thereby determined for award when year 2003 funding is obligated by the DOE to the UTSR Program. The cutoff for number of projects awarded will depend on available funding for 2003.

WORKSHOPS - Three technical workshops were organized and conducted in 2002 under the UTSR Program:

- Combustion Workshop IX at Penn State University on August 26-28
- Materials Workshop III at the University of Connecticut on October 14-16
- Aero/Heat Transfer Workshop V at Louisiana State University on November 11-13

The workshops consisted of presentations by principle investigators of ongoing AGTSR and UTSR university projects, presentations by IRB technical personnel on needed research that might be conducted at universities, presentations by the DOE on HEET program plans and activities, and other presentations of interest to specialists in the technical area of each workshop. Discussion sessions also solicited input and comments from university attendees concerning the organization and activities of the UTSR Program. In addition, the later sessions of the Combustion Workshop were run in conjunction with a HEET regional outreach workshop and a regional outreach meeting followed the Materials Workshop.

OTHER MEETINGS - SCIES participated in the DOE HEET Roadmapping Workshop in Reston, VA to provide input on technical direction for the HEET Program.

SCIES provided a presentation on the university program and university principle investigators participated in the poster session at the DOE Turbine Power Systems Conference in Galveston,
TX. SCIES also participated in other HEET Roadmapping meetings that immediately proceeded and followed the Turbine Power Systems Conference.

SCIES co-authored a white paper on gas turbine research needs for operation with alternate fuels and presented the paper at a DOE/Navy sponsored workshop on alternate fuels for turbines at the Colorado School of Mines in Bolder, CO. SCIES also recommended to the DOE a research effort to address research needs identified in the white paper by providing research topics for UTSR RFP’s. This effort would also provide foundational work and a basis for future university and industry development of turbine protection for adequate lifetimes.

INDUSTRIAL INTERNSHIPS - Fifteen upper level students responded to the Industrial Internship application brochure sent to the more than 100 Performing Member universities. Only eight of these applicants were placed as interns because of citizenship issues (only US citizens of Permanent Resident Aliens qualify) and because several applicants accepted other employment opportunities. The intern assignments ranged from 10 to 12 weeks in duration at seven IRB companies.

MEMBERSHIP - Colorado State University, University of Idaho, Boston University, University of Alaska at Fairbanks, and the University of Massachusetts at Amherst were added as new Performing Member universities in 2002. Performing Member Universities now total 105 in 40 states.

Outreach Activities

Following a nationwide search, Dr. William H. Day was hired by SCIES as the Manager of Outreach for the UTSR program. Dr. Day has approximately 30 years experience in the gas turbine industry, being employed by various divisions of United Technologies Corporation and General Electric. Dr. Day was Director of Gas Turbine Engineering at UTC and Chairman of the Gas Turbine Association. The hiring of Dr. Day was approved by DOE/NETL.

In summary, major outreach activities for 2002 were:

- Regional outreach meetings for input to the HEET Program
- Advocating the HEET Program
- Working with EERE
- Creating linked university research programs
- Changes to the industrial internship program

The regional outreach meetings in 2002 included the following:

<table>
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<th>Location</th>
<th>Office/Region</th>
<th>Date</th>
</tr>
</thead>
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<td>DOE/EERE</td>
<td>Atlanta Regional Office</td>
<td>May 1 and 2</td>
</tr>
<tr>
<td>DOE/EERE</td>
<td>Philadelphia Regional Office</td>
<td>August 28</td>
</tr>
<tr>
<td>NASEO</td>
<td>Pacific northwest Region, Portland</td>
<td>July 22</td>
</tr>
<tr>
<td>NASEO</td>
<td>Denver Region</td>
<td>August 15</td>
</tr>
<tr>
<td>NASEO</td>
<td>San Francisco Region</td>
<td>September 5</td>
</tr>
<tr>
<td>Connecticut</td>
<td>Energy Sector, Office of Policy</td>
<td>October 16</td>
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<tr>
<td>Louisiana</td>
<td>Department of Natural Resources</td>
<td>November 12</td>
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</table>
Discussion of these regional outreach meetings is given in Attachment B along with descriptions of the other major outreach activities listed above.

UTSR UNIVERSITY PROJECT SUMMARIES

The first ten university research subcontracts under the UTSR Program were awarded in 2002. Table 1 summarizes each project and identifies the principal investigator, university, project title and project objectives. Experimental and analyses approaches, results to date, and conclusions to date from these projects are discussed in the next section.

Table 1. Active UTSR Projects - Awarded in 2002

<table>
<thead>
<tr>
<th>Contract No; Applicant; Award Date</th>
<th>Principal Investigator</th>
<th>City/State</th>
<th>Area of Research (Materials, AHT: Aero-Heat Transfer, Combustion, RAM: Reliability, Availability, and Maintainability): Project Title, Goal-Accomplishment</th>
</tr>
</thead>
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<tr>
<td>02-01-SR095; Georgia Institute of Technology; 5/1/02</td>
<td>Ben Zinn 404.894.3033 <a href="mailto:ben.zinn@aerospace.gatech.edu">ben.zinn@aerospace.gatech.edu</a></td>
<td>Atlanta, GA</td>
<td>C: &quot;Understanding and Control of Combustion Dynamics in Gas Turbine Combustors.&quot; Experimentally evaluate factors that cause and sustain combustion instabilities and develop models to analytically predict the occurrence and amplitude of oscillations.</td>
</tr>
<tr>
<td>02-01-SR096; University of Minnesota; 5/1/02</td>
<td>Terrence Simon 612.625.5831 <a href="mailto:tsimon@mc.u">tsimon@mc.u</a> mn.edu</td>
<td>Minneapolis, MN</td>
<td>AHT: &quot;Aerothermal Effects of Interfacial Leakage and Film Cooling Schemes with Endwall and Leading Edge Contouring.&quot; Evaluate the use of cooling flows, cavity flows, and endwall contouring to reduce aerodynamic losses and improve heat transfer for turbine flow passages.</td>
</tr>
<tr>
<td>02-01-SR097; University of Connecticut; 5/1/02</td>
<td>Eric Jordan 860.486.2371 <a href="mailto:jordan@engr.u">jordan@engr.u</a> conn.edu</td>
<td>Storrs, CT</td>
<td>M: &quot;Measurement of Three Critical Parameters as a Basis for a Simple Life Prediction Method.&quot; Develop a TBC life prediction method using measurements of i) bond coat surface defects/irregularities, ii) stress in the thermal grown oxide (TGO), and iii) TGO thickness.</td>
</tr>
<tr>
<td>02-01-SR098; Louisiana State University; 5/1/02</td>
<td>Sumanta Acharya 225.578.5809 <a href="mailto:acharya@alpha2.eng.LSU.edu">acharya@alpha2.eng.LSU.edu</a></td>
<td>Baton Rouge, LA</td>
<td>AHT: &quot;Experiments and Computations on Film-Cooled End Walls with Contouring.&quot; Evaluate a strategy of end-wall contouring and leading edge fillet design to suppress passage aerodynamic losses due to secondary flows and explore coolant injection upstream of blades for effective end-wall cooling.</td>
</tr>
<tr>
<td>Project No.</td>
<td>Institution</td>
<td>I-Name</td>
<td>Phone</td>
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<tr>
<td>------------</td>
<td>-------------</td>
<td>--------</td>
<td>-------</td>
</tr>
<tr>
<td>02-01-SR099</td>
<td>Virginia Polytechnic Institute</td>
<td>Uri Vandsburger</td>
<td>540.231.4459</td>
</tr>
<tr>
<td>02-01-SR100</td>
<td>Virginia Polytechnic Institute</td>
<td>Denesh Tafti</td>
<td>540.231.9975</td>
</tr>
<tr>
<td>02-01-SR101</td>
<td>University of Pittsburgh</td>
<td>Gerald Meier</td>
<td>412.624.9741</td>
</tr>
<tr>
<td>02-01-SR102</td>
<td>Georgia Institute of Technology</td>
<td>Jerry Seitzman</td>
<td>404.894.0013</td>
</tr>
<tr>
<td>02-01-SR103</td>
<td>University of Central Florida</td>
<td>Yong-ho Sohn</td>
<td>407.882.1181</td>
</tr>
<tr>
<td>02-01-SR104</td>
<td>Brigham Young University</td>
<td>Jeffrey Bons</td>
<td>801.422.8036</td>
</tr>
</tbody>
</table>
INTRODUCTION

In this project, Georgia Institute of Technology is investigating the mechanisms and control of detrimental oscillations in gas turbine combustors. This program consists of two main tasks. The first task is investigating the dynamics of uncontrolled combustors. These results are improving capabilities to predict the occurrence and amplitudes of instabilities. The second task is investigating active control of combustion dynamics. This work is developing methods for suppressing these instabilities in the highly turbulent, harsh combustor environment and improving understanding of the factors that effect active control authority. Currently, combustion dynamics severely reduce the reliability and availability of gas turbines by damaging parts and substantially reducing time between overhauls, both of which ultimately affect the consumer by increasing the cost of electricity.

In this reporting period, a major experimental effort to characterize the flame response to large amplitude acoustic oscillations was completed. These studies were performed to develop improved capabilities for predicting instability amplitudes. In all, over 4500 tests were performed and over 4 GB of time series data of unsteady acoustic pressure, radical chemiluminescence, forcing signal, and velocity were obtained. While a complete analysis of these data will require several months, initial analyses indicate several interesting features. First, they show that the unsteady heat release amplitude saturates at large velocity perturbation levels. In addition, the phase between velocity and heat release perturbations can vary substantially with the driving amplitude. Finally, they show that heat release saturation occurs at $q'/q_o$ values of ~30-40%. This result indicates that several nonlinear models in the literature which assume saturation occurs when $q'\sim q_o$ are incorrect.

EXPERIMENTAL

The data presented in this report were measured in a lean, premixed gas turbine combustor simulator, see Figure 1, which was also illustrated schematically and described above. These tests were performed at equivalence ratios and mean pressure of approximately 0.83-0.97 and 1.7 atmospheres, respectively.
Data was recorded with a National Instruments DAQ controlled by Labview software at a sampling rate of 10 KHz. A total of 16384 data points were taken during each test.

Oscillations were driven in the combustor with an actuator developed at Georgia Tech for active combustion control applications. The actuator is capable of driving oscillations over a frequency range of approximately 0-1500Hz. The actuator modulates a secondary supply of air that is introduced near the combustor exit by periodically varying the degree of constriction of a reed valve. Maximum amplitude of driving occurs when the flow passage is completely blocked for a portion of the cycle, and thus the actuator modulates 100% of the mean flow of air through the valve. The amplitude of forcing can be controlled via the supply pressure of air to the actuator.

Acoustic pressure data were measured with Kistler piezoelectric transducers in two locations: the combustor itself and in the premixing section. Dynamic velocity measurements were obtained using a hot film probe. Unsteady chemiluminescence of excited OH* and CH* species were measured using a photo-multiplier tube located at the end of the combustor.

RESULTS AND DISCUSSION

The work performed in this reporting period extends a preliminary study of the nonlinear flame dynamics under the previous contract. These prior data indicated the important role of heat release non-linearities and it was suggested that a larger study was needed to more carefully characterize its dynamics.

Several improvements and additions have been made to the facility to obtain the data obtained in this period. First, the unsteady heat release was characterized using both OH* and CH* emissions. Second, concurrent measurements of the unsteady velocity data were obtained. Third, the fuel supply line was moved upstream of a choke point to ensure that no oscillations in equivalence ratio were present. This was needed to remove some ambiguity in interpreting the chemiluminescence measurements which have sensitivity to both heat release rate and equivalence ratio.

Figure 1 Photograph of the Georgia Tech’s lean, premixed combustor.
Figure 2 plots the results from a typical test, showing the time dependence of the unsteady CH*, pressure, and velocity. The objective of these tests was to characterize the dependence of the relative amplitudes and phases of these oscillations upon amplitude of driving.

![Figure 2](image)

**Figure 2. Time dependence of CH* chemiluminescence, pressure, and velocity**

A summary of the CH*-velocity transfer function as a function of frequency at low driving amplitude levels (i.e., in the linear regime) is shown in Figure 3. The figure shows that the transfer function has two local maxima and then monotonically decays at frequencies above about 240 Hz.

![Figure 3](image)

**Figure 3. Frequency dependence of the linear CH*-velocity transfer function.**
At large enough levels of driving, this transfer function changes with amplitude. This result is summarized in Figure 4, which plots the dependence of the CH* amplitude upon velocity amplitude. The curve clearly shows that their relationship is linear at low amplitudes and saturates at higher driving levels.

**Figure 4. Dependence of oscillating CH* amplitude upon velocity amplitude (f_{drive} = 290 Hz).**

Parametric studies of this relationship were performed at several equivalence ratios and driving frequencies. Figure 5 plots this CH*-velocity relationship at several frequencies. The curve shows a complex frequency dependence which is being further explored and will be discussed further in future reports.

**Figure 5. Dependence of oscillating CH* amplitude upon velocity amplitude at several driving frequencies.**
Figure 6 plots the CH*-pressure relationship at several equivalence ratios. The figure indicates that the slope in the linear regime, as well as the saturation amplitude varies with equivalence ratio. It also shows that the flame blows off at lower amplitudes with decreasing equivalence ratio, as expected.

**Figure 6.** Dependence of oscillating CH* amplitude upon pressure amplitude (in psi) at several equivalence ratios.

**CONCLUSION**

The section above has given a few sample results from a large series of tests that were recently completed. Future reports will present further analyses of these data which are currently in progress.

**REFERENCES**

No publications are referenced.
INTRODUCTION

Research performed under this project focuses on measurements that support the development of improved coolant injection schemes which are needed to accommodate a more uniform temperature distribution across the first stage turbine inlet passage associated with the development of low emission turbine combustors in recent years. The endwall regions of the turbine must support higher thermal stresses than in earlier generation turbines and efficient cooling schemes must be developed. Cooling the endwall region of the turbine is made more difficult by the complex secondary flows that result from interactions between passage and horseshoe vortices, leakage flows from component interfaces and emerging film-cooling flows.

In support of the development of more efficient endwall cooling schemes, experiments are conducted in this project to document the effectiveness of film cooling under various injection and flow path geometries. The objective of this project is to use an experimental and computational approach to understand transport in the endwall region of a gas turbine and to use that understanding to develop cooling strategies and design recommendations. More specific objectives are: 1. Describe the flow features more completely and document their effects on aerodynamics and heat transfer in the endwall region. This is done via detailed measurements of flow and surface heat transfer. 2. Investigate the effects of design variables under simulated engine conditions. This is done via experiments. Variables include airfoil leading edge configurations, endwall contouring shapes and degree of component (endwall segments and combustor–to-turbine transition duct joint) misalignment. 3. Document the performance of selected advanced cooling concepts that more efficiently utilize the available coolant. 4. Improve the analogy factor for converting mass transfer data to heat transfer values for flows such as turbine endwall flows. 5. Evaluate computational tools used for gas turbine thermal design.

One measurement method uses a thermocouple probe to document the thermal field within the passage, including very near-wall temperature profiles that can be used to obtain local heat transfer coefficient values. In a parallel effort, local heat transfer coefficients are measured with a more conventional method in which segment energy balances are made. Concurrently, local mass transfer measurements are made in the same flow to further describe the analogy between heat and mass transfer. The mass transfer measurements allow high spatial resolution of surface transfer coefficients. Also, a better understanding of the analogy will allow further utilization of the extensive mass transfer data set that now resides in the literature.

Progress documented in the present report is in test section development and test plan set up. The two test sections being developed, one to take precise heat transfer measurements in the first stage vane using a thermocouple probe and the second for heat and mass transfer measurements in the first stage rotor, are described. Plans for using these test sections to accomplish the objectives are reviewed.
EXPERIMENTAL

This section includes a description of the experimental facilities and techniques used in the project.

Measurements of Flow and Heat Transfer from a Linear First-Stage-Vane Cascade

This section describes the vane cascade facility that has been made to document passage aerodynamics and thermal fields and endwall heat transfer coefficient distributions for various cases that differ in film cooling injection geometry, endwall contouring geometry, leading edge endwall junction geometry and alignment of segments.

Experimental Facility

Vane Cascade Facility

The test facility is designed to simulate the geometry and flow inside a first stage vane passage of a modern, mid-sized, gas turbine engine. The test section consists of three blades, with two passages. It simulates the nozzle guide vanes and endwalls.

Flow is provided by a wind tunnel that consists of four important parts; fans, turbulence generator, nozzles and transition section (Fig. 1). The wind tunnel is fitted with a settling chamber and flow straightening elements for the elimination of flow swirl and maldistribution. The wind tunnel is of an open configuration. Two fans placed in series supply the primary flow. The first draws room temperature air through a filter box and pressurizes the air before it enters the second fan via a turning header. The second fan is of an axial design.

After the flow has passed thought the flow straightening elements, it enters the turbulence generator section. The turbulence generator is designed following the work of Ames (1994), Chung (1992) and Wang (1996). Essentially, the flow is split into a series of jet flows. The jets interact in such a manner so as to create high turbulence levels with large length scales. Additional jets are provided with a third blower. These additional jets improve the uniformity of the flow.

The nozzle section of the wind tunnel is located just downstream of the turbulence generator. It uses concave-convex curvature on the top and bottom walls, while the side walls are straight. Contraction in the vertical direction is from 85.1 cm to 44.45 cm while there is no contraction in the horizontal direction. Thus, the area ratio is 1.9:1. The total nozzle length is 58.4 cm.

The transition section of the tunnel is downstream of the nozzle. It is a simple box constructed of 1.27 cm thick Plexiglas. Its length from nozzle exit to cascade inlet plane has been modified through the addition of spacer sections to allow the more mild contraction (30°, Fig. 2) than previously used (45°, Fig. 3). The transition section incorporates film cooling through a simulated combustor-to-turbine transition section vane forward gap (see Fig. 3).

The test section is located directly downstream of the transition section. The dimensions of the three airfoils of the passage are included in the Table 1. The geometry is shown schematically in Fig 2. The airfoils are those of a modern vane stage, as supplied by Solar Turbines Inc.
Table 1. Test Section blade dimensions.

<table>
<thead>
<tr>
<th>Blade Dimension and Flow Parameters</th>
<th>Blade True Chord Length, C</th>
<th>Blade Pitch</th>
<th>31.8 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade Axial Chord Length, C_x</td>
<td>19.85 cm</td>
<td>Solidity, C/P</td>
<td>1.24</td>
</tr>
<tr>
<td>Blade Span (Inlet), S_1</td>
<td>31.54 cm</td>
<td>Max Thickness</td>
<td>8.6 cm</td>
</tr>
<tr>
<td>Blade Span (Outlet), S_2</td>
<td>24.4 cm</td>
<td>Stagger Angle</td>
<td>72°</td>
</tr>
<tr>
<td>Aspect Ratio, S_1/C (Inlet)</td>
<td>0.80</td>
<td>Angle of Incidence</td>
<td>0°</td>
</tr>
<tr>
<td>Aspect Ratio, S_2/C (Exit)</td>
<td>0.62</td>
<td>Chord Reynolds Number (Based on Exit Velocity)</td>
<td>257,000</td>
</tr>
<tr>
<td>Fillet Radius (nominal)</td>
<td>0.75 cm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The geometry of the endwalls of the test section is a topic of study of the present project. One endwall has convergence upstream of the airfoil leading edges and is straight throughout the passage while the other is with significant meridional profiling converging throughout the passage. The endwall is constructed to allow a simulation of slash-face (or gutter) leakage in the endwall. This is accomplished with a slot running along the endwall at the angle specified in Table 2. The design will allow component misalignment, simulated by moving the endwall outwards or inwards, thereby slightly modifying the aspect ratio of the blade and creating a step. The slash face slot between the airfoils is placed at an angle of 35.5 degrees, extending over the heated endwall section, from about 6.4% of C_x downstream of the trailing edge of the transition section leakage injection slot to the plane of the trailing edges of the airfoils. The angle and location are chosen to minimize its length without interfering with the airfoils and fillets. The slot is 0.7 cm wide and has a slot flow length of 1.27 cm. The centerline of the slot will pass through the point located at 62.9% of the pitch (or 20.0 cm) from the stagnation point toward the suction wall of the passage (see Fig. 4).

Table 2. Slash-Face Leakage Slot Geometry

<table>
<thead>
<tr>
<th>Slash Face Leakage Slot Geometry</th>
<th>x/C_x (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade Axial Chord Length C_x</td>
<td>19.85 cm</td>
</tr>
<tr>
<td>Normal Gap Width</td>
<td>0.70 cm</td>
</tr>
<tr>
<td>Length of Gap</td>
<td>1.40 cm</td>
</tr>
<tr>
<td>Distance on Leading Edge Plane</td>
<td>20.0 cm</td>
</tr>
<tr>
<td>From Pressure Side Stagnation</td>
<td></td>
</tr>
<tr>
<td>Point Toward Suction Surface</td>
<td></td>
</tr>
<tr>
<td>Angle From Axial</td>
<td>35.5°</td>
</tr>
<tr>
<td>Ratio of Slot Length to Slot</td>
<td>2.0</td>
</tr>
<tr>
<td>Width</td>
<td></td>
</tr>
</tbody>
</table>

The endwall will incorporate combustor-to-turbine transition section leakage through a vane forward gap. This will be located on the slanted portion of the endwall slightly upstream of the leading edges of the airfoils. The gap will run the entire length of the cascade entrance plane (see Fig. 3).
Table 3. Transition Section Leakage Slot Geometry

<table>
<thead>
<tr>
<th>Transition Section Slot Geometry</th>
<th>x/Cx (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade Axial Chord Length Cx</td>
<td>19.85 cm</td>
</tr>
<tr>
<td>Angle of Inclination</td>
<td>30°</td>
</tr>
<tr>
<td>Slot Width</td>
<td>1.39 cm</td>
</tr>
<tr>
<td>Step Height</td>
<td>0.60 cm</td>
</tr>
<tr>
<td>Distance From Slot Trailing Edge to Leading Edge</td>
<td>2.25 cm</td>
</tr>
<tr>
<td>Ratio of Slot Length to Slot Width</td>
<td>3.65</td>
</tr>
</tbody>
</table>

The most downstream section of the test apparatus is formed by the extension of the endwalls and the tailboards. The tailboards are adjusted in order to achieve the appropriate flow over the cascade airfoils. This flow is checked for periodicity of surface pressure while maintaining proper stagnation streamlines.

An important feature of the test section is the newly designed front endwall access panel (see Fig. 5a). This will allow probe access to the entire endwall test surface. The access panel makes use of two circular sections mounted on large-diameter ball-bearings; the smaller circle is located inside of the larger allowing the probe to be moved to any point within the larger circle (see Fig. 5b). The panel is designed to allow easy access into the flow passage.

**Proposed Studies**

Tests will be performed on several different test section configurations (endwalls, leading edges, slot configurations). The first endwall will be contoured to provide acceleration of the fluid throughout the passage (EW1 configuration of Fig. 6). Measurements will be made for several different blowing mass flow rates ranging from 0% to 3% of the passage mass flow rate. Measurements will be made on both an adiabatic (low conductivity and unheated) endwall and an aluminum, heated endwall powered with electric resistance heaters. The heated endwall makes it possible to measure the endwall heat transfer coefficients.

The study will also include an investigation of leading edge contouring. Testing will be with leading edge bulb, fillet and cowcatcher geometries (see Fig. 7).

Studies will be performed on slash-face leakage in order to ascertain its effect on cooling flows (see sketch of engine in Fig. 8).

Tests will investigate the effects of component misalignment by altering the position of endwall segments to create a forward or backward facing step at the combustor/blade interface or steps in the slash-face gap (see Figs. 8 and 9).

A second set of tests will be performed on an endwall that creates the acceleration of the fluid upstream of the plane of the leading edge (EW2 configuration of Fig. 6). Reynolds number based on axial chord and trailing edge velocity for the EW2 case will be the same as in the EW1 study.
The test program is presented in Table 4.

Table 4. Projected Experiment Schedule

<table>
<thead>
<tr>
<th>Case</th>
<th>Geometry</th>
<th>Gap Leakage</th>
<th>Projected Rpt Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>EW1 Contoured Endwall</td>
<td></td>
<td>May-03</td>
</tr>
<tr>
<td>2</td>
<td>EW1 Contoured Endwall w/ Gap</td>
<td>no</td>
<td>Nov-03</td>
</tr>
<tr>
<td>3</td>
<td>EW1 Contoured Endwall w/ Gap</td>
<td>yes</td>
<td>Nov-03</td>
</tr>
<tr>
<td>4</td>
<td>EW1 Contoured Endwall w/ Fwd Step Gap</td>
<td>no</td>
<td>Nov-03</td>
</tr>
<tr>
<td>5</td>
<td>EW1 Contoured Endwall w/ Fwd Step Gap</td>
<td>yes</td>
<td>Nov-03</td>
</tr>
<tr>
<td>6</td>
<td>EW1 Contoured Endwall w/ Bkwd Step Gap</td>
<td>no</td>
<td>May-04</td>
</tr>
<tr>
<td>7</td>
<td>EW1 Contoured Endwall w/ Bkwd Step Gap</td>
<td>yes</td>
<td>May-04</td>
</tr>
<tr>
<td>8</td>
<td>EW1 Contoured Endwall w/ Slash-face Gap</td>
<td>yes</td>
<td>May-04</td>
</tr>
<tr>
<td>9</td>
<td>EW2 Contoured Endwall</td>
<td></td>
<td>May-04</td>
</tr>
<tr>
<td>10</td>
<td>EW2 Contoured Endwall w/ Gap</td>
<td>no</td>
<td>Nov-04</td>
</tr>
<tr>
<td>11</td>
<td>EW2 Contoured Endwall w/ Gap</td>
<td>yes</td>
<td>Nov-04</td>
</tr>
<tr>
<td>12</td>
<td>EW2 Contoured Endwall w/ Fwd Step Gap</td>
<td>no</td>
<td>Nov-04</td>
</tr>
<tr>
<td>13</td>
<td>EW2 Contoured Endwall w/ Fwd Step Gap</td>
<td>yes</td>
<td>Nov-04</td>
</tr>
<tr>
<td>14</td>
<td>EW2 Contoured Endwall w/ Bkwd Step Gap</td>
<td>no</td>
<td>May-05</td>
</tr>
<tr>
<td>15</td>
<td>EW2 Contoured Endwall w/ Bkwd Step Gap</td>
<td>yes</td>
<td>May-05</td>
</tr>
<tr>
<td>16</td>
<td>EW2 Contoured Endwall w/ Slash-face Gap</td>
<td>yes</td>
<td>May-05</td>
</tr>
</tbody>
</table>

**Experimental Method**

The local wall temperature, surface heat flux and convective heat transfer coefficient will be computed from the near-wall temperature profile. The profile can be extrapolated to the wall to give the surface temperature while its slope can be used to find the local surface heat flux (see Fig. 10). The near-wall temperature profile is determined via a specially designed thermocouple probe (see Fig. 11). The design reduces conduction error along the thermocouple wire and allows the wire to touch the wall without damage. Details of the thermocouple design are given in You (1986) and Blackwell and Moffat (1975). As noted in the work of Qiu et al. (1995), application of the technique depends on careful positioning of the probe with respect to the wall. Positioning is accomplished with a motorized linear traverse mechanism that has a resolution of 1 μm. The initial wall-normal position of the probe is determined by running the probe to the wall, then backing it away. Temperatures taken when the probe is pressed against the wall remain uniform as the probe is withdrawn (see Fig. 10). When the probe leaves the wall there is a noticeable drop in temperature. The position of the temperature drop is taken to be one thermocouple radius away from the wall. This is consistent with independent measurements of wall temperature. The method is thoroughly described and verified within 7% uncertainty for flows representative of endwall flows in Qiu et al. (1995). The heat transfer coefficient measurements will have a similar uncertainty of between 7% and 8% in the area of interest.
This method achieves good results while offering flexibility as to where the measurements can be made. Furthermore, the technique allows the endwall to be reconfigured with no modification to measurement equipment. The technique also allows a more complete evaluation of test section conditions. For instance, the heat flux from a nominally adiabatic wall can be determined as can the surface temperature distribution of a nominally isothermal wall.

**Measurements of Mass and Heat Transfer from a Linear Rotor Cascade**

This section describes progress on the second cascade facility, one that is made to study mass and heat transfer on the endwall of a rotor.

**Introduction**

Many techniques have been used to study heat transfer characteristics of a turbine blade and a turbine endwall. One of those is a mass transfer technique in which mass transfer data of the corresponding geometry in similar flow conditions are converted to heat transfer results on the basis of the heat/mass transfer analogy. The applicability of the heat/mass transfer analogy to flow on the turbine blade and endwall will be investigated. In this study, both heat and mass transfer data sets will be compared and used to develop a heat/mass transfer analogy factor.

The effect of upstream component misalignment on fluid flow and heat transfer by introducing a slot in front of the turbine blade cascade is also investigated in this study. Since the endwall of a turbine blade is not made up of one continuous piece, there is a gap at the interface between the rotor and stator components. Leakage flow through the gap is supplied in order to cool the interface and prevent ingestion of hot gases into the gap. Additionally, because of casting, manufacturing, assembly, maintenance and thermal growth mismatches, component misalignment occurs. Gaps with and without forward- or backward-facing steps are being used to study flow and heat transfer characteristics from the turbine blade and endwall. Mass transfer data will be obtained for the gap with and without leakage.

**Measurement Techniques**

Heat and mass transfer coefficients for the endwall and turbine blade (GE-90 profile) are being investigated. Heat transfer data will be obtained under the constant temperature boundary condition for both endwall and turbine blade.

Local heat transfer and mass transfer measurements from the endwall and turbine blade will be taken at equivalent Reynolds numbers. Using a boundary layer temperature probe on a constant temperature surface, the gradient in the thermal boundary layer is measured and used to calculate local heat flux. The local mass transfer coefficients are investigated using the naphthalene sublimation technique.

**Heat Transfer Measurements**

Velocity and thermal boundary layers near a wall can be divided into three zones: the viscous sublayer, in which the flow is described by Newton’s law of viscosity; the buffer zone, in which the laminar and turbulence effects are both important; and the turbulent core zone, in which purely viscous effects are negligible. Thermal energy is transported normal to the wall by heat conduction alone in the viscous sublayer zone.
The heat flux can be measured from the temperature gradient in the viscous sublayer region using the thermal boundary layer probe. The heat flux \( q_w \) from the wall is determined from:

\[
q_w = -k \frac{\partial T}{\partial n}
\]

where \( k \) is a thermal conductivity of the fluid and \( n \) is a distance in the direction normal to the wall. The local convective heat transfer coefficient is calculated from

\[
h = \frac{q_w}{T_w - T_{air}} = -\frac{k}{T_w - T_{air}} \frac{\partial T}{\partial n}
\]

The local Nusselt number is determined as:

\[
Nu = \frac{hC}{k}
\]

The overall heat transfer coefficient will be determined from net input power supplied, temperature difference and total surface area.

**Mass Transfer Measurement**

Local mass transfer coefficients will be investigated using the naphthalene sublimation technique. The mass transfer rate is measured by the sublimation depth change of the naphthalene coated on the endwall or turbine blade. Since the naphthalene vapor pressure and concentration on the surface is uniform, the boundary condition for the mass transfer experiment is equivalent to the isothermal boundary condition in the heat transfer experiment. The mass transfer coefficient is determined from

\[
h_m = \frac{m^*}{\rho_{n,w} - \rho_{n,\infty}}
\]

where \( m^* \) is the mass transfer rate per unit area, \( \rho_{n,w} \) is a vapor concentration of naphthalene on the wall and \( \rho_{n,\infty} \) is a vapor concentration of naphthalene in the approach flow. The mass transfer rate per unit area can be determined from the net sublimation depth of naphthalene during exposure to the flow by

\[
m^* = \rho_s \frac{\delta y}{\delta t}
\]

where \( \rho_s \) is the density of solid naphthalene, \( \delta y \) is the net sublimation depth which is the function of local position, and \( \delta t \) is the duration of exposure to the flow. Since the vapor concentration of naphthalene in the approach flow, \( \rho_{n,\infty} \), is zero, the mass transfer coefficient can be written as:

\[
h_m = \frac{\rho_s (\delta y/\delta t)}{\rho_{n,w}}
\]

The result of this study will be presented in terms of the Sherwood number, which is defined as:

\[
Sh_y = \frac{h_m \cdot C}{D_{na}}
\]

where \( C \) is blade chord length and \( D_{na} \) is the binary diffusion coefficient for naphthalene in air.
Net sublimation depth, $\delta y$, is the sublimation depth solely induced by the forced convection mass transfer during the wind tunnel run. The total depth differences evaluated using the before and after run surface-profile measurement data include excess sublimation loss by free convection during the surface profile measurement, the assembly and disassembly of test pieces in wind tunnel and the storage of test pieces in a container. Therefore, the excess sublimation depth is evaluated and subtracted from the total sublimation depth to determine the net sublimation depth.

The natural sublimation rates will be determined experimentally by leaving the naphthalene-cast test pieces on the measurement table.

The density of naphthalene vapor at the wall is determined using the ideal gas law

$$\rho_{n,w} = \frac{p_{n,w}}{R \cdot T_w}$$

where $p_{n,w}$ is a naphthalene vapor pressure on the wall, $R$ is a gas constant of naphthalene vapor, and $T_w$ is a time-averaged temperature measured on the naphthalene surface in degree Kelvin.

**Improvement of test rig and experimental facilities**

The experimental facilities for this study include a blown type wind tunnel, a test section, a linear cascade section, a heat transfer endwall plate, a mass transfer endwall plate, a heat transfer test blade, a mass transfer test blade, thermal boundary layer probes and surface profile measurement tables.

The wind tunnel is a multi-purpose blowing type. It supplies air to the test section with the maximum velocity of 40 m/s and 0.2% free stream turbulence intensity. The test section, shown in Figure 12, is modified to accommodate newly designed endwall heat and mass transfer plates. All of the walls of the test section, except the top of the cascade section, are made of 19 mm thick Plexiglas. The top wall of the cascade section is made of aluminum with a rectangular (20 mm x 30 mm) Plexiglas in the middle for observation purpose. The bottom endwall has a large hole to hold a heat or mass transfer test plate. The assembled bottom endwall is shown in Figure 13. The test section has slots in front of the cascade for generating free stream turbulence using various grid turbulence generators.

The linear turbine cascade used in this study consists of five, 45.7 cm long turbine rotor blades made of aluminum. One of the five blades, the test blade, is at the central location. Parameters of the turbine cascade are given in Table 5.

<table>
<thead>
<tr>
<th>Table 5. Turbine cascade parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of blades</td>
</tr>
<tr>
<td>Chord length of blade – C</td>
</tr>
<tr>
<td>Axial chord length of blade – C_x</td>
</tr>
<tr>
<td>Pitch of cascade – P</td>
</tr>
<tr>
<td>Height of cascade – H</td>
</tr>
<tr>
<td>Aspect ratio (Span/Chord) – H/C</td>
</tr>
<tr>
<td>Solidity (Pitch/Chord) – P/C</td>
</tr>
<tr>
<td>Blade inlet angle – $\beta_1$</td>
</tr>
<tr>
<td>Blade outlet angle – $\beta_2$</td>
</tr>
<tr>
<td>Inlet/Exit area ratio of the cascade (AR)</td>
</tr>
<tr>
<td>Area ratio of the contraction</td>
</tr>
<tr>
<td>Exit Reynolds number – $Re_{ex}$x10^5 range</td>
</tr>
</tbody>
</table>
A uniform temperature blade, Figure 14(a), is designed with a high performance blade profile. It is made of high thermal conductivity material to help smooth temperature variations. The blade has fourteen holes for cartridge heaters and one slot near the trailing edge for a strip heater. Thermocouples are installed near the blade surface on both the suction and pressure sides. To reduce heat conduction losses, an insulating section is used. It is made of ultra high molecular weight polypropylene with low conductivity (~ 0.4 W/mK). This insulating section is hollow with 0.3 cm wall thickness and 5.4 cm height. This hollow is also used to facilitate passage of heater and thermocouple wires. Thermal analysis of the heat transfer blade on both suction and pressure sides using an ANSYS program is shown in Figure 15. The free stream temperature is set to be 290 K and temperature of the blade is maintained at 304.8±0.2 K. To obtain the uniform surface boundary condition, the outputs of the fifteen heaters are individually adjusted.

A mass transfer blade, Figure 14(b), is already available. Both suction and pressure surfaces of the blade are coated with naphthalene using a casting technique which can produce high surface quality (smoothness).

The heat transfer endwall plate is shown in Figure 16(a). It consists of a balsa wood plate, aluminum plate and bottom insulating plate, 25.4 mm x 25.4 mm strip heaters and thermocouples. One hundred strip heaters are used to make a uniform temperature endwall. Balsa wood is used to provide an unheated region in front of the aluminum plate. Thermocouples are installed close to the surface of the aluminum plate at the center of each heater. To reduce heat loss to the bottom wall, an insulating wall made of ultra high molecular weight polypropylene is placed underneath the heaters. Thermal analysis of temperature distribution on the endwall plate is done using an ANSYS program and the temperature distribution on the endwall is shown in Fig. 15. The free stream temperature is set to be 298 K and temperature of the endwall is maintained at 305.65±0.15 K. To obtain the uniform surface boundary condition, one hundred heaters are individually controlled to adjust their outputs.

To maintain uniform temperature on the turbine blade and endwall, a multiple-output digital power supply is designed to control 115 heaters (15 in blade and 100 on endwall). Figure 17 shows the digital power supply which is built in our research lab. Its specifications are summarized in Table 6.

<table>
<thead>
<tr>
<th>Table 6. Specification of multiple-output digital power supply</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total power</strong></td>
</tr>
<tr>
<td><strong>Power at each output</strong></td>
</tr>
<tr>
<td><strong>Number of output</strong></td>
</tr>
<tr>
<td><strong>Voltage range</strong></td>
</tr>
<tr>
<td><strong>Control method</strong></td>
</tr>
</tbody>
</table>

To accurately measure temperature gradients near the turbine endwall and blade surface, a five-axis system, shown in Figure 18, was developed. It consists of four unislides equipped with stepper motors and one rotating table equipped with a stepper motor. This system has a resolution of 0.005 mm. The rotating table is used to maintain the x-axis unislide parallel to the blade surface.

For measurement of the temperature gradient near the surface, three thermal boundary layer probes shown in Figure 19 were designed. Two probes, Figures 19(a) and (b), are used for measurement on the suction side and pressure side of the blade, respectively. The probe in Fig.
19(c) is used for endwall measurements. Each probe consists of three parts; the bare thermocouple wire (E type), the hypodermic needle holding the wire and the stem of the probe.

A mass transfer plate is shown in Figure 16(b). It is made of aluminum with a 2.54 mm deep recess area that will be filled with naphthalene. Two thermocouples are installed in the recess area to measure naphthalene surface temperature. Casting is used to fill naphthalene into the recess area.

For mass transfer measurements, surface profiles of the test blade before and after exposure in the wind tunnel are measured using the four-axis measurement table shown in Fig. 20. Surface profiles of the test endwall plate before and after exposure in the wind tunnel are measured using a two-axis measurement table shown in Figure 21. It is modified to accommodate a newly-designed endwall plate.

The effect of upstream component misalignment on fluid flow and surface heat transfer will be studied by introducing an upstream slot in front of the turbine blade cascade, as shown in Fig. 22. The pieces of endwall are completely fabricated as shown in Figure 23. Three gap configurations, i.e. flat surface, forward-facing step and backward-facing step, will be used. A summary of cases to be studied is given in Table 7. Mass transfer coefficients on the turbine blade and endwall will be measured using the naphthalene sublimation technique described above. A schematic diagram of gap configuration is shown in Figure 24. In this study, the gap has a 4 mm width, a 45° angle and a 25.5 mm length. The distance from the gap to the leading edge of the turbine cascade is 13 mm. For the cases of forward and backward-facing step, a step height of 4 mm (corresponding to a ratio of gap width to step height of 1) is to be used. A summary of geometric parameters is given in Table 8.

Table 7. Summary of cases studied

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Gap geometry</th>
<th>Gap Leakage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>flat endwall without gap</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>flat endwall with gap</td>
<td>no</td>
</tr>
<tr>
<td>3</td>
<td>Forward-facing step gap</td>
<td>no</td>
</tr>
<tr>
<td>4</td>
<td>backward-facing step gap</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>flat endwall with gap</td>
<td>Yes</td>
</tr>
<tr>
<td>6</td>
<td>Forward-facing step gap</td>
<td>Yes</td>
</tr>
<tr>
<td>7</td>
<td>backward-facing step gap</td>
<td>Yes</td>
</tr>
</tbody>
</table>
### Table 8. Summary of geometry parameters

<table>
<thead>
<tr>
<th>Geometry Parameter</th>
<th>X/C_x (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blade Cord Length C</td>
<td>184 mm</td>
</tr>
<tr>
<td>Axial Cord Length C_x</td>
<td>130 mm</td>
</tr>
<tr>
<td>Blade Pitch P</td>
<td>138 mm</td>
</tr>
<tr>
<td>Normal Gap Width W</td>
<td>4 mm</td>
</tr>
<tr>
<td>Projected Gap Width W</td>
<td>5.6 mm</td>
</tr>
<tr>
<td>Step Height H</td>
<td>4 mm</td>
</tr>
<tr>
<td>Distance from gap to leading edge</td>
<td>13 mm</td>
</tr>
<tr>
<td>Length of gap L_g</td>
<td>25.5 mm</td>
</tr>
<tr>
<td>Ratio of gap length to gap width L_g/w</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Experiments will be conducted at a free steam velocity of 17 m/s, which corresponds to a Reynolds number of $2 \times 10^5$ based on axial cord length and inlet velocity. Slot velocity will be varied from 5 to 15 m/s. A summary of flow parameters is given in Table 9.

### Table 9. Summary of flow parameters

<table>
<thead>
<tr>
<th>Flow Parameter</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Stream Velocity U_infinity</td>
<td>17 m/s</td>
</tr>
<tr>
<td>Reynolds number at the inlet Re_in</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td>Reynolds number at the exit Re_ex</td>
<td>$5 \times 10^5$</td>
</tr>
<tr>
<td>Slot Velocity U_s</td>
<td>5.1, 10.2, 17, 25.5 m/s</td>
</tr>
<tr>
<td>Slot-to-main mass flow ratio (%) SFR</td>
<td>0.26, 0.52, 0.87, 1.31</td>
</tr>
<tr>
<td>Slot-to-main mass flux ratio M</td>
<td>0.3, 0.6, 1.0, 1.5</td>
</tr>
<tr>
<td>Slot-to-main momentum flux ratio I</td>
<td>0.09, 0.36, 1.0, 2.25</td>
</tr>
<tr>
<td>Density Ratio DR</td>
<td>1</td>
</tr>
</tbody>
</table>

SFR = $\frac{m_{bleed}}{(\rho U S P)}$

$M = \frac{m_{bleed}}{(\rho U A_{bleed})} = \frac{(\rho_{bleed} U_{bleed})}{(\rho U_l)}$

$I = \frac{m_{bleed}^2}{(\rho U^2 A_{bleed})} = \frac{(\rho_{bleed} U_{bleed}^2)}{(\rho U_l^2)}$

$DR = \frac{\rho_{bleed}}{\rho_l}$

### RESULTS AND DISCUSSION

The activities in this first reporting period have been experiment set up. No experimental results have been obtained to date.
CONCLUSION

Progress in the past six months has included much test section development and test plan preparation. Development highlights include the design and construction of a digital power supply for rotor heat transfer experiments with a uniform temperature boundary condition, positioning systems including a five-axis measurement table for handling the precise movement of the thermal boundary layer probe in the rotor cascade and a front access panel to allow complete freedom in the positioning of probes in the vane cascade. Other major test rig components, like wind tunnels and data acquisition devices, will be used from previous experiments.

Progress in the next report period will likely include final test section preparations, qualifications, further test plan modifications and the results from the first round of experiments.
Figure 1. Linear Cascade wind tunnel layout.

Figure 2. Nozzle and transition section geometry.

Figure 3. Film cooling injection location.
Figure 4. Slash-gap leakage detail

Figure 5a. Access panel detail.

Figure 5b. Disk-in-disk section detail
Figure 6. Endwall Configurations showing acceleration of the fluid before the blade (EW2) and acceleration of the fluid throughout the blade (EW1). The contoured endwall shapes are constructed of (1) a 30 degree inclined surface, (2) a curved surface of radius $r$ where $r/C_x=1.23$ and (3) a horizontal plane (for EW2).

Figure 7. Leading edge configurations.

Figure 8. Details of slash-face leakage.
Figure 9. Area of component misalignment. Figure 10. Example temperature profile plot.

Figure 11. Boundary layer thermocouple probe.
Figure 12. Linear cascade test section

- Bottom endwall plate
- Inserted endwall test plate

Figure 13. Assembled bottom endwall of test section

(a) Heat transfer blade  
(b) Mass transfer blade

Figure 14. Test Blades
Figure 15. Numerical thermal analysis by ANSYS program

(a) Suction surface         (b) Pressure surface

(c) Endwall surface

Figure 16. Endwall test plates

(a) for heat transfer measurement        (b) for mass transfer measurement
Figure 17. Digital power supply

Figure 18. Five-axis measurement table for heat transfer endwall measurement

(a) for suction side measurement  
(b) for pressure side measurement  
(c) for endwall measurement

Figure 19. Thermal boundary layer probes
Figure 20. Four-axis measurement table

Figure 21. Two-axis measurement table

Figure 22. Schematic of assembled endwall test plate with upstream gap
Figure 23. Photo of test pieces

(a) Flat endwall  (b) forward-facing step  (c) backward-facing step

Figure 24. Schematic diagram of gap configurations
REFERENCES


INTRODUCTION

This program is designed to examine the feasibility of using the measurement of thermally grown oxide (TGO) stress, TGO thickness and the initial bondcoat geometry as a basis for making predictions of remaining life. In order to carry out the proposed research it is necessary to create a sample set that can be used to validate the proposed approach. It is essential that the bondcoat geometry be recorded using the interferometric profilometry before the TBC is applied.

While waiting for samples to be fabricated, TGO stress data collected under our previous AGTSR program was deconvoluted and plotted. It was discovered that the stress vs. life fraction was a single curve for data taken at 3 different temperatures (1100°C, 1121°C and 1151°C) fell on a single curve. This is a very important result with respect to using this type of data for NDE purposes. Lacking such a result it would be necessary to use different curves for different locations on hot section parts by virtue of the non-uniform temperature experienced by such parts.

One important failure mode for TBCs involves TGO/bondcoat separation caused by tensile stresses at asperities. As an essential component of the present program initial bondcoat surface geometry has been quantitatively recorded using an interferometric profilometer. To take best advantage of that information it is desirable to quantitatively relate that data to expected TGO/bondcoat asperity stress levels. The mechanics of highly stressed films such as the TGO is such that the surface geometric property needed to estimate stresses is the mean radius of curvature which is obtained from second derivatives of the surface profile. Differentiation of measured data is always challenging because of the potential large effects of noise on derivatives and especially on second derivatives. A computer program that successfully extracts mean radius of curvature and plots the results on a contour map has been produced. This can be used as a qualitative assessment tool for bondcoat surfaces in its present form. Surfaces with large contiguous regions of high curvature are expected to be poor bondcoat surfaces. The goal is to combine the curvature information with commercially available feature extraction software and fracture mechanics to compute the TGO thickness at which a TGO/bondcoat delamination of a fatal size would arise. Calculated critical TGO thickness could be used as a metric for surface finish process development as a substitute for very time consuming and costly furnace testing. Testing would then be used only to validate the most promising selected finishing processes.

In this reporting period the samples for the test program were produced. Production included performing appropriate surface finishing, recording the initial surface geometry using optical profilometry and preoxidation heat treatment. Initial assessment of TGO stress and calibration of TGO thickness measuring technology has been completed and testing with periodic measurement of TGO thickness and stress is now underway. Two results potentially of interest to industry were produced: (a). The temperature independence of the stress vs. life fraction was demonstrated. This provides increased motivation for the consideration of photo luminescent piezospectroscopic measurement of TGO stress as a NDE method. (b). Software for creating maps of the mean radius of curvature of surfaces was produced. Such maps are potentially valuable for assessing the quality of bondcoat surface finishes.
EXPERIMENTAL

Samples Preparation

All specimens were supplied by Howmet Corporation. All the specimens were disk coupon with the diameter of 25 mm (1 inch) and thickness of 3.125 mm (1/8 inch). The Substrate was CMSX-4 (a nickel based superalloy) single crystal. Three different bond coats were used (Ni, Pt)Al, MCrAlY, and MCrAlY+Si+Hf (see Table 3.1). Different surface finishes and pre-oxidations have been applied to bond coat. All specimens have been coated with 7wt%-YSZ in the Howmet Corporation.

<table>
<thead>
<tr>
<th></th>
<th>TBC COATING</th>
<th>BOND COAT</th>
<th>SUBSTRATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ZrO$_2$-7wt.%Y$_2$O$_3$</td>
<td>(Ni, Pt)Al</td>
<td>CMSX-4</td>
</tr>
<tr>
<td>2</td>
<td>ZrO$_2$-7wt.%Y$_2$O$_3$</td>
<td>MCrAlY</td>
<td>CMSX-4</td>
</tr>
<tr>
<td>3</td>
<td>ZrO$_2$-7wt.%Y$_2$O$_3$</td>
<td>MCrAlY+Si+Hf</td>
<td>CMSX-4</td>
</tr>
</tbody>
</table>

Table 3.1: Summary of TBC sample system.

Surface finishes

According to previous study, surface geometry of bond coat is critical to both life estimation and process control in TBC life. Different surface processing procedures have been deliberately carried in order to have a wide variety of surface geometry characterization scheme. The processing procedures are as follows: (1) as-received; (2) 90 minutes’ barrel finishing. The barrel finishing is done by USF Surface Preparation Group and is suitable for industrial processing of gas turbine blades. The surface morphology and roughness of the specimens were recorded using optical microscopy and ZYGO™ surface profilometry.

Pre-oxidation

All specimens have been pre-oxidized in an Ar-H environment (Po$_2$ -10$^{-8}$) at 1100°C for 2 hours prior to TBC coating. The TGO scale formed on the specimens during the heat treatment has been characterized with respect to phase constituents, residual stress and morphology by Cr$^{3+}$ photoluminescence piezo-spectroscopy (PLPS), optical microscopy and X-ray diffraction. All specimens have been coated with 7wt%-YSZ in the Howmet Corporation. The TGO scale for as-coated specimens has been characterized by Cr$^{3+}$ photoluminescence piezospectroscopy (PLPS), optical microscopy.

Non-destructive Inspection of TBC Samples

The latest development of NDI techniques have been used to measure the three critical parameters of the obtained TBC coatings. A Photo-stimulated Luminescence Piezo-Spectroscopy (PLPS) technique, recently developed by UConn and UC-SB, has been used to measure the stress in the thermally grown oxide (TGO), the location where TBC spallation occurs. Zygo NewView 5020, an
interferometric surface profiler, has been used to quantitatively measure the surface geometry of the initial bond coat surface. A conformable electrode Meandering Winding Magnetometer (MWM), recently developed by JENTEK sensors Inc., has been used to determine the thickness of the TGO layer.

**Measurement of TGO stress by PLPS**

The structure of typical TBC systems and their failure locations are shown in Fig. 3.1. For both plasma sprayed and EB-PVD TBCs, failure occurs by spallation of the ceramic very near the TGO. X-ray diffraction and laser fluorescence measurements have shown the stress in the TGO to be very high, about 3-6 GPa (400-800 ksi) in compression.

Under the AGTSR contract 95-01-SR030, “Bond Strength and Stress Measurements in Thermal Barrier Coatings”, and a subcontract from AGTSR Grant 96-01-SR046, “Chemical and Mechanical Instability at Thermal Barrier Coating Interfaces”, UConn and UC-SB have demonstrated the feasibility that laser fluorescence has the potential for becoming an NDI technique for assessing TBC coating quality and life remaining [1,2,3]. Here we briefly describe this laser fluorescence technique.

The residual stress in the thermally grown oxide (TGO) layer has been measured using the shift in the peak position of the fluorescence peak for chromia ions residing in the TGO layer. A schematic drawing of the method is shown in Fig. 3.2. This measurement is performed by sending a laser beam though the ceramic layer to impinge on the TGO layer. The TGO contains sufficient chromia to fluoresce. The fluorescence passes back through the ceramic layer and is collected. The wavelength of fluorescence for the fluorescence originating in the TGO is determined using a spectrometer and appropriate peak fitting software. The fluorescence peak position (solid line in Fig. 3.2) compared to that of an unstressed oxide (dashed line) is used to determine the hydrostatic component of stress in the TGO.
Measurement of Bond-coat Profiler

Surface geometry is critical to coating design and prediction of coating life. Zygo’s NewView 5000 with Zygo’s advanced MetroProTM software is used in measurement of surface geometry. NewView 5000 is a precision microscope which uses Scanning White Light Interferometry (SWLI) to generate quantitative three-dimensional images. Scanning White Light Interferometry (SWLI) is a traditional technique in which a pattern of bright and dark lines (fringes) result from an optical path difference between a reference and a sample beam. Incoming light is split inside an interferometer, one beam going to an internal reference surface and the other to your sample. After reflection, the beams
recombine inside the interferometer, undergoing constructive and destructive interference and producing the light and dark fringe pattern (see Fig. 3.3).

Figure 3.3: Schematic drawing of Zygo Surface Profiler

In the NewView 5000, an interferometer objective is mounted in a precision closed loop piezo-scanning device that moves vertically (in the Z direction) over the sample. Data is collected from a precision vertical scanning transducer and CCD camera and processed in a computer. The phase relationship of individual components of the white light spectrum in the interferogram are analyzed by Frequency Domain Analysis. Quantitative 3-D image (surface map) with ultra high Z resolution is generated. Available data includes 3D plots, filled plots, multiple 2D profiles of 3D data, and a wide range of surface roughness parameters: PV, Ra, Rms (see Fig. 3.4). PV is the height between the lowest and highest point on the test part surface. Ra (average roughness) is the average deviation of all points from a plane fit to the test part surface. Rms is the root-mean-square deviation of all points from a plane fit to the test part surface. Measurements have up to 1-angstrom resolution. Measurements can be made over long vertical distances up to 5 mm and large fields of view up to 17.3 mm. All specimens in the program were measured by Scanning White Light Microscope with 20X objective. Surface roughness data were recorded and quantitative information about surface geometry were extracted.
Measurement of TGO thickness by MWM Eddy Current Technique

JENTEK Sensor Inc. has recently demonstrated the capabilities of the conformable electrode Meandering Winding Magnetometer (MWM) eddy current sensor in measuring of ceramic topcoat thickness and metallic bond coat thickness.

In this technique, a spatially periodic field conformable Meandering Winding Magnetometer (MWM) sensor has been used to make the measurement. The winding pattern of this eddy-current-based sensor permits the interaction of the periodic magnetic field with multiple layered media to be modeled accurately. This significantly reduces calibration requirements. For characterization of coating with MWM, standards with coatings are not required; calibration can be performed on an uncoated section of materials.

In making these measurements it is possible to directly measure the thickness of the insulating layer and get the TGO thickness by measurement of "lift off" The alternative method is to measure the beta depletion zone thickness and correlate that to the TGO thickness. Beta depletion zone measurement has the advantage that the beta depletion zone typically increases 10+ microns for each micron of TGO thickness increase offering the possibility of greater sensitivity. In the case of Pt-Al bondcoat the beta depletion is complete in the first fraction of life (20% for example).
Because of this both lift off and beta depletion will be examined. Eddy current methods are particularly adept at measuring the beta rich zone thickness. More detailed description of this technique can be found in reference [4].

RESULTS AND DISCUSSION

Initial Testing of Previous Samples

In the early part of the present reporting period samples were being fabricated and during the time we were waiting for these samples more complete analysis of samples tested under our recently expired program (Development of Laser Fluorescence as a Non-Destructive Inspection Technique for “Thermal V Barrier Coatings, AGTSR 099-01- SR073) were further analyzed to explore the promise of the measurement of TGO stress to predict remaining life. Very promising results were obtained as described below. Under the previous program, cyclic oxidation tests were performed at 1100°C, 1121°C and 1151°C and over 1 hour and 24 hour cycling periods, during which the spectra from which the residual stress in the thermally grown oxide (TGO) can be determined were measured using photoluminescence spectroscopy (PLPS). Under the present program these spectra were deconvoluted. This single batch of specimens had been subjected to different cycling conditions, as is typical of industrial turbines. The residual stress in the TGO was found to evolve in systematic manner with cycles and the evolution was qualitatively similar at the different cycling temperatures (see Fig. 4.1).

![Figure 4.1: Evolution of TGO Stress as a Function of Cycling Temperature and Time at Different Life Fractions.](image-url)

Remarkably the rate of stress evolution with respect to life fraction was also relatively insensitive to total hot time and temperature and seemed to depend primarily on cycles (see Fig 4.1, 4.2, 4.3).
Figure 4.2: Evolution of TGO Stress at Different Cycling Frequencies.

Figure 4.3: Evolution of TGO Stress at Different Life Fractions.
Thus, there is only one repeatable stress versus cycle curve/profile for this TBC system, irrespective of the cycling temperatures or cycling time (see Fig. 4.4). This could eliminate the large uncertainty created by lack of precise temperature information for industrial turbines.

![Graph showing TGO Stress at Failure](image)

Figure 4.4: Schematic Illustration of TGO Stress Evolution as a Function of Thermal Cycling.

The measured TGO stress was found to be relatively constant at failure of the TBC specimens for the various temperatures examined (see Fig. 4.5).

![Bar chart showing TGO Stress at Failure](image)

Figure 4.5: Measured TGO Stress at Failure.
This single relationship between life remaining and TGO stress, for these given batch of specimens, despite the large variation in their failure lives (see Fig. 4.6) would allow TGO stress alone to be a useful predictor of component life.

Thus the PLPS behavior has been found to be systematic and consistent enough to allow reliable remaining life predictions for the given TBC system. The implication of the observed trends in the TGO stress for non-destructive determination of the remaining life is very promising.

Surface Profilometry Results for Specimens before TBC coating

Surface geometry of bond coat is one of critical parameter in determining coating life. Surface geometry of all specimens was recorded by ZYGO™ surface profilometry. Figure 4.7 shows surface profilometry of an as received specimen. It is shown that the surface of this specimen is very rough and has very large ridges. The distance between highest and lowest points within sample (PV) is 18.6 um. The peaks are about 10 um high. Figure 4.8 shows surface profilometry of a specimen after barrel finishing. The surface roughness of specimen after barrel finishing decreases significantly compare to as coated specimen. The PV value is 5.623 um. The change of surface roughness proves that barrel finishing is very successful in removing large peaks. From summary of surface roughness data (Fig. 4.8), surface roughness of specimen changes significantly after barrel finishing. The surface of as coated specimens is the roughest. The average surface roughness (Ra) is from 1.75 um to 3.72 um. The surface of specimens after barrel finishing is smoother. The average surface roughness (Ra) of specimens after 90 minutes barrel finishing is in the range of 0.31um to 0.45 um. Various surface defects/features are also included in the specimens due to various surface processing: as coated (ridges at full height), barrel finished (rough surface with reduced ridge height). Finally we note that multistage centrifugal barrel finishing can produce a surface approaching the hand polished finish if performance improvements justify such an effort.
Figure 4.7: Surface profilometry of an as coated specimen
Figure 4.8: Surface profilometry of a specimen after barrel finishing

Geometry Feature Extraction from Zygo Measurements
Surface geometry is one of critical parameters in predicting life of TBC. Surface roughness of bond coat is measured by Zygo surface profilometry. But the measured data cannot be directly used in calculating the lifetime of TBC coating. It is necessary to extract the critical feature such as local radius of curvature and size of bond coat asperity from surface data. We have established a new method which allows us to extract the quantitative information of critical features from the raw data.

Surface map measured by surface profilometry is constructed by 3 dimensional data \((x, y, z)\). Before extract critical feature, raw data of surface needs to be smoothed. Data smoothing and removing of noise is successful by using Fourier filtering (see Fig. 4.9). Surface characteristics of test data are broken down into waviness, roughness and high frequency results (see Fig. 4.10). By setting filter type, filter parameter and filter window size, test data is digitally filtered. Noise is removed and data becomes smooth.

The 3D data of surface map comprises a \((320\times240\times3)\) matrix. In an attempt to deal with the randomness of huge amount of data, polynomial interpolation is involved and cubic splines is used to fit the data. Generally, splines can be considered as a mathematical model that associate a continuous representation of a curve or surface with a discrete set of points in a given space. Spline fitting is an extremely popular form of piecewise approximation using various forms of polynomials of degree \(n\), or more general functions, on an interval in which they are fitted to the function at specified points, known as control points, nodes or knots. A cubic spline is a spline constructed of piecewise piecewise polynomials which pass through a set of \(m\) control points. The second derivative of each polynomial is commonly set to zero at the endpoints, since this provides a boundary condition that completes the system of \(m-2\) equations. Cubic spline is used to curve fit the data by Matlab.

Given the cubic spline description of surface \(z=\) a cubic polynomial in \(x\) and \(y\), principal curvatures can be got by the equation below. Principal curvatures \(k_1, k_2\) are the roots of: \(k_1+k_2=2H; k_1*k_2=K\) (\(H\) is mean curvature; \(K\) is Gaussian curvature).

\[
H=(1/2)*(r*(1+q^2)-2*p*q*s+t*(1+p^2))/(1+p^2+q^2)^{1.5};
\]

Where \(p=\text{diff}(z, x)\);
\(q=\text{diff}(z, y)\);
\(r=\text{diff}(z, x^2);\)
\(s=\text{diff}(z, x, y)\);
\(t=\text{diff}(z, y^2)\).

Local mean curvature can be calculated by derivatives and radius of mean curvature is extracted from surface map. Curvature map is thus constructed (see Fig 4.11). Surface map and curvature map showed same feature.

In order to prove that cubic spline processing to get curvature is reasonable, artificial surfaces are constructed and same process is applied to get curvatures of surfaces. Curvatures from two artificial surfaces that are obtained by the above process and by exact mathematic calculation are mapped and compared, respectively (see Fig. 4.12 and Fig.4.13). One artificial surface is surface satisfied by equation \(z=x^2+y^2*0.5\) (Fig 4.12 (a)). The other one is surface satisfied by the equation \(z=\cos(x)\) (Fig. 4.13 (a)). It is shown that the curvature map through cubic spline process and exact calculation matches very well. The maximum percent error between two processes in two cases is very small (less than 1%). It proves that cubic spline in fitting surface data and getting curvature is applicable and successful.
Before Filtering

After Filtering

Figure 4.9: Noise of data is removed by Fourier filtering.

Figure 4.10. Breaking of surface characteristics.
Figure 4.11. Mapping of curvature by Matlab
(a) Original Surface
$Z = x^2 + y^2/2$

(b) Mean Curvature (H)
By Spline Process

(c) Mean Curvature (H) by Mathematic Calculation

Figure 4.12: Comparison of curvature map by spline process and mathematic calculation.
Figure 4.13: Comparison of curvature by spline process and mathematic calculation.
PLPS Results

*Before TBC Coating*

The PLPS technique is based on the shift of wavelength with stress of the R-line fluorescence of Al2O3: Cr3+, causing the piezospectroscopic effect. The R1 and R2 lines of α-Al2O3 are two closely spaced lines that occur at 14,402 cm⁻¹ and 14,432 cm⁻¹ respectively. If stress is applied to the oxide, the wavelength of R-line will shift. From the shift of wavelength, the stress in the oxide can be obtained. The stress in the TGO plays important role in leading to TGO and TBC spallation. Furthermore, information about phase constituency can be got by PLPS. There are θ-Al2O3 peaks that occur in the 14,520 cm⁻¹ to 14,630 cm⁻¹ range. Phase constituents of TGO, especially during early states of oxidation, have been identified as critical factor influencing the adhesion at TGO/coating interface [5,6,7]. It has been proposed by Clarke and coworkers [6,7] that transformation from θ-Al2O3 to α-Al2O3 is responsible for additional residual stress from the volumetric constraint in the TGO scale and nucleation of sub-critical cracks, eventually leading to the spallation of α-Al2O3 TGO. Stress measurement and phase constituency were done by PLPS. From observation of PLPS, no θ-Al2O3 is shown (see Fig. 4.14) in any of the specimens which have different surface conditions (as received, barrel finishing). All specimens which have 2 different surface conditions contain complete α-Al2O3. The initial stress value of α-Al2O3 is low (in the range of 0.1-0.4 GPa), and shows scattering (see Fig. 4.15). This indicates that TGO is very thin and maybe discontinuous.
After TBC Coating

From observation of PLPS, no $\theta$-Al$_2$O$_3$ is shown in any of the specimens which have different surface conditions (as received, barrel finishing). All specimens which have 2 different surface
conditions contain complete $\alpha$-Al$_2$O$_3$. The $\alpha$-Al$_2$O$_3$ peaks become broadening and R2 and R1 peak comes closer (see Fig. 4.16). It indicates that there may have stress distribution in the prove volume. 30 spectrums were recorded for every specimen. All spectrums are being deconvoluted by software. TGO stress, intensity ratio of R2 and R1, full width ratio of R2 and R1 are being extracted and documented.

![Graph](image.png)

**Figure 4.16**. PLPS spectrum for as-coated TBC.

**CONCLUSIONS**

1. Suitable bond-coated, TBC coated samples have been produced which enables cyclic furnace testing to begin.
2. The samples were subject to suitable surface finish and pre-oxidation treatments prior to heat TBC coating.
3. Preliminary tests show that TGO stress vs. life fraction is nearly independent of test temperature, which is very positive news for use of the method as an NDI tool.
4. The TGO stress at failure in preliminary tests is nearly constant.
5. A suitable method for estimating surface curvature from optical profilometry data has been found. This curvature data enables the construction of a map of stress normal to the TGO/BC interface as a function of position as required in the life prediction scheme.

**REFERENCES**


PROJECT 02-01-SR098; Louisiana State University, "Experiments and Computations on Film-Cooled End Walls with Contouring."

INTRODUCTION

Lean premixed combustors used in modern industrial gas turbine systems have relatively flat temperature profiles at the combustor exit. Thus, effective cooling strategies for the end walls have become increasingly important. Film cooling of the end walls is commonly employed. However, strong secondary flows in the blade passage interfere with the injected coolant, and make effective cooling of the end wall a difficult problem. The secondary flows in the passage are driven by the development of the horseshoe vortex at the leading edge and the strong pressure gradients in the blade passage. Therefore, for effective cooling of the end-wall region, strategies for reducing or eliminating the passage secondary flows must be explored. The ongoing work aims to investigate a hybrid strategy of end-wall contouring and using a leading edge fillet to suppress passage secondary flows, and to further explore coolant injection upstream of the blades for effective end-wall cooling.

The goal of the project is to provide the turbine designer improved strategies for reducing the heat load to the end wall, and lowering aerodynamic losses. The strategies to be explored include contouring the end wall, placing a fillet along the leading edge of the blade, and in strategically locating film cooling injection holes. The results from the work will provide guidance for improved end wall designs leading to the lower utilization of coolant air, greater aerodynamic efficiency and greater reliability.

Specific tasks for the project include:

- Investigation of the effects of end-wall contouring on reducing secondary flows in the blade passage, and to further explore the potential of using coolant jets to reduce the deleterious effects of secondary flows on aerodynamic losses and heat transfer. Of specific interest again are coolant jets upstream of the blades; however, coolant jets strategically located in the blade passage (as directed from validated CFD studies) will also be explored as a potential mechanism for reducing secondary flows.
- Investigation of the effects of leading edge fillet on reducing secondary flows on contoured end walls with film-cooling. It is postulated that the most effective solution for reducing secondary flows in the blade passage would be achieved by using a combination of end-wall contouring and the appropriate choice of the leading edge fillet. Validated CFD studies will be used extensively to optimize the fillet-geometry. Further, the effectiveness of coolant injection for these hybrid configurations (contouring plus leading-edge fillet) will be explored in detail.
- To use validated CFD to explore detailed flow physics, and to optimize coolant injection configuration and blowing parameters, and leading edge fillet geometries. The results of these parametric investigations will be utilized in defining the experimental test matrix.
EXPERIMENTAL

Experimental and Analytical Approach

The ongoing research includes both an experimental and computational effort. Both approaches are described in detail later. The experimental effort will be performed on two cascade facilities:

- An atmospheric cascade facility which will permit detailed flow measurements and relatively easier modifications to accommodate a variety of end wall and leading edge contours. The detailed flow measurements are necessary for model validation in the computational effort. Measurements planned include velocity measurements (using hot-wire anemometry and Particle Image Velocimetry), heat transfer measurements (using Infra-red Imaging), and surface pressure measurements.

- A pressurized hot cascade facility that will allow the simulation of realistic Mach numbers, Reynolds number, turbulence levels and length scales, and density ratios. The results from the atmospheric cascade tests and computations will define a more limited test matrix for this phase of study. Primarily surface heat transfer coefficient, cooling effectiveness, and pressures will be measured in this phase.

The computational work will primarily involve validated RANS approaches for predicting the in-passage flow and heat transfer. The goal of the computational effort is to make a detailed parametric study with different end wall and leading edge contours that will enable a more limited set of cases to be studied experimentally. Further, the simulations would provide additional information to help assess the flow and heat transfer behavior.

Test Facility

The schematic of the low speed cascade facility is shown in Fig. 1. The cascade operates in a suction mode with a 3.4:1 contraction section upstream of a smooth rectangular inlet channel of aspect ratio 1.36. The test section can accommodate three vanes/blades (in this study tests are planned with both the vane and blade geometries) forming two passages with active suction-bleeds along the side-walls that can adjust the stagnation planes. Mass flow rate in the vane passages can be adjusted by changing the positions of the side tailboards with a traverse mechanism. Vane/blade profiles for this investigation is obtained from the hub side section of the vane/blade GE-EEE geometry. The GE vane/blade geometry is scaled up ten times for the present cascade configuration. Table 1 provides the geometry of the present cascade and the flow conditions employed for measurements.

As shown in Fig1, The top wall of the test section has cut out sections for optical and hot-wire sensor or five-hole miniature pressure probe access for infrared thermal measurements and flow measurements. The flat bottom end-wall and vane profiles are instrumented with thermocouples, foil heaters, and static pressure taps. The pressure taps of diameter 0.3 mm are drilled on 1.65 mm diameter stainless steel tubes mounted in the grooves on the vane/blade profile. The tube surface flushes with the vane surface when placed in the groove. Bottom end of each tube is blocked to any air flow while the top end is connected to a Validyne pressure transducer. Signals from the thermocouples and pressure transducer are obtained in a HP3497A data acquisition system that is controlled with a Dell Dimension desktop PC. The boundary layer suction bleeds in the top, bottom, and side walls of the inlet channel provide uniform flow conditions at the test section inlet. The 2.20 cm diameter cylindrical rods located 3.2C upstream of the vane passage inlet plane in Fig. 1 are inserted through the top wall of the inlet channel and act as a passive turbulence grid system.

The first set of measurements that were performed were pressure measurements at the mid-span on the pressure and suction sides of the center blade, and the pressure/suction side of adjacent blades.
These measurements are shown below in Fig. 2, and indicate that an adjustment in the incidence angle is necessary. These adjustments are currently being performed along with visualization studies.

Figure 1: Schematic of the test cascade test facility for flow structure, pressure, and heat transfer measurements.

<table>
<thead>
<tr>
<th>Table 1: Cascade Test Section Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual chord length, C (cm)</td>
</tr>
<tr>
<td>Axial chord length, Cx (cm)</td>
</tr>
<tr>
<td>Aspect ratio (true chord length to vane span), C/S</td>
</tr>
<tr>
<td>Solidity ratio (true chord length to vane pitch), C/P</td>
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<tr>
<td>Inlet velocity, $U_{in}$ (m/s)</td>
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<tr>
<td>Inlet Reynolds number, $Re_{in}=(\rho U_{in} C/\mu)$</td>
</tr>
<tr>
<td>Stagnation temperature, $T_{o,in}$ (K)</td>
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<tr>
<td>Stagnation pressure, $P_{o,in}$ (Pa)</td>
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<tr>
<td>Flow inlet angle (degrees)</td>
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</table>
Figure 2 shows flow visualization measurements at different planes using smoke wires and a digital camera. The horseshoe vortex that forms along the stagnation plane can clearly be seen. The planes PS1 and PS2 show the pressure side, while SS1 Represents the suction side. In all these images the existence of the secondary flow structures are clearly apparent.

The following experimental tasks are currently being pursued:

- Hot-wire anemometer measurements of the approach flow and the passage flows with the blades.
- Preparation for the PIV measurements
- Collaboration with the computational effort to help define the end wall contour to be designed and built for testing
- Preparation for IR measurements once the flow measurements are completed.

All of the above tasks for the flat end wall, and one selected contoured end wall are expected to be completed by May 2003.
<table>
<thead>
<tr>
<th>Visualization Plane</th>
<th>s/C (s: blade coord. From stag. Point, C=chord length)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS1</td>
<td>0.18</td>
</tr>
<tr>
<td>PS</td>
<td>0.0</td>
</tr>
<tr>
<td>PS1</td>
<td>-0.02</td>
</tr>
<tr>
<td>PS2</td>
<td>-0.04</td>
</tr>
</tbody>
</table>

Figure 3: Flow visualization Pictures at different planes
RESULTS AND DISCUSSION

The geometry used for the CFD domain employs the same blade and passage geometry as in the experimental test facility and is presented in Fig. 3. The number of grid points used is generally over one million with near-wall stretching of the grid points toward the bottom end-wall. Standard k-ε with two-layer near wall turbulent model is employed to simulate the flow. The grids are made fine enough near the walls so that the Yplus values are below unity. The preliminary baseline computations with the flat end-walls are performed with a uniform inlet velocity of 9.40 m/s. Inlet turbulent boundary conditions employed for the domain are $k/U_{in}^2=0.134$ and $\varepsilon C/U_{in}^3=0.245$, which are determined based on the results in Radomsky and Thole (2000).

Calculations were initially performed with the blade located as shown in Fig. 3 (same configuration as in the experiments with non-zero angle of incidence). These results were in reasonable agreement with the data. Next the incidence angle was varied over a limited range, and these results are shown in Figure 4 below. These calculations were done in order to help identify the zero-incidence case and the corresponding orientation of the blade in the cascade tunnel. The angles identified in Fig. 4 are with reference to the SP plane in Fig. 5. With this reference, a 55-degree incidence angle would provide a stagnation point on the leading edge of the blade, and the test-section orientation in the experimental facility is done accordingly.
Figure 4: Pressure coefficient at various incidence angles
Figure 5: Locations of the planes normal to the bottom end-wall for the analysis of the computational results. \( s \): distance along the blade profile from the stagnation point, \( y \): local coordinate normal to the blade profile.

![Figure 5](image)

Figure 6: Velocity vector in plane SP plane

![Figure 6](image)

Figure 7: Turbulence intensity magnitudes along the plane in the mid-span \((z/S=0.5)\) of the vane passage for \(Re_C=2.3 \times 10^5\), standard \(k-\varepsilon\) model: (a) present GE-E3 vane, (b) Vane, Thole and Zess, 2001-GT-0404.

Figure 6 shows the velocity vectors in the SP plane, and the development of the horseshoe-vortex can be clearly seen in this plane. The initial horseshoe vortex does depend on the boundary layer.

![Figure 7](image)
development upstream, and currently the computations are being tailored to match the experimental velocity profiles.

The turbulence intensity magnitude predictions along the mid-span plane of the vane passage are shown in Fig. 7. Also shown are the measurements of Thole and Zess (2001) on a P & W vane. Qualitative agreement in the trends is observed. No quantitative agreement is expected due to differences in blade profile.

Computations were next performed for eight different cases and are tabulated in Table-2. The simulations were done for both uniform and non-uniform (with boundary layer development) inlet velocity profile. For the non-uniform inlet profile, a one-seventh turbulent boundary-layer profile is used. However, in all cases, the average inlet velocity is 7.924 m/s. For contoured end-wall cases, only one endwall is made contoured while the other is flat. The blade surface and one end wall (contoured bottom wall for contoured end-wall cases) is heated while the other flat wall is insulated.

Figure 8 shows the pressure coefficient distribution on the blade surface at 15% of the blade span from the bottom wall. It is clear that the higher angle of attack provides a secondary peak on the pressure side. The data from experiments at this angle of attack (550°) was included in the figure for comparison. The experiments and computations are found to match quite well. The zero-incidence angle computations are shown to have the expected behavior and no significant influence of the inlet profile was found on the pressure distribution at this location.

Streamlines and vorticity contours were plotted at three axial positions shown in Fig. 9. The first position corresponds to the stagnation plane (plane 1 in Fig. 9), and the second and third positions correspond to axial chord locations s/S=0.5 (planes 2 and 3 in Fig. 9), and 0.85 (planes 4 and 5 in Fig. 9) respectively. At each axial chord location, two cross-sectional planes, one normal to the pressure side (planes 3 and 5) and the other normal to the suction side (planes 2 and 4) are plotted.

The streamlines on the transverse planes 2 and 3 are shown in Figure 10 for Cases 4 and 6. Also shown are the contours of vorticity normal to the plane. The formation of horseshoe vortices is evident from the recirculation (red and blue vorticity contours) near the blade-endwall junction. The pressure-side vortex is seen to be smaller in size. With end wall contouring, the pressure-side vortex near the contoured end-wall is considerably reduced. The suction side flow is effected by the end wall contour, but the size of the vortex is not significantly altered. Figure 11 shows the streamlines and vorticity contours at planes 4 and 5. Contouring is again seen to alter the flow field.

Figure 12 shows the Nusselt number distribution on the endwall. Higher heat transfer is obvious in the region of horseshoe vortices. Unlike the flat endwall, heat transfer coefficient distribution along the contoured end wall is significantly different and upstream of the blade the signature of the horse show vortices is less apparent.
Case 1: Flat End Wall, Uniform inlet velocity, Zero degree angle of attack.
Case 2: Flat End Wall, Uniform inlet velocity, 55° angle of attack.
Case 3: Flat End Wall, Non-uniform inlet velocity, Zero degree angle of attack.
Case 4: Flat End Wall, Non-uniform inlet velocity, 55° angle of attack.
Case 5: Contoured End Wall, Uniform inlet velocity, Zero degree angle of attack.
Case 6: Contoured End Wall, Uniform inlet velocity, 55° angle of attack.

Table 2: Various Flow Cases (Angle of Attack Defined w.r.t the Stagnation Plane)

<table>
<thead>
<tr>
<th>Case</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Flat End Wall, Uniform inlet velocity, Zero degree angle of attack.</td>
</tr>
<tr>
<td>Case 2</td>
<td>Flat End Wall, Uniform inlet velocity, 55° angle of attack.</td>
</tr>
<tr>
<td>Case 3</td>
<td>Flat End Wall, Non-uniform inlet velocity, Zero degree angle of attack.</td>
</tr>
<tr>
<td>Case 4</td>
<td>Flat End Wall, Non-uniform inlet velocity, 55° angle of attack.</td>
</tr>
<tr>
<td>Case 5</td>
<td>Contoured End Wall, Uniform inlet velocity, Zero degree angle of attack.</td>
</tr>
<tr>
<td>Case 6</td>
<td>Contoured End Wall, Uniform inlet velocity, 55° angle of attack.</td>
</tr>
</tbody>
</table>

Figure 8: Distribution of pressure coefficient on the blade surface at 15% of the blade span from the bottom wall.
Figure 9: Positions of the different planes with respect to the blade geometry.

Figure 10: Normal Vorticity and Streamlines at Plane 2 (s/S=0.5, Plane Normal to the Pressure Side) for Flat and Contoured End Wall

Plane3. (normal to suction side) Flat end wall

Plane3 Contoured end wall

Plane2 (normal to pressure side) Flat end wall

Plane2 Contoured end wall

Figure 10: Normal Vorticity and Streamlines at Plane 2 (s/S=0.5, Plane Normal to the Pressure Side) for Flat and Contoured End Wall
Work In Progress

The present experimental and computational results provide some preliminary data on the stationary cascade. Preparations for further experimental and computational work with the flat end-walls are in progress to obtain more baseline data for the cascade project. The work now in progress is listed below. All these activities are simultaneously being addressed.

- Flow visualization in streamwise planes normal to the center vane/blade profile and above the flat end-walls using smoke (experimental).
- Flow structure (time-averaged velocity components and vorticity) measurements using a five-hole miniature pressure probe in spanwise normal planes in the vane/blade passage with the flat end-walls (experimental).
- Turbulence structure measurements over the flat end-walls in the vane/blade passage using hot-wire sensors and PIV technique (experimental).
- Heat transfer measurements on the flat bottom end-wall and center vane/blade surface using the infrared thermography (experimental).
Figure 11: Normal Vorticity and Streamlines at Plane 2 (s/S=0.5, Plane Normal to the Pressure Side) for Flat and Contoured End Wall

Figure 12: Nusselt number distribution on endwall (a) flat endwall (b) contoured endwall.

-Numerical predictions of the flow structure and heat transfer in the vane/blade passage with flat end-walls and using fully developed velocity profile at the inlet boundary condition (computational).
-Numerical predictions of the flow structure and heat transfer in the vane/blade passage with contoured end-walls and using fully developed velocity profile at the inlet boundary condition (computational).

```
(a)  (b)
```

Inlet

```
(a)  (b)
```

h1=0.15 S
l1=0.85 C

h2>h1
l2=l1=0.85 C
Figure 9: Proposed configurations of the two-dimensional contoured bottom end-wall: (a) baseline end-wall contour from GE-E3 rotating vane cascade, (b) modified and slightly steeper contour end-wall than the baseline contours.

CONCLUSIONS

Strategies for controlling the secondary flows in blade passages through end wall and leading edge contouring are being explored. Reduction in the secondary flows are expected to lead to a reduction in aerodynamic losses and end wall heat transfer coefficient. The ongoing study involves both experimental and computational activities.

In the first six months of the effort, the activities have focused on taking baseline measurements with a flat end wall, and in performing computations for validation purposes and in exploring the effect of contouring. Preliminary results are described in this report. In the next six months, the computational effort will focus on studying an array of different contouring strategies aimed at reducing the secondary flows. The best contour will then be selected for a detailed experimental study.

REFERENCES

INTRODUCTION

This project is developing reduced order models and control methodologies for ultra-lean premixed combustion dynamics. Specifically, the study includes the measurement and modeling of heat release dynamics, equivalence ratio fluctuations, high temperature acoustics, and lean blowout characteristics. Schemes to control flame stabilization and thermo-acoustic instabilities are also being investigated.

There is currently a debate in the combustion community about the efficacy of reduced-order models versus CFD models for combustor design. It is believed that highly complex CFD models will ultimately deliver the most accurate predictions of dynamic behavior in combustors. However, even if one assumes that available transient, reacting CFD codes are accurate, such models are unwieldy and extremely time-consuming when used as an iterative design tool. The proposed project, therefore, focuses on so-called “reduced-order models.” The two key reasons for this focus are the natural link between achievable experimental measurements and reduced order models, as well as the easy transformation of reduced order models into linear stability models. Stability prediction is urgently needed by virtually all gas turbine designers, particularly for ultra-lean combustor designs.

Although it is relatively easy to qualitatively “explain” why instabilities might tend to occur under certain conditions and at certain frequencies, the problem of accurate prediction is much more difficult. Our approach to combustor stability predictive tools is based on systems theory and models the instability feedback loop as an interconnected set of subsystems, each corresponding to a relevant physical mechanism. For accurate stability prediction, it is absolutely necessary that all subsystem (dynamic) models accurately characterize the gain and phase versus frequency behavior of the actual subsystem in physical units. For example, it is not enough to show that a model predicts the trends of a voltage observed at the output of a transducer responding to heat release rate – it is necessary to accurately predict the total heat release rate in J/sec. It is obvious, therefore, that the current knowledge in this area needs to be advanced and the work tasks outlined in the following sections describe how this will be accomplished.

Ultra-lean premixed combustor operation is significantly more susceptible to lean-blowout of the flame. Thus, this project seeks to understand better the critical parameters that define both static and dynamic flame stability, with particular emphasis on the dynamic coupling between combustion oscillations and dynamic stability of the flame and the effects of fuel variability on these phenomena. Through a series of experiments conducted using university, government, and industry combustors, dynamic models will be progressively defined in order to predict critical dynamic velocities that must be maintained in the combustors to ensure stable operation.

Several control strategies, including passive, active, and a blend of both, will then be considered in order to demonstrate the feasibility of extending the limits of flame stabilization while
simultaneously minimizing the occurrence or severity of combustion oscillations during ultra-lean combustor operations.

The payoff from successful development of the types of models proposed here is enormous for the gas turbine community since such models will lead to predictive capabilities that can rapidly discern whether a specific combustor design is susceptible to unstable operation at any operating conditions. The great attraction of these tools is the potential significant shortening of the development cycle.

Project Description

Quantifying Heat Release Dynamics for Turbulent Swirled, Premixed, Lean Flames (Task 1).

Objectives  This task focuses on obtaining the frequency-resolved response of the heat release rate, in physical units, to perturbations in mass flow rate and equivalence ratio. Using the response, physics-based, reduced-order models will be derived. The models will then be validated on self-excited combustors in the Virginia Active Combustion Control Group laboratory, at the National Energy Technology Laboratory, and in industry.

Methodology  To accurately measure heat release rate, Tunable Diode Laser Absorption Spectroscopy (TDLAS) and chemiluminescence will be used simultaneously. TDLAS methods will be used to measure the unsteady temperature of the products in the immediate post-flame zone. The temperature measurement is based on the ratio of the absorption of water lines at 1392 nm and 1343 nm. In this manner, the sensible part of the change in enthalpy can be obtained. Hydroxyl radical (OH*) chemiluminescence has been shown to be an excellent indicator of chemical heat release rate in premixed flames. Thus, it will be used to determine the chemical change in enthalpy. Both measurements will enable true characterization of the driving source term for thermo-acoustic instabilities.

Variations in equivalence ratio will be measured via methane absorption using an infrared Helium-Neon laser with a power rating of 1.8 mW. The absorption will be calibrated to known concentrations using a static gas cell.

Modeling time Lag and Dispersion of Equivalence Ratio Variations (Task 2).

Objectives  This task focuses on investigating the effect of time lag on flame stability and dynamics. The time lag is defined as the time for a perturbation in equivalence ratio to result in a perturbation in heat release rate. The effect of diffusion and turbulent mixing on equivalence ratio variations will also be studied.

Methodology  The Helium-Neon laser system, described in the previous task, will be used to measure variations in equivalence ratio. The equivalence ratio will be modulated through a system employing high-frequency solenoid valves, rotating valves, voice coils, or loudspeakers. The effect of equivalence ratio variations on heat release rate will be measured via chemiluminescence and TDLAS methods, as described previously. The time lag will be measured as the time from when a perturbation is given to the equivalence ratio to the time a
response is observed in heat release rate. Computational Fluid Dynamics (CFD) will be used to model the velocities and flame location in the combustor. This information can then be used to solve for the time lag and compare to the experimental values. Using this data, observations can be made on the effects of time lag on flame dynamics and stability. These observations will then be incorporated into reduced-order models. As in other tasks, the experimental methods will be verified on the laminar burner before beginning work on the turbulent burner.

**High Temperature Acoustics Validation (Task 3).**

**Objectives** Using experimental data acquired from actuator excitations and flow noise, 3D FEA acoustical models for both cold, no-flow and actual operating conditions will be verified.

**Methodology** FEA models of combustor acoustics, with ability to handle complex boundary conditions, and combustor CAD models as inputs will be developed. Recent experience in formulating FEA models of industrial combustors will serve as a baseline. Goals include developing a neutral file format for sharing geometric data, integration with CFD models, and developing guidelines for partitioning models.

**Premixed Flame Stabilization and Lean Blowoff Limits (Task 4).**

**Objectives** This task will focus on the measurement and modeling of static and dynamic lean blowoff limits over a range of operating conditions.

**Methodology** The flame dynamics measurements will be extended to the lean blowoff limits. In addition, a system will be implemented to force fluctuation in equivalence ratio. The impact of equivalence ratio perturbations on flame stability will be investigated.

**Prediction of Combustor Instabilities and Dynamic LBO (Task 5).**

**Objectives** The entire modeling methodology will be validated through prediction of combustion instabilities and lean blowoff limits on various combustors. Reduced-order models will be applied to VACCG test combustors, the NETL rig, and the Solar test rig.

**Methodology** Using models for combustion system components developed in the preceding tasks, a model of the combustion instability feedback loop will be built for the target combustors. Stability predictions will be compared to experimental data over a wide range of operating conditions.

**Simultaneous Control of Flame Stabilization and Thermoacoustic Oscillations (Task 6).**

**Objectives** The LBO margin of combustors will be extended through application of control schemes.

**Methodology** Modeling results from Tasks 1 through 5 will be used to develop strategies to control lean blowoff. Possible methods of extending the LBO margin include staged premix piloted flames, pulsed pilot flames, and pulsed primary fuel modulation.
EXPERIMENTAL

Chemiluminescence

Species Candidates. Many chemiluminescent species have been used as an indicator of heat release rate, including CH*, CO2*, C2*, and OH* (where the * indicates an excited radical). OH* was chosen for many reasons. First, it is a simple molecule, and thus exhibits a relatively finite spectrum. The levels of OH* observed in a flame are far greater than the levels predicted by equilibrium chemistry at the flame temperature. This means the OH* is produced as an intermediate step in combustion reactions, and should be a good indicator of chemical reaction rate. Haber (2000) confirmed this hypothesis for the static case. Current work in the VACCG focuses on confirming the relationship for the dynamic case.

Experimental Hardware. The chemiluminescence experimental setup includes optics, fiber optic cables, a monochrometer, and a photomultiplier tube, as seen in Figure ?? . The details of the system are given by Haber (2000). All optics are fused-silica to ensure transmission (98%) of ultraviolet light. Two 25.4 fused silica lenses are used to collect the light from an area with a diameter 1.2 times the diameter of the flame and focus it onto the fiber optic cable. A fiber optic positioning module (Newport) couples with the SMA termination on the fiber. The optical fiber used is 1-mm in diameter with a fused-silica core and 0.48 numerical aperture, SMA terminations. The fiber optic cable carries the light to a 0.5 m Ebert Monochrometer (Jarrell Ash 82-020) with a 400 nm diffraction grating set to 309 nm for OH* chemiluminescence. The light flux is converted to an electric current flux via a photomultiplier tube (Hamamatsu R995).

Diode-Laser Absorption Measurements – Water temperature

Near-IR Line Candidates. The transitions of water vapor in the infrared region are shown in Figure 1 [Furlong, 1998]. The absorption features overlap the wavelengths of available semiconductor lasers in many places. The choice of the particular wavelengths used in this study was a product of several factors. For a transition to be attractive with respect to spectroscopy, it must exhibit isolation from other absorbing species. The linestrength must be intense enough to insure adequate absorption. Since temperature will be calculated from these measurements in particular, temperature sensitivity, and thus lower-state energy, is also a consideration.

From Figure 1, it can be seen that the 1.4 µm and 1.8 µm region are attractive. At 2000K, two of the strongest transitions are at 1.392 µm (7185.59 cm⁻¹) and 1.343 µm (7444.37 cm⁻¹), as seen in Figure 2. The temperature sensitivities of the transitions are shown in Figure 3.
Figure 1. Water Absorption Spectra. Calculated absorption spectrum of water at 2000K overlaid with available diode laser wavelengths (gray bars). The heavy arrows indicate candidate transitions [Furlong, 1998].

Figure 2. Selected Transitions. Expanded view of transitions used in this study.
Experimental Hardware. The experimental setup for TDLAS includes the diode lasers, controllers, optics, and detectors (Figure 4). The diode lasers, one at 1343 nm and one at 1392 nm, were obtained from Laser Components GmbH, Inc. They have a nominal power of 5 mW and can be tuned with respect to wavelength and power depending on case temperature and injection current. The lasers are mounted in diode mounts (ILX Lightwave LDM-4407) with Thermo-electric Coolers (TEC) to control the case temperature. A laser diode controller (ILX Lightwave LDC-3908, LDC-3916370 modules) is used to set temperature and injection current. The controller allows the injection current to be modulated via an external connection to a function generator. A laser diode beam is very diffuse, so off-axis paraboloidal reflectors (Melles-Griot) are used to collimate the beam. The beam is then focused across the flame. A flat mirror (Newport 05D20ER.2-PF) reflects the beam through a 2” focusing lens (Thorlabs LB1917-C) and onto a InGaAs photodiode detector (Thorlabs FGA10). The circuit diagram for the detector is shown in Appendix E. The circuit converts the current signal from the photodiode to a voltage signal and provides amplification. The bandwidth of the circuit is 10 kHz.
Infrared Helium-Neon Laser – Equivalence Ratio Fluctuations

**IR Line Candidates.** The Infrared Helium-Neon Laser determined the transition probed for equivalence ratio fluctuation measurements. A strong methane transition overlaps with the emission of an IR He-Ne laser at 3.39 µm. Since the He-Ne laser cannot be wavelength-tuned, this transition must be used. As seen in Figure 5, the methane transition is very strong. Although this allows measurement of very low concentrations of methane, it severely limits the pathlength at higher concentrations. For combustion experiments, with methane concentrations from 4% to 10%, the pathlength was limited to approximately 4 cm to maintain adequate signal to noise ratios.
Figure 5. Methane Transition. The transition at 3392 nm (2948.1 cm⁻¹) was used in this study.

Experimental Hardware. The hardware for methane absorption measurements includes an Infrared Helium-Neon laser, optics, and detectors (Figure 6). The laser (Particle Measurement Systems LHIR-0100-339) operates at 3392 nm with a nominal power of 1.8 mW. Unlike the diode lasers, the He-Ne laser operates at only one wavelength and power. First, part of the beam is split off using a quartz window as a beamsplitter and sent to an InAs detector (Electro-Optical Systems IA-010-H) to monitor power fluctuations. The main beam is collimated with a long-focal length lens (Oriel). Sapphire windows are fused onto the ends of 5/8-inch stainless steel tubes to allow optical access upstream of the flame. The tubes can be moved to adjust the path length. Since the emission of the IR He-Ne corresponds to a very strong methane transition, the path length is limited to 2-3 cm in order to maintain adequate signal to noise ratios. After the beam is sent through the combustor, it is sent to a second InAs detector.
RESULTS AND DISCUSSION

Quantifying Heat Release Dynamics for Turbulent Swirled, Premixed, Lean Flames (Task 1).

Work to date. Currently, the experimental setup for measurements is underway. First, the laminar, flat-flame burner will be modified to allow for optical access. The TDLAS and equivalence ratio measurements will be tested and calibrated on the laminar flame. The turbulent, swirl-stabilized burner must be modified to allow optical access for equivalence ratio measurements. The burner previously used a dynamic swirler, through tangential jets. The new design will incorporate a static swirler. The design, seen in Figure 7, is complete and parts are being machined. A static cell for calibration of the laser diagnostics is also being built, as seen in Figure 8. The static gas cell will be used to measure the absorption of known methane concentrations. Components necessary to complete the unsteady temperature measurements and equivalence ratio measurements are on order. These components include the diode lasers, detectors, and optics.

Figure 6. Methane-Absorption Experimental Setup. A reference detector is used to measure laser power variations.

Figure 7. Turbulent, Swirl-Stabilized Burner: (a) modifications to head, (b) photo of rig.
Workplan (Nov.-May). During the next six months, measurements will be taken on the turbulent, swirl-stabilized combustor. First, calculations must be completed to verify the sensitivity of laser-based diagnostics. Using spectroscopic data from the HITRAN database, the absorbance of the TDLAS and He-Ne systems will be calculated. Software will be developed to process the raw data. A PC-based data acquisition system, based on Labview, will be used to acquire the data. To calibrate the TDLAS system, the data must be fitted, nonlinearly, to spectroscopic parameters. The experimental setup will be completed by January. After calibrating and verifying the measurement system, the response of the heat release rate to perturbations in mass flow rate and equivalence ratio will be acquired for a range of operating conditions (flow rate, equivalence ratio, swirl, fuel composition). The data will be analyzed to determine governing dynamics.

Modeling time Lag and Dispersion of Equivalence Ratio Variations (Task 2).

Work to date. Before beginning work on the turbulent rig, the measurement system will first be verified on a laminar, flat-flame burner. The swirl-stabilized, turbulent combustor, as stated previously, is also currently being modified to allow for measurement of equivalence ratio variations. The modulation system for equivalence ratio fluctuations is under development. Various methods for modulating the equivalence ratio are being considered. CFD model development of the combustor to predict flame location is underway. A commercial code from CFD Research Corporation (http://www.cfdrc.com), CFD-ACE+, is being utilized for the simulations. The software is a beta-version and includes a LES module that has been exclusively developed for combustion modeling. The code includes the following implementations:

- Pressure-based, Finite-volume flow solver – SIMPLEC for pressure-velocity correction, second-order accurate temporal (Crank-Nicholson) and spatial differencing (second order upwinding) schemes, conjugate gradient (CGS) and algebraic multi-grid (AMG) iterative equation solvers
• Multi-block structured and unstructured hybrid grids
• Parallel flow solver – K-way, X-orientation and physics-weighted partitioning methods
• Models for reacting flow systems:
  ▪ Turbulence – Smagorinsky and dynamic subgrid models, LDKM subgrid model
  ▪ Chemistry – advanced chemical mechanisms (steady-state reduced)
  ▪ Turbulence-chemistry interactions – LEM subgrid chemistry modeling, efficient chemical tabulation/retrieval methods (ISAT/Neural Net)

Figure 9 shows a preliminary CFD simulation of velocities in the combustor.

Figure 9. Swirl-Stabilized Burner CFD Model. Velocity and path data will be used to determine time lag.

Workplan (Nov.-May). The design for imposing equivalence ratio fluctuations will be completed in the next couple of months. The design goals include 75% modulation of equivalence ratio and a bandwidth of 500 Hz. As stated in the previous section, designs incorporating rotating valves, high-frequency solenoids, and loudspeakers are being considered. In order to verify the design, the diffusion of methane in air must be simulated. A one-dimensional model of laminar methane diffusion is currently being produced. As design iterations may be necessary, the goal is to have a validated design by March 2002.

High Temperature Acoustics Validation (Task 3).

Work to date. Work in this area has focused on developing simple models to gain familiarity with ABACUS software, as well as validate the process.
**Workplan (Nov.-May).** Guidelines for the sharing of geometrical data will be developed. To integrate CFD and FEA models, a standard “analysis geometry” must be conceived. During this work period, models will be developed for the gaseous turbulent combustor.

**Premixed Flame Stabilization and Lean Blowoff Limits (Task 4).**

**Work to date.** A literature review has been completed to determine the physical parameters effecting lean blowoff (LBO).

**Workplan (Nov.-May).** The stability limits of the swirl-stabilized, turbulent combustor will be mapped, both with and without excitation. Equivalence ratio fluctuations will be measured through methane absorption of an IR He-Ne laser in the excited case. Laser diagnostics will be used to determine the dynamics of heat release rate near the lean blowoff limits. LBO experiments will be conducted after May 2002.

**Prediction of Combustor Instabilities and Dynamic LBO (Task 5).**

**Work to date.** Work on this task will commence in year 2.

**Workplan (Nov.-May).** The task hinges on reduced-order models of combustion subsystems and requires mean temperature and velocity profiles from CFD simulations and FEM acoustic models. Thus, work on this task will progress after May 2002.

**Simultaneous Control of Flame Stabilization and Thermoacoustic Oscillations (Task 6).**

**Work to date.** The VACCG has developed active control algorithms that will be used to control fuel modulation. Future work on this task will commence in year 2.

**Workplan (Nov.-May).** This task is dependent on the completion of Tasks 1-5. Thus, work on this task will take place in year 2.

**CONCLUSION**

Work during the reporting period was mostly preparatory in nature as a result of the project starting on August 22, 2002 (for that reason the subcontract was not charged stipends, which equals the 7% funding returned to SCIES-UTSR). The preparations in the areas of optical diagnostics for combustion dynamics, reduced-order modeling of combustors, and variable-property acoustic modeling of combustion systems will all lead to significant and practically implementable measurement and modeling techniques, for unsteady combustion systems. This statement is based on the late date of submission of this report. Once techniques have been verified on turbulent lab combustors, they will be tested at NETL and industry.
REFERENCES


Bibliography

Laser Diagnostics


Chemiluminescence


Lean Blow-out


**Combustion Instabilities**


**Equivalence Ratio Fluctuations**


Acoustics


List of Acronyms and Abbreviations

CAD  Computer-Aided Design
CFD  Computational Fluid Dynamics
FEA  Finite Element Analysis
He-Ne  Helium-Neon
IR  Infra-red
LBO  Lean BlowOff
NETL  National Energy Technology Laboratory
p’  pressure perturbation
TEC  Thermo-Electric Cooler
TDLAS  Tunable Diode Laser Absorption Spectroscopy
u’  velocity perturbation
VACCG  Virginia Active Combustion Control Group
INTRODUCTION

The objective of this project is to evaluate and develop prediction techniques for the internal cooling of turbine blades based on time-accurate methods. The project plan calls for a systematic evaluation of these methods in different flow regimes encountered in the cooling passages, namely, fully-developed conditions, developing flow conditions, and flow and heat transfer in 180 degree bends. The initial geometry chosen for evaluation of different techniques is a square duct with normal ribs of $e/D = 0.1$ and $P/e = 10$ at a nominal bulk Reynolds number of 20,000. This geometry, together with the action of Coriolis and buoyancy forces, contains all the essential elements for testing and evaluation. There are no fundamental shortcomings in the techniques used and implemented which prevent the simulation of other geometries such as angled or profiled ribs, pin fins, impingement cooling, etc.

The initial focus has been on the fully developed regime. Initial steps are being taken to stage the developing flow, and flow in the 180 degree bend calculations, which need data from other auxiliary calculations as boundary conditions. In the fully developed regime, several calculations have been initiated with and without rotation, two of which are reported in detail in this report. The purpose of these calculations is to evaluate the prediction accuracy of sub-grid shear stress models. These were preceded by a number of trial calculations. Additional calculations with rotation and Coriolis forces are in progress. The inclusion of centrifugal buoyancy forces into code GenIDLEST has been implemented, and preliminary calculations with centrifugal buoyancy effects have been attempted.

EXPERIMENTAL

Computational Method

GenIDLEST (Generalized Incompressible Direct and Large-Eddy Simulations of Turbulence) is a computer program developed for application to turbulent flows in complex geometries. It utilizes a nonstaggered finite-volume mesh with Cartesian velocities and temperature as the primary dependent variables. A fractional-step algorithm, with explicit as well as semi-implicit time advancement, is used. It uses both, Message Passing Interface (MPI) and OpenMP for parallel execution. Full details about GenIDLEST are described in Tafti [2001]. Here we give a brief overview.

GenIDLEST solves the incompressible Navier-Stokes and energy or temperature equations. The transformed non-dimensional time-dependent incompressible Navier-Stokes and the energy equations are written in conservative form as1:
Continuity:
\[
\frac{\partial}{\partial\xi_j}\left(\sqrt{g} U^j\right) = 0
\]  
(1)

Momentum:
\[
\frac{\partial}{\partial t}\left(\sqrt{g} u^i\right) + \frac{\partial}{\partial\xi_j}\left(\sqrt{g} U^j u_i\right) = -\frac{\partial}{\partial\xi_j}\left(\sqrt{g} \left(\alpha^j, P\right)\right) + \frac{\partial}{\partial\xi_j}\left(\frac{1}{\Re} \sqrt{g} g^{ik} \frac{\partial u_i}{\partial\xi_k}\right) + s_{gs} + \sqrt{g} S_{u_i}
\]  
(2)

Energy:
\[
\frac{\partial}{\partial t}\left(\sqrt{g} T\right) - \frac{\partial}{\partial\xi_j}\left(\sqrt{g} U^j T\right) - \frac{\partial}{\partial\xi_j}\left(\frac{1}{\Pr \Re} \sqrt{g} g^{ik} \frac{\partial T}{\partial\xi_k}\right) + s_{gs} + \sqrt{g} S_{T}
\]  
(3)

where \(\tilde{a}^i\) are the contravariant basis vectors, \(\sqrt{g}\) is the Jacobian of the transformation, \(g^{ij}\) is the contravariant metric tensor, \(\sqrt{g} U^j = \sqrt{g} (\tilde{a}^i) u_i\) is the contravariant flux vector, \(u_i\) is the Cartesian velocity vector, \(T\) is the temperature, \(S_u\) and \(S_T\) are the source terms in the momentum and energy equations, respectively. Here \(s_{gs}\) denotes a subgrid scale stress model or a RANS model as the case may be.

---

1. Henceforth, all usage is in terms of non-dimensionalized values.

2. The notation \(\tilde{a}^i_j\) is used to denote the \(j\)th component of vector \(\tilde{a}^i\), \(\tilde{a}^i_j = \partial \xi_j / \partial x_i\)

Eqns. (1-3) are solved using an overlapping multi-block structured mesh topology. In each block, the equations are mapped from physical \((\tilde{x})\) to logical/computational space \((\xi)\) by a boundary conforming transformation \(\tilde{x} = \tilde{x}(\xi)\), where \(\tilde{x} = (x, y, z)\) and \(\xi = (\xi, \eta, \zeta)\). Inter-block connectivity can be structured (\(\xi^+\) face adjoining a \(\xi^-\) face) or unstructured. In an unstructured inter-block topology a \(\xi^-\) face boundary can adjoin a \(\eta\) or \(\zeta\) face with arbitrary axes orientations.

GenIDLEST can handle non-matching or non-conformal boundary interfaces, i.e., there does not have to be a one-to-one correspondence between meshes of adjoining block faces. This allows additional flexibility in meshing complex domains and can also be used for local refinement. In such cases dependent variables have to be interpolated between faces. For this purpose, bilinear interpolation functions are used together with integral conservation of mass, momentum, and energy fluxes. The fluxes are conserved globally (over face) versus local, which would constrain the generality of the nonmatching interfaces. Since the gradient of pressure is the driving force, it, instead of pressure, is conserved across non-matching interfaces. The multiblock framework provides a natural framework for parallelization. Depending on the total number of blocks and processors, each processor is assigned multiple blocks. Further within each block, “virtual cache blocks” are used. The “virtual” blocks are not explicitly reflected in the data structure but are used only in the solution of linear systems. The motivation to construct much smaller “cache” blocks is to extract performance on cache based hierarchical memory systems. These small “cache” blocks form the basic computing units for preconditioning linear
systems. Hence, underneath the coarse grained parallelism of MPI processes, there exists additional parallelism across multiple blocks, or across the mesh nodes in each block, and across the multiple cache blocks. Hence, GenIDLEST is instrumented for coarse-grained parallelism with MPI and for embedded or fine grained parallelism with OpenMP.

The governing equations are discretized with a conservative finite-volume formulation. In nonorthogonal coordinate systems, there are a number of choices in the selection of the grid topology and the dependent variable in the momentum equations. In GenIDLEST, we adopt a non-staggered grid topology with Cartesian velocities as dependent variables. The Cartesian velocities, pressure and temperature are calculated and stored at the cell center, whereas contravariant volume fluxes are stored and calculated at the cell faces. The convection term can be approximated in a number of different ways. Presently, there are two basic approximations, second-order central difference, and the third-order upwind biased approximation to calculate the cell face values. These two approximations can either be used in their basic form or combined with TVD criteria to preserve monotonicity of the convected variable. The TVD criteria is applied to the convected variable during the predictor step at time level \( n \) to obtain the intermediate velocity \( \bar{v} \). In addition to the TVD limiter, a multi-dimensional flux limiter [Thuburn, 1996] is also implemented. The flux limiter is based on the less restrictive universal limiter proposed by Leonard [1991]. In this scheme, the intermediate velocities are first calculated with the base approximations and then checked for monotonicity in a multidimensional framework. Two subgrid-scale stress models are available at this time; the Smagorinsky [1963] and the dynamic Smagorinsky model [Germano, et al., 1991]. Additionally several high and low \( Re \)-number RANS models; based on the \( k-\varepsilon \) model [Wilcox, 1988; Wilcox, 1994; Wilcox, 1998; ] and Mentor’s [1993] models are also available.

A variety of boundary conditions are available in GenIDLEST and are specified individually for each computational block. With the exception of periodic or inter-block boundaries, each boundary face can have multiple boundary conditions assigned to it.

(a) Periodic or inter-block boundaries: Both these boundaries precipitate the same action, which involves exchanging boundary information between adjacent faces. For unstructured block connectivity and/or non-conformal interfaces, the boundary information is filtered by coordinate rotations and interpolations as required. Coordinate rotations and interpolation factors are calculated at the beginning of each run.

(b) Wall boundary: When the velocity normal to the boundary is zero or there is no influx (outflux) of mass, the boundary is specified as a wall. Wall boundaries can have slip velocities imposed on them and temperature or heat flux (gradients) specified.

(c) Inlet boundary: When there is known net influx (outflux) of mass from the boundary, it is specified as an inlet. Only temperature can be specified at this boundary.

(d) Outflow boundary: Outflow boundaries use a convective boundary condition in which the dependent variable is allowed to convect out of the domain. Both temperature and heat flux can be specified.

(e) Symmetry boundary: At this boundary, the normal velocity, and gradients of tangential velocities and temperature are set to zero.

(f) Pressure boundary: Pressure and not velocity is specified at this boundary. The velocities are derived from the flow generated by the pressure.

For increased flexibility in meshing, internal blanked zones or solid obstacles can also be specified in each computational block. Boundary conditions on these regions use Dirichlet conditions on velocities, including suction or blowing. Temperature or heat flux can be specified.
The discretized continuity and momentum equations are integrated in time using a projection method. The temporal advancement is performed in two steps, a predictor step which calculates an intermediate velocity field, and a corrector step which calculates the updated divergence free velocity at the new time step. The predictor step can be fully explicit in time or semi-implicit, in which the viscous terms are treated implicitly. Both methods are incorporated in GenIDLEST. The semi-implicit method is useful for low Reynolds number flows (large effective viscosities) by allowing larger time steps than what would be allowed by the viscous stability condition. The corrector step, uses the continuity equation to formulate the pressure equation. The computed pressure is then used to update the intermediate velocity field.

The linear system generated in the solution of the pressure equation and the implicit treatment of viscous terms is non-symmetric on non-orthogonal meshes. Further, the presence of non-conformal or non-matching boundaries creates additional strong non-symmetries. In GenIDLEST, we use Krylov methods based on the method of Conjugate Gradients (CG) for symmetric systems and BiCGSTAB or GMRES(m) for non-symmetric systems. These are coupled with preconditioners based on a two-level Additive Schwarz domain decomposition (DD) method [Wang and Tafti, 1998a-b, 1999].

GenIDLEST is very portable between different computer architectures and compilers. It has a front end Java AWT/Swing interface for the creation of input files. A number of post-processing utilities are present, including the ability to obtain mean and turbulent statistics in a distributed computing environment, time-dependent data dumps for analysis and visualization, and vortex identification techniques based on the \( \text{v} \) [Chong et al., 1990] and \( \lambda_2 \) method [Jeong & Hussain, 1995] are also available.
Fully Developed Flow and Heat Transfer Assumption

In a fully-developed flow and heat transfer model, a periodically repeating spatial unit consisting of two ribs (one on either side of the duct) is simulated. This is shown in Fig. 1. The duct walls as well as all six faces of the two ribs exposed to the main flow are heated by imposing a constant heat flux ($q''$) boundary condition. The governing flow and energy equations are non-dimensionalized by a characteristic length scale which is chosen to be the hydraulic diameter of the channel ($D_h$), a characteristic velocity scale given by the friction velocity $u_\tau = \sqrt{\frac{fD_h}{2}}$, and a characteristic temperature scale given by $q''D_h^2/k$. The assumed periodicity of the domain in the streamwise or x-direction requires that the mean gradients of pressure and temperature be isolated from the fluctuating periodic component as follows:

$$P(x,t) = P_\infty - u_\tau x + p(x,t)$$
$$T(x,t) = T_\infty + \gamma x + \Theta(x,t)$$ (4)

On substitution, Eqs. (2-3) take the following form:

Momentum:

$$\frac{\partial}{\partial \xi} \left( \sqrt{g} U \phi \right) + \frac{\partial}{\partial \eta} \left( \sqrt{g} U' \phi \right) = -\frac{\partial}{\partial \xi} \left( \sqrt{g} (\phi^j U) \Phi^j \right) + \frac{\partial}{\partial \eta} \left( \frac{1}{\Re} \sqrt{g} \Phi^\alpha \frac{\partial \phi}{\partial \xi} \right) + \sqrt{g} \beta \Phi$$ (5)

Energy:

$$\frac{\partial}{\partial \xi} \left( \sqrt{g} \theta \right) + \frac{\partial}{\partial \eta} \left( \sqrt{g} \theta' \phi \right) = \frac{\partial}{\partial \xi} \left( \frac{1}{Pr \Re} \sqrt{g} \Phi^\alpha \frac{\partial \theta}{\partial \xi} \right) + \sqrt{g} \gamma \Phi$$ (6)

In the calculations, $\beta$ is assumed to be unity, whereas $\gamma$ is calculated from a global energy balance as: $\gamma = q'' \Omega / \Re \Pr \Omega x L_c$. The boundary conditions imposed on the duct walls and the ribs are as follows:

$$\hat{n} = 0$$
$$\nabla p \cdot \hat{n} = 0$$
$$\nabla \Theta \cdot \hat{n} = 1 - \nabla \Theta \cdot \hat{n}$$ (7)

and in the streamwise direction as:

$$\phi(x + L_c) = \phi(x)$$

Experimental Method (K. Thole)

Since August, the work that has been conducted with regards to this task include the following: a) review of the literature on designs of internal cooling test sections; b) contacting industry to find out the needs for data on internal cooling methods.

The primary geometry being considered for these tests includes a ribbed channel with a developing section, a fully-developed section, a 180° bend, and a return leg. The channel aspect ratio is one but, to allow for future testing, larger aspect ratios are also being considered. Although the primary goal of this work was only to conduct flow field measurements, we are also pursuing methods for measuring heat transfer coefficients to allow for a more complete data set. Our goal for the next reporting period is to provide a complete design for the test rig.
RESULTS AND DISCUSSION

Our objective is to evaluate and develop techniques based on the time-accurate resolution of these flows. Large-Eddy Simulation (LES), by resolving only the energy containing eddies reduces the computational complexity of Direct Numerical Simulations (DNS) by several orders of magnitude. However, the application of LES to complex flows still remains elusive for a number of reasons. Chief among them is the high computational cost. However, with the exponential increase in computational power in the last decade, the computational barrier is being lowered dramatically.

There are a number of approaches one could follow to perform LES, and which have seen varied use. In one approach, explicit subgrid stress models are used to model the unresolved subgrid stresses. Another is to approach the problem from the point of view of a quasi-DNS or LES with no subgrid scale modeling. The third approach is the use of Monotonic Integrated Large-Eddy Simulations (MILES).

These methods have been used in the past in varied forms and combinations mostly for hydrodynamic calculations. Our objective is to perform a systematic study of the different approaches to LES, particularly for demanding heat transfer applications encountered in internal cooling flows, and shed light on the accuracy and suitability of different methods. Here we present results for two calculations performed with a second-order central differencing scheme and without the use of any subgrid stress models. Two mesh resolutions, 128 x 128 x 128 and 96 x 96 x 96 are evaluated for a nominal bulk Reynolds number of 20,000 in a square channel with normal ribs with $e/D_h=0.1$ and $P/e =10$. The results are compared extensively with the hydrodynamic and heat transfer data of Rau et al. [1998] \(^3\). The experimental conditions are somewhat different than the present computational study but provide the only source of hydrodynamic and turbulence measurements in the literature. Their results for a bulk Reynolds number of 30,000 in a 2-sided ribbed duct with $P/e = 9$, $e/D_h = 0.1$ is used for comparison. Unheated ribs are used in the experiments, whereas the ribs are heated in the computations.

Besides the two calculations reported here, calculations with nominal rotation numbers of 0.6, 0.3 and 0.15 are ongoing. Calculations evaluating the effect of subgrid scale stress modeling and non-heated are also in progress.

Mean Flow Characteristics

Fig. 2 shows the mean streamline pattern in the center of the duct ($z=0.5$) for the two mesh resolutions. The flow is nominally two-dimensional in the symmetry plane. Both meshes reproduce the recirculation zones observed at the leading edge of the rib-wall junction, in the rib wake, and on top of the rib. Reattachment in the wake of the rib occurs at $4.6e$ and $4.8e$ downstream of the trailing edge of the rib. This compares favorably with the values between $4e$ and $4.5e$ observed by Rau et al. The recirculation zone upstream of the rib extends about $0.7-0.8e$. Rau et al. reported a value between $1.0-1.5e$.

In the vicinity of the smooth walls ($z=0.0$) the flow field becomes strongly three-dimensional with mean cross flow velocities ($w_b$) approaching 30% of the mean streamwise velocity ($u_b$). Fig. 3 shows contours of $w_b$ in a plane $z=0.05$ in the vicinity of the smooth wall. Strong cross flow components are seen to occur. Of particular interest is the high lateral velocity
moving towards and impinging on the smooth wall in the shear layer which forms and separates at the leading edge of the rib. The lateral velocity impinges on the smooth wall augmenting the heat transfer coefficient. This phenomenon was also observed by Rau et al. On the other hand there is net movement away from the smooth wall in the recirculation zone downstream of the rib.

Fig. 4(a-b) compares the $x$-distribution of streamwise ($ub$) and cross-stream velocity ($vb$) in the symmetry plane ($z=0.5$) at $y=0.1e$ and $y=1.0e$, respectively, with the measurements of Rau et al. The predicted streamwise velocity clearly shows the existence of the leading edge eddy at the rib-wall junction, the recirculation zone behind the rib, and the counter-rotating eddy which forms immediately downstream of the rib. The cross-stream velocity increases rapidly as it approaches the rib. Considering the differences in geometry and Reynolds number, the comparisons are quite good.

**Turbulent Statistics**

Contours of $urms$ in the symmetry plane $z=0.5$ are shown in Fig. 5(a-b). For comparison, results from both calculations are plotted. $urms$ is maximum in the separated shear layer at the leading edge of the rib with values between 45 to 50%. It is lowest in the stagnating flow at the rib and in the recirculation region immediately behind the rib. In the boundary layer on the ribbed wall, $urms$ maintains a peak value between 20 to 25% over most of the ribbed surface. Rau et al. report maximum values of 35% in the shear layer behind the ribs and 14% at the centerline, which compare very well with the predictions.

We observe some differences in the predicted magnitudes of $urms$ between the two mesh resolutions. In general, the finer mesh resolves the separated shear layer with more accuracy and predicts larger intensities in the shear layer and lower intensities at the center of the channel. The tendency to underpredict on the coarse mesh also manifests itself in the other directional components. However, the differences are smaller and less evident.

The transverse fluctuations $vrms$, plotted in Fig. 6(a) exhibit values of 25-27% in front of the rib as well as in the separated shear layer downstream of the rib. The predicted values compare very well with a maximum of 24% observed by Rau et al. in the shear layer and between 10-11% at the center. Fig. 6-b plots comparisons of $vrms$ with Rau et al. along the streamwise direction at a distance $y = 0.3e$ from the ribbed wall. About one rib height upstream of the rib, there is a sharp increase in the cross-stream fluctuations, which reaches a maximum of 25% at the rib surface. Downstream of the rib, the fluctuations recover from 10% to a maximum of 20% in the middle of the recirculation zone after which they decay.

Similar to $vrms$, $wrms$ plotted in Fig. 7 exhibits a maximum values of 44% at the top leading edge of the rib. The large intensities are a result of the highly unsteady flow dynamics in this region caused by the unsteady eddies which form at the junction of the rib with the wall and the unsteady nature of the shear layer which periodically forms and sheds vortices from the leading edge of the rib. Both of these phenomena are responsible for the large transverse and lateral fluctuations. The lateral fluctuations are also high in the shear layer downstream of the rib with intensities of 32%.

**Heat Transfer Augmentation**

Fig. 8 shows the Nusselt number ratios ($Nu/Nu0$) for the fine and the coarse mesh. For comparison, we include results from Rau et al. In general, the distribution and the augmentation...
of Nusselt numbers is captured with more fidelity on the finer mesh, which has higher values of augmentation. However, there are no fundamental structural differences in the results between the two meshes.

On the ribbed wall, the heat transfer reaches a maximum in front of the rib and is caused by the highly unsteady eddies induced in this region. The induced vorticity provides enhanced mixing and increases the heat transfer coefficient. Immediately downstream of the rib, the flow is not very energetic as can be surmised from the turbulence intensities, and consequently, there is minimal augmentation. Further downstream, in the main recirculation zone, the augmentation increases and reaches a maximum at 3.3e downstream of the rib. The region of maximum heat transfer occurs where vortices from the separated shear layer “touch down,” and in the mean coincides not so much with the mean reattachment but rather with the region of maximum surface shear, which usually lies upstream of the reattachment point [Tafti, 1993]. It is noted that augmentation on the ribbed wall decreases as we approach the side (smooth) walls. Comparison with the measurements of Rau et al. (for \( P/e = 9 \)) in Fig. 8(c) shows good agreement in the general trends, but the calculations underpredict the Nusselt number.

On the smooth wall there is a strong correlation between the shear layer which forms on the rib and the region of large augmentation. This region also coincides with the lateral movement of fluid which impinges on the wall as shown in Fig. 3. Moving out further from the ribbed wall, the augmentation decreases to 1.2 in the center plane of the duct. On comparison with Rau et al., large differences are observed at the center of the channel. In the experiments, augmentation values as high as 1.8-1.9 are sustained at the center of the duct, whereas the computational values quickly drop to 1.2 at the center. Another fundamental difference is the large augmentation obtained behind the rib (2-3) in the experiments versus the computed values which are less than 1. We also note that mesh resolution does not seem to be a factor for both of these observations, and the finer mesh makes very little or no difference in the augmentations. Fig. 8(d) plots a comparison at \( x = 0.5e \) upstream of the rib on the smooth wall. At this location, the predicted Nusselt numbers are uniformly underpredicted across the height.

On the rib itself, the heat transfer coefficient is maximum at the top leading edge with values as high as 5. Near the junction with the ribbed wall the augmentation decreases to 2.0. On the top surface of the rib, a maximum augmentation between 3-3.25 is obtained. On the trailing side of the rib, the augmentation varies from a factor of 2 to less than 1.

**CONCLUSION**

Our overall objective is to evaluate time-accurate prediction techniques of heat transfer in the internal cooling of turbine blades. LES results are presented in a square channel with normal ribs for two mesh resolutions of 963 and 1283. Both calculations utilize a second-order central difference scheme without any explicit subgrid scale modeling. Mean flow, turbulence, and heat transfer results are compared with the experiments of Rau et al.

Both calculations reproduce the major flow structures with fidelity; namely the eddy formed at the junction between the rib and the wall, a recirculation zone formed on top of the rib, and the recirculation zone behind the rib with the corner eddy. Comparison of mean flow and turbulence quantities with experiments shows excellent agreement. To the best of our knowledge, detailed results of the spatially varying turbulence have not been reported in the past.
Table 1 summarizes the component and overall heat transfer augmentation obtained from the calculations. These are compared to the data of Rau et al. at \(Re=30,000\) and \(P/e = 10\). The fine mesh calculation predicts Nusselt numbers which are more in line with those observed experimentally. However they are still underpredicted by 15%.

A Similar trend is found in the prediction of the friction factor, which is underpredicted by 24% on the fine mesh. On the other hand, the calculated friction factor agrees very well with the correlation of Han [1984]. We note that the friction factor is extremely sensitive to the calculated time-averaged bulk velocity; a 10% error in bulk velocity translates to a 20% error in \(f\).

It is not known how much the heated ribs in the computations (versus nonheated in the experiment) contribute to this deficiency. It is conceivable that non-heated ribs would augment the heat transfer coefficient on the smooth walls at the junction with the rib, because the shear layer and the lateral flow impingement will not be thermally saturated as the case would be if the rib were heated. Also the separated shear layer and vortices that impinge on the ribbed wall could have a larger effect on the heat transfer coefficient if the ribs were not heated. There is some evidence in the literature that unheated ribs could at least lead to a 10% augmentation in the heat transfer coefficient on the ribbed surface [Boyle, 1984]. However, it seems more likely that the underprediction of both the friction factor and Nusselt number is linked to the absence of a suitable subgrid scale stress model. Early indications with the use of a suitable subgrid scale stress model indicate that indeed this is the case.

REFERENCES


Table 1. Summary of heat transfer and friction data and percentage error with data of Rau et al.

<table>
<thead>
<tr>
<th></th>
<th>Computations</th>
<th>Rau et al. ( e/D_b=0.1, P/e = 10, )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>96 (^3)</td>
<td>128 (^3)</td>
</tr>
<tr>
<td>( Nu / Nu_a )</td>
<td>( (Nu_a = 0.023 \cdot Re_a^{0.8} \cdot Pr^{0.3}) )</td>
<td></td>
</tr>
<tr>
<td>rib</td>
<td>2.22 (26%)</td>
<td>2.54 (17%)</td>
</tr>
<tr>
<td>Smooth wall</td>
<td>1.78 (32%)</td>
<td>2.00 (17%)</td>
</tr>
<tr>
<td>overall</td>
<td>1.67 (24%)</td>
<td>1.89 (14%)</td>
</tr>
<tr>
<td>( f/f_a )</td>
<td>( f_a = 0.046 \cdot Re_b^{0.2} )</td>
<td></td>
</tr>
<tr>
<td>overall</td>
<td>6.11 (36%)</td>
<td>7.23 (24%)</td>
</tr>
</tbody>
</table>

Fig. 1: One-fourth of full computational domain. The full extent of the domain is 1.0 in all three directions. Flow is from left to right.
Fig. 2: Mean streamline distribution in the z-symmetry plane. Reattachment occurs between 4.6-4.8e downstream of rib. The leading edge eddy extends between 0.7-0.8e upstream.
Fig. 3: Lateral or spanwise flow velocity ($w_\beta$) in the vicinity of the smooth wall. Flow impingement on the smooth wall contributes to the high Nusselt numbers in this region.
Fig. 4: Comparison of predicted mean velocity profiles with data of Rau et al. at $P/e = 9$ and $Re_x=30,000$. (a) Streamwise velocity at $y/e=0.1$. (b) Cross-stream velocity at $y/e = 1.0$. 
Fig. 5: Rms distribution of streamwise fluctuations ($u_{rms}$) at the z-plane of symmetry. Maximum values occur in the separated shear layer near the separation line.
Fig. 6: Rms distribution of cross-stream fluctuations ($v_{rms}$) at the plane of symmetry. Maximum values occur in the separated shear layer. The leading edge of the rib also exhibits high values. (b) Comparison with experiments at $P/e=9$ and $Re_e=30,000$ at $y/e = 0.3$. There is a sharp increase in intensity as the flow approaches the leading edge.
Fig. 7: Rms distribution of lateral fluctuations ($w_{rms}$) at the plane of symmetry. Maximum values occur in the vicinity of the rib leading edge. Note that the mean component is nominally zero at symmetry plane.
Fig. 8: Maps of Nusselt number on ribbed wall, smooth wall and ribs for (a) $96^3$ mesh; (b) $128^3$ mesh; comparison with experiments of Rau et al. with $Re=9$ on (c) ribbed wall at symmetry plane, $y=0, z=0.5$ (d) smooth wall at $e/2$ upstream of rib, $z=0.0, x=0.4$. Experimental values are uniformly higher than computations on smooth wall.
INTRODUCTION

The primary goal of this research is to advance accelerated testing methods for cyclic oxidation, erosion, and hot corrosion tests of interest to the gas turbine and coating manufacturing industries. Emphasis is on the study of fundamental mechanisms controlling coating degradation and matching these mechanisms in industry standard and accelerated tests. The mechanisms of cyclic oxidation are being systematically studied via imaging of oxide and interface structures, mechanics models of interface decohesion, and stress and toughness measurements of coating systems as a function of exposure. The PIs are working closely with National Laboratories in conducting the research and with industrial collaborators to transition their findings to the coating and gas turbine industries, where the current standard is to perform time and cost-intensive burner rig tests to quantify coating durability. As the project proceeds, studies will be extended to erosion/foreign object damage and hot corrosion. The test results are being used in an attempt to develop a life prediction protocol.

The project team members and their areas of responsibility are as follows. Professors Pettit and Meier of the University of Pittsburgh are leading the effort and performing corrosion studies and acoustic emission and x-ray diffraction experiments. Professor Beuth of CMU is performing indentation and impact tests and fracture mechanics analysis. Professor Scott Mao is exploring the possibility of making A.C. impedance measurements. Dr. Michael Lance of ORNL is performing piezospectroscopic stress measurements and Dr. William Ellingson of ANL is performing optical backscatter experiments. Dr. William Fuller of NIST will attempt to model the degradation modes using the input from the various experiments. Dr. Kenneth Wright of GE Aircraft Engines will perform some of the erosion/foreign object damage experiments. Specimens are being prepared by Praxair and Howmet. GE will provide input on testing conditions for the various degradation modes.

EXPERIMENTAL

The initial focus of this project has been on developing techniques for accelerated cyclic oxidation testing and measuring the fundamental properties of coatings systems that control oxide adherence. The coating systems studied consist of alumina scales grown on nickel superalloy substrates, coated superalloys, and analogous thermal barrier coating (TBC) systems that contain an alumina scale. Both types of coating systems typically include an oxidation-resistant bond coat, which is deposited onto the superalloy substrate.

Materials

Two nickel-base single-crystal superalloy substrates are being studied: René N5 and CMSX-4.

Four coatings on these substrates will be studied. These are:

- A NiCoCrAlY Overlay Coating
- Diffusion Aluminide and Platinum-modified Aluminide Coatings
A TBC with NiCoCrAlY Bond Coat
A TBC with Platinum-modified Aluminide Bond Coat

Evaluation Techniques

Destructive

Cyclic Oxidation Experiments

Cyclic oxidation exposures are being performed in two furnaces, a bottom-loading furnace and a vertical tube furnace, in laboratory air. The initial exposures have involved one-hour cycles between 1100°C and approximately 35°C. Failure of the TBC-coated specimens is taken as the time at which a significant amount of the TBC has separated from the substrate. Failure of the specimens without TBC coatings is taken as the time at which the mass change of the specimen reaches negative values.

Indentation Tests

Indentation tests [1, 2] are also being performed on the specimens. The test, shown schematically in Figure 6, consists of indenting the TBC system with a Brale type conical indenter (a Rockwell hardness tester or mechanical testing machine can be used for this purpose). The indenter penetrates the TBC and thermally grown oxide (TGO) layers and plastically deforms the metallic bond coat and substrate below. This deformation in the substrate increases the stored elastic strain energy in the TGO and TBC layers which results in the axisymmetric debond.

![Figure 6. Schematic diagram of the indentation test.](image)

Nondestructive

Stress Measurement by X-ray Diffraction

The stresses in the oxide films grown on specimens without TBCs are being measured by x-ray diffraction (XRD). The stress normal to the free surface of a film is usually assumed to be zero. Neglecting shear stresses, the resulting biaxial stress can be expressed quite simply for an isotropic elastic medium, as described by Noyan and Cohen [3]. The quantities measured are strains, which can be measured by XRD as a change in lattice spacing with inclination with respect to the surface of a sample. This strain is usually expressed as:
\[ \varepsilon_{\phi\Psi} = \frac{d_{\phi\Psi} - d_o}{d_o} \] (1)

in which \(d_o\) is the stress-free lattice spacing of the selected (hkl) planes and \(d_{\phi\Psi}\) is the lattice spacing of these (hkl) planes for a given tilt \(\Psi\). It can be shown that this strain is expected to be proportional to \(\sin^2 \Psi\). For a biaxial stress in the irradiated layer, equation 1 can be expressed as [3]:

\[ \frac{d_{\phi\Psi} - d_o}{d_o} = \frac{1 + \nu}{E} \sigma_\phi \sin^2 \Psi - \frac{\nu}{E} (\sigma_1 + \sigma_2) \] (2)

If the \(\sin^2 \Psi\) curve is linear, as is expected from an isotropic surface layer which is polycrystalline and not textured, the stress in any direction \(\phi\) can be calculated from \(E, \nu, \) and \(d_o\). It is measured from the slope of the \(d\) vs. \(\sin^2 \Psi\) line. This is the well known \(\sin^2 \Psi\) method. Often the lattice spacing at \(\Psi = 0\) is substituted for the unstrained value, with little error since it is in the denominator of the expression for the strain.

Capabilities have been developed at the University of Pittsburgh in four XRD stress measurement methods. These methods are the classical tilting and rocking techniques, which are equivalent and are based on the determination of the \(\sin^2 \Psi\) curves. In the third method, the tilting method has been extended to thinner films by the use of fixed low incidence techniques. An XRD machine with an open Eulerian cradle provides the tilting of the specimen in symmetrical diffraction (“classical” method) or asymmetric diffraction with fixed low incidence. The rocking technique is performed on a powder machine. The powder machine and the dual arm are also used with a hot stage.

The design of the powder machine and the hot stage make it desirable that the specimen be nearly horizontal during high temperature experiments. For this purpose a new fixed (low) incidence XRD technique, the fixed incidence multiplane method (FIM), using more than one set of (hkl) planes has been developed. Usually for residual stress measurements, one (hkl) plane is tilted (or rocked) in order to measure the strain at various angles to the surface. With fixed incidence and a fixed specimen, diffraction occurs for different sets of (hkl) planes with different inclinations with respect to the surface thus providing the equivalent of the tilting or rocking in other methods.

The four methods have been tested at room temperature and shown to give equivalent results. They have already been used for the measurement of residual stresses in chromia and alumina scales. The room temperature data are well behaved i.e. the \(\sin^2 \Psi\) plots are good straight lines with no splitting or oscillation [4-6]. Results for alumina scales on FeCrAl alloys are in close agreement for the calculated residual stresses with data obtained by piezospectroscopy [5]. The FIM method has been shown capable of application to the measurement of growth stresses at temperatures to 1100\(^\circ\)C while still maintaining the advantages of the \(\sin^2 \Psi\) analyses of the diffraction data [5].
Stress Measurement by Piezospectroscopy

Stresses in the alumina scales formed on specimens with and without TBCs are being measured by piezospectroscopy by Dr. Michael Lance at ORNL. Aluminum oxide formed by high temperature oxidation invariably contains a minor concentration of chromium, either as a result of it being an alloying addition or as an impurity in the alloy. On oxidation, chromium is incorporated as Cr\(^{3+}\) into the aluminum oxide crystal structure, substituting for Al\(^{3+}\) and occupying an octahedral site. When appropriately stimulated, for instance with a laser beam or an electron beam, the chromium ion luminesces, emitting two particularly intense, narrow lines, the R\(_1\) and R\(_2\) lines. In the absence of any strain, the R\(_1\) and R\(_2\) lines have energies of 1.790 and 1.794 eV at room temperature.

When aluminum oxide is strained, the oxygen octahedra around the Cr\(^{3+}\) are distorted which, in turn, alters the crystal field of the d\(^3\) electrons in the Cr\(^{3+}\) ions and thereby the energies of the R\(_1\) and R\(_2\) lines. The shift in energy of the luminescence spectrum with strain is termed the piezospectroscopic effect. For small strains, the shift in the R lines can be written phenomenologically in terms of the stress as:

\[
\Delta \nu_{\text{stress}} = \Pi_{ijkl} \sigma_{ij} \]

where \(\Delta \nu\) is the shift, expressed as a frequency, \(\sigma_{ij}\) is the stress and \(\Pi_{ijkl}\) is the piezospectroscopic tensor. When the stress is a hydrostatic pressure, the frequency shift is linearly related to the pressure and the equation reduces to the well-known equation used in the high pressure community to monitor the pressure in high pressure, diamond anvil cells:

\[
\Delta \nu = \Pi_{ij} \sigma_{ij} \]

Since the frequency shift is related through equation 3 to the stress, equation 3 can be inverted so as to determine the stress from a measurement of the frequency shift. This is the basis of the piezospectroscopic measurement of stresses in alumina films proposed in this work.

In the technique pioneered by Prof. D. R. Clarke at UCSB [7], an optical probe is used to excite the R-line luminescence and the luminescence is recorded from all the Cr\(^{3+}\) ions within the probed volume. Thus, the measured frequency shift is the integration of the frequency shifts from the individual Cr\(^{3+}\) ions and the local stress within the probed volume. In addition, for polycrystalline materials, the probed volume, if it is larger than the grain size, also includes different orientations of the Cr-O octahedra. As a result, it can be shown that the measured frequency shift is related to the average stress within the probed volume as:

\[
\overline{\Delta \nu} = \Pi_{ii} \langle \sigma_{ii} \rangle \]

An important feature of equation 4 is that the frequency shift is related to the trace of the stress tensor not simply the hydrostatic pressure. Thus, if the orientation of the stress field is known, for instance, for a thin film on a substrate well away from the edge, the stress field is biaxial, and so equation 4 can be used directly to measure the biaxial stress.

The precision of measurement depends on the accuracy to which the piezospectroscopic coefficients can be determined and the precision to which the frequency shift can be measured. The piezospectroscopic coefficients, including nonlinear terms, have been determined [8]. The accuracy of the frequency measurements depends on the spectral resolution of the spectrometer used as well as the temperature dependence of the spectrometer. It was found that the stress in
single crystals of sapphire can be measured to ± 20 MPa and in polycrystalline films to ± 40 MPa. By using a focused optical probe, for instance, using an optical microscope or fiber optic, measurements can be made down to regions a few microns across.

A number of comparisons have been made between measurements of the stress in alumina films, grown by high temperature oxidation, made by X-ray diffraction and piezospectroscopy with good agreement [5].

Optical Backscatter Experiments

Experiments to image damage in the alumina scales and at the interfaces between the alumina and the underlying metallic coating and/or the overlying TBC are being performed by Dr. William Ellingson and coworker Robert Visher at ANL using an optical backscatter technique. This technique is shown schematically in Figure 7.

![Figure 7. Schematic Diagram of the optical backscatter apparatus.](image-url)

In this technique a laser is focused on the specimen and the backscattered radiation is collected as the specimen is moved in the x and y directions, which gives the effect of the laser being rastered across the specimen surface. The backscattering process is sensitive to surface roughness and debonds between layers in the specimen. Thus, in principle one can image damage that has been produced by thermal cycling well before specimen failure.

Acoustic Emission Measurements

Cracking caused by cyclic oxidation can be detected in-situ using acoustic emission measurements. The stresses that develop in the oxide scale are the driving force for cracking and ultimately spallation. This type of event leads to the release of the stored elastic strain energy within the oxide. Associated with this dynamic fracture, a portion of the released energy manifests itself as a propagating elastic wave (acoustic emission, AE) that can be monitored and recorded on a per event basis. Features of the AE such as peak amplitude, duration, frequency and energy are characteristic of the type and magnitude of each event. Another parameter used to quantify an AE event is the AE-energy which is the integration of the squared signal. This
quantitative description cracking and spallation of the oxide scale of the event is sensitive to amplitude and duration.

![Acoustic Emission Testing Apparatus](image)

**Figure 8. Acoustic Emission Testing Apparatus.**

AE equipment is the commercially available Physical Acoustic Group AEDSP-32/16B acquisition and processing hardware with the Mistras-2000 data acquisition software. A R15 transducer with the frequency range from 100 to 1000Hz was attached to a stainless steel cone. The cone acts as a transition from the transducer diameter to the Pt-wave guide diameter of 1mm. This 80cm wave-guide was necessary for this application because of the incompatibility of the transducer and the high temperatures in the furnace. The apparatus being used is shown schematically in Figure 8.

**Modeling**

A number of models have been created to describe the isothermal growth kinetics of oxide scales, but to describe the cyclic oxidation behavior, Lowell et. al. [9] have developed COSP (Cyclic Oxidation Spall Program). COSP is a statistical model that deals with each cycle as a step in an iterative process of growth and spallation of the scale. Oxide growth only occurs only during the high temperature exposure and the behavior follows the isothermal growth kinetics to determine the weight of the oxide after the heating portion of the cycle prior to cooling, W’r. During the subsequent cooling step of the cycle, a portion of the oxide will spall with a mass of Ws. After the cycle is complete, the total mass of the oxide retained, Wr, is the starting point for the next cycle as graphically shown in Figure 9a.
In the COSP model, the fraction, $F$, of the oxide that spalls is proportional the amount of oxide that is present where

$$F = Q_o \cdot W'r.$$  \hspace{1cm} (5)

Here $Q_o$ is introduced as the spall constant and the bearing on the weight of the spalled oxide is

$$W_s = F \cdot W'r.$$  \hspace{1cm} (6)

With the $W'r$ and $W_s$ for this cycle, the $W_r$ can then be calculated by

$$W_r = W'r - W_s.$$  \hspace{1cm} (7)

Monitoring the amount retained and spalled oxide through the duration of the model, mass change curves can then be calculated and the effect of $Q_o$ on these curves is shown Figure 9b.

**RESULTS AND DISCUSSION**

**Task I: Processing Comparisons and Modifications**

Two nickel-base single-crystal superalloy substrates are being studied: René N5 and CMSX-4.

Four coatings on these substrates will be studied. These are:
- A NiCoCrAlY Overlay Coating
- Diffusion Aluminide and Platinum-modified Aluminide Coatings
- A TBC with NiCoCrAlY Bond Coat
- A TBC with Platinum-modified Aluminide Bond Coat

The aluminide coated N5 specimens (with and without TBCs) have been received and are being studied. Specimens with NiCoCrAlY coatings are currently being fabricated by low pressure plasma spraying and Argon-shrouded plasma spraying. Coatings, which have received different surface preparations, are also being fabricated.
Task II: Compositional Modifications

The approach being followed here involves modifying the surface of the coatings rather than the bulk coating composition. Specimens of NiCoCrAlY which have thin platinum layers electroplated onto them are currently being fabricated. It will be attempted to grow a very pure and adherent alumina scale on these alloys.

Experiments to control the grain size of the alumina scale are also planned.

Task III: TBC Selection and Fabrication

Thermal barrier coatings with platinum aluminode bond coats have been received and are currently being studied. Specimens with NiCoCrAlY bond coats are being fabricated.

Task IV: Specimen Testing

Cyclic Oxidation Testing

Previous experiments have involved testing of EBPVD TBCs to failure (See Figure 2). Typically when one-hour cycles are used at 1100°C the lives of systems with platinum-modified aluminide bond coats are about 1000 cycles and those with NiCoCrAlY bond coats are about 100 cycles.

The results of this type of test for specimens with platinum-modified aluminide coatings (without a TBC) are presented in Figure 10. The mass change of the specimens turns negative after about 2000 cycles. This is taken as coating failure.

![Figure 10. Cyclic oxidation plot for Pt-aluminide showing 2000 cycle failure.](image)

The results from these cyclic oxidation tests are taken as the baseline for the design of nondestructive and accelerated tests whose objective is to detect damage after relatively short exposures and provide the basis for life prediction.

Impact Testing

The PIs have developed a plan for high-speed impact testing of TBC systems with collaborators at GE Aircraft Engines in Evendale, Ohio. Elevated temperature tests will be performed at
GEAE using a pressurized gas gun impact system, to relate the losses in toughness measured in room temperature indentation tests to losses of resistance to high-speed impacts occurring at gas turbine operating temperatures. The procedure for these tests will be:

1) Exposure of a TBC button specimen under isothermal or cyclic thermal conditions, at temperatures above gas turbine operating temperatures to accelerate coating system degradation (e.g. at 1100°C).
2) High-speed impact of the button specimen at a temperature representative of gas turbine operating temperatures (e.g. 1000°C) at the GE facility. Impact velocities in the range of 100 to 300 m/sec are planned, which should result in penetration of the TBC, indentation of the base metal, and some TBC spallation.
3) Cooling of the specimen to room temperature, noting changes in the size of induced spalls.
4) Measurement of spall and indent size.
5) Fracture modeling to relate measured spall and indent sizes to TBC system interfacial fracture toughness.

A set of preliminary tests will be performed at GEAE during the next reporting period. These tests will determine the feasibility of this test as a means for tracking loss of TBC system toughness and impact resistance as a result of simulative thermal exposures.

Hot Corrosion Testing
The hot corrosion experiments have not yet been initiated.

Tasks V and VI: Nondestructive and Destructive Evaluation of Coating Systems

Oxide Scale Systems
Based on the results of Task IV four specimens of René N5 with platinum-modified aluminide coatings were exposed for 400 cycles (approx. 20% of life). The temperature profile for the cycle consists of 45 minutes at 1100°C and 15 minutes in the cool zone above the furnace where the samples are exposed to laboratory air. Two of the specimens were exposed in the as aluminized state and two were polished to remove the grain boundary ridges of the aluminide coating. Both the polished and unpolished samples have exhibited similar oxidation kinetics but more cracking and debonding of the oxide scale is apparent in the unpolished samples as shown in Figure 11. This cracking is associated with the top of existing grain boundary ridges of the aluminide coating of the unpolished sample. On the polished surface, valleys formed that mark the position of the original aluminide grain boundaries.
Figure 11. SEM surface micrographs Pt-Al coatings after 400 Cycles at 1100°C exposure where a) is unpolished and b) is polished surfaces.

The purpose of surface polishing is to provide a uniform flat surface for XRD stress measurements. Although some asperities develop with thermal cycling, the stress in the alumina formed on one of the polished specimens was measured by the XRD technique to be -1.8GPa. It appears that the cycling and valley formation have reduced the residual stress since the calculated thermal stress in an alumina scale on the aluminide coating deposited on low sulfur N5 is -4.3Gpa. In addition, stress measurements on scales grown by isothermal exposures on nominally the same material and surface treatment have yielded -4.1Gpa.

Two of the specimens (one polished and one unpolished) were sent to ORNL for piezospectroscopic measurement of the stress in the alumina and the other two were sent to ANL for optical backscatter imaging. These experiments have not been completed.

**TBC Systems**

The goal of these tasks is to combine the expertise of the PIs and their collaborators in both nondestructive and destructive testing methods, to further develop the nondestructive techniques as a means of tracking TBC system degradation due to thermal exposure. More specifically, the PIs have initiated a TBC testing regimen that combines destructive measurements of TBC system interfacial toughness with nondestructive measurements of TGO layer stress via piezospectroscopy and imaging of TGO layer surface characteristics by optical backscattering techniques.

In order to carefully track TBC system adherence, the PIs have employed a destructive indentation test for TBC system interfacial toughness developed under a previous DOE ATS.
grant AGTSR 96-01-SR046 [1]. The test involves indenting a standard TBC button specimen using a Rockwell hardness tester and a conically-shaped bralle indenter. The TBC and oxide layers are penetrated by the indenter and the metallic bond coat and superalloy substrate are plastically deformed. This plastic deformation induces compressive radial strains in the substrate, which are transferred to the TBC and oxide layers. This causes an axisymmetric debond, with the debond crack running at or near the interface between the alumina scale and the metallic bond coat. The radial extent of the debond is directly related to the fracture toughness of the interface region. By indenting multiple locations and single locations multiple times, a single button-shaped TBC specimen can yield many toughness values for different exposure times. The mechanics analysis presented in reference [1] details how measured debond radii can be related to TBC system toughness. The PIs have used this test to characterize the loss of interfacial toughness or adhesion in EBPVD TBC systems with a PtAl bond coat as a function of the duration of isothermal exposures at 1100, 1135 and 1200°C in dry air [2].

Testing Plan: The PIs have begun a first round of destructive/nondestructive testing on (3) EBPVD/PtAl TBC specimens. Measurement of specimen interfacial toughness in as-processed and exposed states is being carried out in parallel with nondestructive tests. Toughness measurements are used to not only track TBC system degradation, but also as a quality control method for ensuring that individual specimens are equivalent before and after thermal exposure. Specimen exposures consisted of thermal cycles of 10 minutes heating, 45 minutes at 1100°C and 10 minutes cooling. The test plan for the 3 specimens is shown in Table 1.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Cycles</th>
<th>Time at Temperature (hrs)</th>
<th>Tests Performed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>Indent, Piezo, Opt Back</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>Indent</td>
</tr>
<tr>
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<td>37.5</td>
<td>Indent</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>127</td>
<td>Indent, Opt Back</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>Indent</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>37.5</td>
<td>Indent</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>127</td>
<td>Indent, Piezo</td>
</tr>
</tbody>
</table>

Indentation Results: Figure 12 provides a plot of indentation test results for TBC specimens #2 and #3. The times of exposure for identically exposed specimens are shifted slightly to allow clear viewing of the plotted points. As indicated in the plot, specimens #2 and #3 had highly similar toughnesses in the as-processed state and after 50 and 170 thermal cycles. Furthermore, their toughness values were similar to those measured in another specimen fabricated during the same processing run. Although it is not plotted in Fig. 12, the as-processed toughness for specimen #1 (which was not subsequently thermally exposed) was comparable to those of specimens #2 and #3 and the previously tested specimen. The consistency in measured toughnesses for all three specimens tested for this project confirmed that they were comparable with respect to their resistance to spallation. This allowed specimens #2 and #3 to be sent separately to ORNL and Argonne after 170 cycles of exposure, with confidence that both techniques were being applied to comparable specimens. It also allowed results from
nondestructive evaluations of specimen #1 to be treated as indicative of the as-processed state for all 3 specimens.

Figure 12. Plot of TBC Interfacial Toughness vs. Exposure Time for Specimens #2 and #3 of this Project

Nondestructive Test Results:
Specimens 1 and 2 were sent to ORNL for piezospectroscopic measurement of the stress in the alumina TGO layer and identification of the alumina polymorphs making up the TGO. Results from the stress measurement are values of -3.85+/-0.30GPa in the as-processed condition and -1.46+/-0.11GPa after 170 cycles 1100°C exposures. The as-processed stress values are comparable to the calculated thermal stress, but significant decrease in the stress occurs from the thermal cycling. This stress decrease with cycling is analogous to thermally grown alumina without the TBC as presented above.

Specimen 3 was sent to ANL for optical backscatter imaging. The results of these experiments are presented in Figure 13.
In contrast to the Piezospectroscopic measurements of TGO stress, Optical Backscattering has not given a clear indication of degradation in the TBC specimens between the as-processed state and 170 thermal cycles. However, the method has proven to be an effective means for quantifying the size of debonds induced via indentation.

The PIs have developed a means for visualizing debonded regions in TBC systems using high voltage settings on a standard SEM. The high voltage induces charging in the debonded portions of the coating, which is clearly evident in SEM images. Examples of such images are given in Fig.13, where the debond is again viewed from above. This imaging technique has allowed more accurate determination of debond radii. Table 2 gives debond size results from three indent tests performed on a single TBC button specimen, using the SEM charging and Optical Backscattering techniques. In each case, an effective debond radius is obtained by measuring a debond area, then taking the square root of that quantity divided by Pi. Although indentations were done in the as-processed, 50 cycle and 170 cycle conditions, all debond size measurements were all taken after 170 cycles. The initial goal of these measurements was to obtain an understanding of the amount of stress relaxation occurring at elevated temperatures after an indentation test is performed. Because there is relaxation of indentation-induced stress at 1100°C, the size of the debond induced by indentation after 170 cycles (with no subsequent
thermal exposure) is the largest, followed by the debond from indentation after 50 cycles, with the debond from indentation at 0 cycles the smallest.

This specimen also allowed a direct comparison between the SEM charging technique developed by the PIs at the University of Pittsburgh and the optical backscattering technique in quantifying the size of the debonded regions. As indicated in Table 2, both methods give similar values for R, with the charging technique yielding slightly smaller values. This is consistent with the expectation that the charging technique may not be able to distinguish debonded TBC and oxide layers that are still in contact with the substrate from fully bonded layers, thus underestimating debond size. The debond radius values given in Table 2 indicate, however, that this underestimation may be small. The difference is also small if it is put in terms of a fracture toughness value, $K_c$, calculated from the measured debond radii.

Table 2 SEM Charging vs. Optical Backscattering Measurements of Debond Size

<table>
<thead>
<tr>
<th>Cycles for Initial Indent</th>
<th>R SEM (mm)</th>
<th>R Backscatter (mm)</th>
<th>$%$ Diff</th>
<th>$K_c$ SEM (MPa m$^{3/2}$)</th>
<th>$K_c$ Backscatter (MPa m$^{3/2}$)</th>
<th>$%$ Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.39</td>
<td>1.40</td>
<td>0.7</td>
<td>2.55</td>
<td>2.51</td>
<td>-1.6</td>
</tr>
<tr>
<td>50</td>
<td>1.60</td>
<td>1.66</td>
<td>3.8</td>
<td>2.12</td>
<td>2.01</td>
<td>-5.2</td>
</tr>
<tr>
<td>170</td>
<td>1.74</td>
<td>1.82</td>
<td>4.6</td>
<td>1.88</td>
<td>1.81</td>
<td>-3.7</td>
</tr>
</tbody>
</table>

Task VII: Definition of Effective Nondestructive Evaluation Procedures

Work on this task will begin when sufficient data have been obtained in Task VI.

Task VIII: Modeling and Prediction of Failures

Life time prediction can be achieved by the use of the COSP model and known oxide growth and spallation behavior for a particular material. Although the isothermal kinetics are readily available in literature or by simple thermogravimetric experiments, obtaining information about the spallation behavior, in particular $Q_o$, requires a novel testing approach. This approach has employed the AE equipment to measure the amount oxide that spalls during cooling and quantify $Q_o$ from short-term testing.

With the AE equipment, degradation of the oxide scales can be analyzed and quantified during short-term high temperature exposures. The amount of scale cracking and spallation is measured from the total AE-energy from these short-term tests. Damage to the oxide scales was only detected during cooling from the 24 hour elevated temperature oxidizing exposures. Since scale cracking and spallation occurred during cooling, the fraction of oxide scale that spalls from this one cycle is then used to calculate the spall factor for use in a cyclic oxidation model. Figure 14 shows the spall factor calculated from short-term AE experiments plotted against the long-term cyclic oxidation life for selected alloys and coatings and the relation to the oxidation model. Cyclic oxidation life is the time to crossover to negative weight change for both experimental and calculated data. With known growth kinetics and spall factor, long-term cyclic oxidation behavior can be predicted.
Task IX: Definition of Optimized Coatings for Specific Applications

This task will be performed in the third year of the program after sufficient data have been obtained from the other tasks.

CONCLUSION

- This new project is directed at evaluating (at early times) critical factors leading ultimately to coating failures.
- Some of the evaluation techniques are destructive but the emphasis is on nondestructive evaluation.
- The evaluation results are being incorporated into lifetime models.

REFERENCES

INTRODUCTION

This project is developing sensing strategies for monitoring gas turbine combustor health and performance. These new sensing capabilities will enable the development of control systems that actively manage engine condition and compensate for changes in ambient conditions or system degradation. Used for monitoring purposes, they will help gas turbine operators to more quickly identify potential system problems, before they become serious, and allow them to vary conditions to remove the problem. Used as long term monitors of system operation, they can also be used to help schedule required maintenance. Thus the development of these advanced sensor capabilities will improve combustor reliability and operability, achieve optimal performance (e.g., lower NOx emissions) over extended periods of time, reduce maintenance costs, prevent forced outages, and increase system life.

The approach is to develop methods to extract relevant combustor performance and status information from the light and sound naturally produced by the combustion processes. For example, some of the chemical reactions involved in combustion produce molecules in electronically excited states that give off light as they decay to their ground state. This is called chemiluminescence, and one example is the blue light produced by most hydrocarbon flames. Similarly, the turbulence and fluctuations in the heat released by the combustion processes are sources of sound (acoustics) in a gas turbine combustor. These optical and acoustic emissions can easily be monitored without requiring the placement of sensors directly into the most hostile regions of the flow. Furthermore, acoustic and optical sensors are already employed to some extent in currently fielded industrial gas turbines. In our work, we measure the optical and acoustic signatures of a number of different types of combustors as a function of operating conditions, such as fuel-air ratio, pressure, temperature, flow velocity, and system stability. We then use physics-based analysis methods to relate these system parameters to changes we observe in the sensor outputs.

During the current reporting period, significant progress has been made on development of flame zone sensors and dynamic stability margin sensors. In the area of flame zone sensors, we have demonstrated that we can use the ratio of CH to OH chemiluminescence (CH/OH) as a robust measure of the local fuel-air ratio in the reacting gas. CH/OH varies nearly linearly with equivalence ratio, and its slope sensitivity is similar in a wide range of combustor types. In addition, it does not seem to be sensitive to moderate changes in flow velocities or to small changes in the natural gas composition. We have found the CH/OH ratio has some pressure dependence. This is not unexpected, since the flame chemistry is also pressure dependent. Because key performance metrics, such as NOx emissions and turbine inlet pattern factor, are very sensitive to changes in the local fuel-air ratio, the development of this sensing capability can provide reduced pollutant emissions and increased hot section life.

Similarly, we have found a promising method for determining the dynamic stability margin of turbine combustors. By monitoring both the acoustic pressure amplitude, and the decay rate of its autocorrelation, one can determine the stability margin. This has been demonstrated in the
Georgia Tech gas turbine combustor simulator. Generally when turbines are being commissioned or during routine operation, the operator has no real-time information on how the relative stability of the system is affected by changes to fuel splits or other operating conditions (unless, of course, the system actually becomes unstable – leading to possible damage or shutdown). When incorporated into a complete sensor package (including analysis hardware/software), this will allow an operator (or control system) to monitor the proximity of the combustor to combustion instability. If the proximity sensor indicates a potential problem, the system operating conditions can be adjusted before damage is done, or before the system is forced to shut down.

EXPERIMENTAL

Three combustors have been employed in this project. As noted previously, we are studying multiple combustor geometries to ensure that the sensor methodologies developed here are robust. The first system is an atmospheric pressure, open burner, shown in Figure 1. The burner is supplied with air from compressed air tanks. The supply air passes through a plenum containing lined baffles for reducing flow noise. The duct transitions to a diverging/converging section to change the duct diameter from its supply value to the desired burner diameter. This section is followed by a straight section for flow conditioning. Fuel is introduced either after the baffle section, or near the exit in order to vary the amount of premixing. The figure shows a pilot stabilized configuration, where an array of closely spaced external pilot flames are placed around the burner exit. Besides this current circumferential piloting, several additional flameholding schemes can be examined, including swirl and bluff body approaches.

Figure 1. Simplified schematic of open burner assembly.
A confined, atmospheric pressure combustion is also being used (see Figure 2). It includes many of the attributes of a lean, premixed gas turbine combustor, including a swirl inlet and a dump plane. In this design, a combustible mixture of fuel (methane or natural gas) and air flow passes through swirl vanes housed in a 22 mm i.d. tube, producing a swirl number of ~0.4. Upon leaving the swirler, the flow expands into a cylindrical, quartz combustor of 70 mm i.d.. The combustor typically operates with an average (post-combustion) gas velocity of 6-9 m/s.

The third combustor is a small scale, high pressure gas turbine combustor simulator (see Figure 3). This facility is designed to simulate conditions in typical gas turbine combustors, i.e., the air is preheated, the fuel is injected, the two are premixed and pass through a swirler. It can operate at pressures up to 30.4 kPa (30 atm) with air preheated up to 540 °C (1000 °F). The combustor is also optically accessible through the two side windows (one of which can be seen in the figure) as well as from the exhaust; i.e., both side and “end on” imaging of the flame is possible.

**Measurement Approaches**

As noted above, the sensing approaches are based on measurement of the optical and acoustic radiation from the combustors. The optical signatures are measured using a variety of techniques. For measurement of “complete” optical spectra, we employ an imaging spectrometer. The spectrometer, with a 300 groove per mm grating, is coupled to a 1024 x 256 multi-element detector (intensified CCD). The system can simultaneously capture emission spectra from ~280–550 nm. In order to mimic the anticipated resolution of practical engine optical sensors, the resolution of the spectrometer is typically set to ~5-10 nm through control of the entrance slit width. With this sensor, flame spectra can be acquired at a range of pressures, inlet air temperatures and equivalence ratios, but with relatively low temporal resolution (~10 Hz). Temporal variations in the spectral signature are measured using a group of miniature photomultipliers, with built-in amplifiers (bandwidth of 20 kHz) to convert the detector current to voltage. In this case, the optical collection occurs through a fused silica optical fiber. The radiation can then pass through different interference filters to isolate specific spectral bands,
e.g., a filter centered at 308 nm with a full-width-half-maximum of ~10 nm collects ultraviolet emissions from the OH \( \text{A}^{2}\Sigma - \text{X}^{2}\Pi \) transition. The acoustic radiation is measured by monitoring the acoustic pressure oscillations. Pressure oscillations are measured with Kistler pressure transducers (Model 211B5). For the flame holding measurements, a single transducer is used. For the dynamic stability sensing, two transducers are used, one in the inlet section and one in the combustor. The transducers are mounted 33.2 cm upstream and 5.1 cm downstream of the conical flame holder, respectively. The latter transducer is flush mounted and water-cooled.

RESULTS AND DISCUSSION

During the current reporting period, efforts have focused on two of the sensor tasks, flame zone and combustor dynamics stability margin sensing. The accomplishments are detailed below.

Flame Zone Sensors

We are currently focused on examining the ratio of chemiluminescence from different species to monitor equivalence ratio (\( \phi \)). Our previous work showed relationships between the chemiluminescence from CH, OH and \( \text{C}_2 \) in liquid-fueled combustors. In our initial work under this program, we examined the chemiluminescence signals from the open tube burner (see Figure 1) and the confined, swirling combustor (see Figure 2). The first observation was that over most equivalence ratios of interest to modern gas turbines (\( \phi < 1.1 \)), the chemiluminescence from \( \text{C}_2 \) is negligible. For example, Figure 4 shows a spectral signature from a lean methane-air flame obtained in the tube burner. The OH and CH peaks are clearly visible, but the \( \text{C}_2 \) peak is barely discernible above the broadband background (a combination of radiation from species such as \( \text{CO}_2 \)). Therefore, we have primarily limited our analysis to the CH and OH radiation from natural gas systems.

Figure 5 shows the measured CH/OH ratio as a function of equivalence ratio for both the tube and swirl combustors. Data are included for methane (99.99% purity) and natural gas (city gas) fuels in the tube burner, and for methane in the swirl combustor. To demonstrate the level of repeatability in the current system, two methane data sets from the tube burner are also included. Within the accuracy of the measurements, the difference between methane and natural gas is
negligible. This shows that small variations in the composition of the natural gas should not effect this sensing approach. We also see good agreement between the results from the simple, laminar tube burner and the much more complex and turbulent swirl combustor. The CH/OH ratio in both combustors shows the same dependence on fuel-air ratio. However, it should be noted that the swirl combustor data has been normalized – all the ratios have been divided by ~4, i.e., the absolute ratio of CH to OH chemiluminescence is nearly four times greater in the swirl combustor. Part of this change is due to the changes in the spectrometer parameters. A different magnification and slit width were used in the two experiments. Also, the tube burner data entered the measurement system directly, while the chemiluminescence from the swirl combustor must also pass through the quartz tube. This would tend to lower the OH (ultraviolet) signal more than the CH signal and produce the higher CH/OH ratio. However, there may be other causes and this is still being investigated. So we can conclude from the results shown in Figure 5 that the relative slope sensitivity, $S$, of the chemiluminescence signal, defined as

$$S = \frac{d\left(\frac{CH}{OH}\right)}{d\phi} \frac{1}{\left(\frac{CH}{OH}\right)}$$  \hspace{1cm} [1]$$

is not a strong function of small variations in the fuel content for natural gas fuels and is also not a strong function of combustor geometry.

Another parameter that can change in a gas turbine combustor, independently of the equivalence ratio, is the overall flow rate. Therefore, results were acquired in the swirl combustor and the tube burner at different flow rates. Figure 6 shows results from the swirl combustor for two different air velocities: 2.6 and 4.7 m/s (but for constant swirl).* The CH/OH chemiluminescence ratio does not seem to be a sensitive function of the overall flow velocity.

We have also begun examining the effect of pressure on the measured CH/OH. Figure 7 shows results obtained in the Georgia Tech high pressure gas turbine combustor simulator for
three pressures: 125 kPa (18 psi), 220 kPa (32 psi) and 300 kPa (44 psi). Again for comparison to the previous results, the chemiluminescence ratio has been normalized – all the data shown in Figure 7 have been multiplied by a factor of nearly 3. With this normalization, the trends seen in the gas turbine simulator agree quite well with the swirl combustor data shown in Figure 6 (the trendline shown in Figure 6 is repeated in Figure 7). On an absolute basis, however, the CH/OH data are closer to the values measured in the simple tube burner. Again, the effect of changes in the optical system are partly the cause for this. The effect of pressure seems to be to increase the CH/OH ratio at lower equivalence ratios (lean mixtures), while having less influence on the more stoichiometric mixtures. This pressure dependence is not unexpected, since the flame chemistry is also pressure dependent. However, part of the pressure dependence, especially at very low $\phi$ may be due to flowfield changes. As the equivalence ratio approaches ~0.8 for the two high pressure cases, the flame begins to collapse on the flameholder. This may be the cause of the larger deviations seen in this region of Figure 7.

Figure 6. CH to OH chemiluminescence ratio measured in the swirl combustor, for two flow velocities (solid line is shows nearly linear trend in data).

Figure 7. CH to OH chemiluminescence ratio measured in the high pressure gas turbine combustor simulator, for three operating pressures (the solid line represents the same trendline shown in Figure 6).
Combustor Dynamics Stability Margin Sensors

Currently, when turbines are being commissioned or simply going through day to day operation, the operator has no idea how the stability of the system is affected by changes to fuel splits/operating conditions unless, of course, the system actually becomes unstable (which could result in, for example, flame blowoff and complete system shutdown). This point is illustrated in Figure 8 below, which plots combustor pressure amplitude data obtained from Georgia Tech’s gas turbine combustor simulator. This figure shows that the combustor was stable and unstable at inlet velocities above and below, respectively, about 23.5 m/s. Suppose now that this system is operated under a stable condition, say at an inlet velocity of 22 m/s. Although the turbine operator will know that the system is stable, they will not, in general, know how close the system is to instability.

![Figure 8. Variation of 630 Hz dynamic pressure amplitude in combustor with inlet velocity. Data obtained from Georgia Tech’s gas turbine combustor simulator.](image)

During the reporting period, we tested the use of autocorrelation analysis of pressure data as a methodology for ascertaining stability margin. The autocorrelation of a signal is defined as:
Figure 9 plots two autocorrelations of the same data shown in Figure 8 measured under stable and unstable conditions. It is important to note the qualitatively different characteristics of these autocorrelations with increasing delay, $\tau$. Under stable conditions, the amplitude of the autocorrelation steadily decays, while it remains relatively constant under unstable conditions. It is this behavior under stable conditions that is of interest here. Under these conditions the oscillations are driven by ambient background noise, but are damped. The decay in autocorrelation is physically due to the fact that this damping causes a loss of “memory” in the system, which causes oscillations at separate time instants to become increasingly decorrelated. These points are illustrated by referring to the following equation:

$$C(\tau) = \frac{\int_0^T p'(t)p'(t+\tau)dt}{\int_0^T p'^2(t)dt}$$  \[2\]

Such a second order oscillator equation resembles that typically used to model small amplitude oscillations in combustion chambers.\(^2\) The variables $p'$, $\zeta$, $\omega_0$, and $\xi$ denote the unsteady pressure, damping, natural frequency, and background noise excitation, respectively. It should be noted that this linear equation would not be suitable for describing combustor dynamics under unstable conditions, because inclusion of nonlinearities is necessary. The Fourier transform of the unsteady pressure described by this equation can be determined using standard techniques in spectral analysis. In turn, once the Fourier transform of the unsteady pressure is known, the autocorrelation, $C(\tau)$ can be determined from the inverse transform of the power spectrum using the Wiener-Khinchin theorem. It can be shown that the autocorrelation of Eq. [3] is given by:

$$C(\tau) = e^{-\omega_0\tau} \left( \cos(\omega_0\tau\sqrt{1-\zeta^2}) + \zeta / \sqrt{1-\zeta^2} \sin(\omega_0\tau\sqrt{1-\zeta^2}) \right)$$  \[4\]

The result is an expression that relates the autocorrelation to the system damping.
This approach was tested by bandpass filtering raw pressure data (bandwidth = 100 Hz) about the instability frequency, which was known \textit{a priori}. The pressure data was filtered about its two instability frequencies and the autocorrelation of the filtered data was calculated. The figures below plot the time dependence of the envelope of the autocorrelation at several runs for the data shown in Figure 8. It can be seen that the autocorrelation curve drops off dramatically within the first few cycles and that the rate of dropoff varies with the inlet velocity.

Figure 10 shows the autocorrelations for the data filtered about both 430 Hz and 630 Hz for the first 10 cycles of data collection. Plot ‘a’ displays the autocorrelations for data filtered about the 630 Hz instability frequency, and plot ‘b’ is the data filtered about the 430 Hz instability frequency. Each of the two plots displays four characteristic sets of data with varying inlet velocity. The dots in the graphs are the peaks of the autocorrelation curve (defined by Eq. [4]). The solid lines are curve fit for the data through the first 5 cycles, and will be discussed in further detail below.

For an inlet velocity of 19 m/s, the dominant instability frequency is 430 Hz. Thus the oscillations at this frequency are highly correlated with themselves for a number of cycles, and its autocorrelation coefficient stays near unity throughout the first 10 cycles, and only gradually falls off. The data filtered about 630 Hz, however, shows a sharp decline. The lack of major pressure oscillations in the stable operation of this mode means that the pressure oscillations in this frequency band are rapidly damped. As the inlet velocity increases, the dominance of one instability mode gives way to the other mode. For an inlet velocity of 24.5 m/s, neither frequency is very dominant, thus the shape of the autocorrelation curve for both modes is similar. In each plot, it is evident that as the inlet velocity is varied, the drop-off rate of the autocorrelation curve changes. As the stability transition point is approached, the slope of the curve is reduced.

In order to quantify this decay rate, it is noted the autocorrelation follows a relationship of the following form:

\[ C = e^{-cycles \times a} \tag{5} \]

where ‘C’ is the autocorrelation coefficient, ‘cycles’ is the instability frequency multiplied by time, and ‘a’ is the slope of the autocorrelation curve. Because ‘C’ is already calculated by the autocorrelation relationship defined above, and the number of cycles is known, ‘a’ can be found using simple linear regression between cycles and the logarithm of ‘C’. By examination of the

![Figure 10. Autocorrelation curves for varying inlet velocities: (a) data filtered about 630 Hz; (b) data filtered about 430 Hz.](image-url)
data, it is evident the relationship used to find ‘a’ best describes the data only for the beginning of the autocorrelation curve. The exact location that this relationship was valid for varied from run to run. For an inlet velocity of 33 m/s, for example, one can see by looking at Figure 10 that the relationship for the 430 Hz mode holds for roughly the first five cycles. To further verify this relationship, the resulting curves defined by Eq. [5] were plotted with the autocorrelation found using Eq. [4]. The results are displayed as the solid-line curves in Figure 10. By examining these graphs, one can see that within at least the first five cycles for every run, the curves show good agreement. Because we are solely interested in the initial drop off of the autocorrelation curve, for our analysis of the slope trends the slope coefficient ‘a’ calculated only on the first five cycles is valid.

Figure 11 shows the slope trends for the entire range of inlet velocities. In order to see how well the autocorrelation predicts the onset of instabilities, the slope data (circles) is plotted with pressure amplitudes (crosses) (see Figure 8). It is readily apparent by examining Figure 11 that as instability is approached, the slope data gradually decreases. The pressure data in conjunction with the slope data shows us that using autocorrelation analysis not only determines whether or not a combustor is operating stably, it can be used as a method to determine the margin of that stability.

CONCLUSION

To date, we have had made good progress towards flame zone and dynamic stability sensing. We have obtained chemiluminescence results in three significantly different (premixed) combustors: an open tube burner, a confined swirl burner, and a high-pressure gas turbine simulator. Results in all three combustors indicate that, for lean to stoichiometric mixtures, the CH/OH chemiluminescence ratio is nearly linearly proportional to the equivalence ratio. More importantly, the relative slope sensitivity, $S$, is nearly identical in all three for atmospheric pressures. Similarly changes in fuel from methane to city natural gas do not produce measurable changes in the CH/OH signal. This suggests that a sensor based on the chemiluminescence ratio
would be widely applicable to many gas turbine combustors. We have seen some pressure dependence that must be investigated further. If this is found to be a true pressure effect (i.e., changes in the chemical rates) rather than changes in the flowfield, it is likely to be something that can be accounted for in the sensor analysis methods. Finally, we still have to examine the effect of air preheating on the signal. Still, the results look favorable for creating a sensor that could look for variations between fuel injectors that suggest nonuniform fuel mixtures that lead to increased NOx levels and hot spots on the turbine.

Similarly, we have made good progress in finding an approach to analyze acoustic pressure data for monitoring dynamic stability margin in gas turbine combustors. Data acquired in a reasonable simulator of a gas turbine combustor (though decoupled from compressor and turbine effects) has shown that an autocorrelation analysis of the acoustic pressure can provide a measure of the stability margin. By monitoring the decay rate of the autocorrelation of the pressure, in conjunction with the acoustic pressure amplitude, one can determine whether or not a combustor is operating stably. More importantly, the two parameters can be used as a method to determine the margin of that stability. When incorporated into a complete sensor package (including analysis hardware/software), this will allow an operator (or control system) to monitor the proximity of the combustor to combustion instability, for example as changes in fuel split are made. If the proximity sensor indicates a potential problem, the system operating conditions can be adjusted before damage is done, or before the system is forced to shutdown.

REFERENCES


INTRODUCTION

Durable and reliable service of thermal barrier coatings (TBCs) increases the performance efficiency and reduces the harmful emission during the operation of advanced gas turbine engines. Enhanced reliability, availability and maintainability (RAM) of advanced turbine engines require robust non-destructive evaluation (NDE) techniques for TBCs. There is a need for a clearer scientific understanding for TBC failure mechanisms based on the fundamental foundation of thermo-kinetics and thermo-mechanics. There is even a greater need for NDE techniques that can monitor the degradation in TBCs, and can be correlated to the fundamental materials phenomena associated with mechanisms of TBC failure.

The overall objective of this program is to provide a clearer understanding of TBC failure by concurrently utilizing two NDE techniques, namely photostimulated luminescence spectroscopy (PSLS) and electrochemical impedance spectroscopy (EIS), and state-of-the-art characterization techniques including in-situ focused ion beam (iFIB) lift out [10] and high resolution scanning transmission electron microscopy (HR-STEM). The PSLS and EIS were selected for this program since these two techniques can provide non-destructive methods to examine the critical materials phenomena associated with TBC.

The main objective of this program is being achieved by accomplishing the following goals:

1. Evaluate and examine five different types of commercial production TBCs during thermal cyclic oxidation concurrently by PSLS and EIS NDE techniques.
2. Evaluate five types of commercial production TBCs after specified thermal cyclic oxidation and after failure by the state-of-the-art characterization techniques including SEM, EDS, iFIB and HR-STEM equipped with n-EDS, CBED, HAADF and EELS.
3. Define clearer failure mechanisms for five types of commercial production TBCs.
4. Demonstrate the relationship between the results of NDE techniques, microstructural analysis and failure mechanisms for five types of commercial production TBCs.
5. Transfer to industrial partners the attained knowledge on TBC failure, refinement of NDE techniques, feasible approaches to improve TBC durability and to develop/refine lifetime prediction models for TBCs.
6. Provide collaborative/competitive team-based research activities for student research teams with active interaction from industrial partners.

To achieve these goals, six tasks were defined, structured, and scheduled. In this program, the University of Central Florida is privileged to have a strong and supportive partnership with four industrial gas turbine manufacturers and a coating manufacturer. The industrial partners will contribute to this program by supplying commercial production TBCs, providing non-proprietary experience to the program and interacting (technically, educationally and professionally) with student research teams.
EXPERIMENTAL

Description and Thermal Cycling of Thermal Barrier Coatings

Five TBC systems, identified in Table II as type I through V, were selected for this program. The industrial partners of this program have committed to supply 20 specimens of each TBC type with geometrical specification schematically illustrated in Figure 3 (25.4 mm in diameter and 3.2 mm in thickness). To date, specimens of type I, III, IV and V have been delivered to the University of Central Florida, while the TBC system II is expected by early 2003.

Table II. Specifications for five types of commercial production thermal barrier coating systems employed in this program.

<table>
<thead>
<tr>
<th>TBC System</th>
<th>7YSZ Deposition and Thickness</th>
<th>Bond Coat Type and Thickness</th>
<th>Superalloy Substrate</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>APS: 600 µm</td>
<td>NiCoCrAlY: 175 µm</td>
<td>Haynes 230</td>
<td>-</td>
</tr>
<tr>
<td>II</td>
<td>EB-PVD; TBA</td>
<td>NiCoCrAlY: TBA</td>
<td>CM247</td>
<td>-</td>
</tr>
<tr>
<td>III</td>
<td>EB-PVD: 145 µm</td>
<td>(Ni,Pt)Al: 50 µm</td>
<td>CMSX-4</td>
<td>As-Coated Bond Coat</td>
</tr>
<tr>
<td>IV</td>
<td>EB-PVD: 140 µm</td>
<td>(Ni,Pt)Al: 35 µm</td>
<td>Rene’N5</td>
<td>Grit-Blasted Bond Coat</td>
</tr>
<tr>
<td>V</td>
<td>APS: 200 µm</td>
<td>NiCoCrAlY: 100 µm</td>
<td>MAR-M-509</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 4. Specimen geometry for thermal barrier coatings employed in this program.

Thermal cyclic oxidation for each type of TBC will be carried out using CM. Rapid Temperature furnace with vertical cycling package. Each cycle will consist of 10-minute heat-up to 1121°C (2050°F), 1, 10 or 50-hour hold at 1121°C, and 10-minute forced-air quench. A schematic illustration of thermal cycling is presented in Figure 5. Temperature of the specimen stage (20 cm by 20 cm) will be monitored by S-type thermocouples attached to YSZ disk (25.4 mm in diameter and 3 mm in thickness). For 20 specimens of each TBC type, thermal cyclic oxidation testing will be carried out using the matrix given in Table III. At specified thermal cycles, TBCs will be visually inspected, photographed and examined by PSLS and EIS. TBC specimens after specific thermal cycles will be also employed for microstructural analysis according to Table III.
Photostimulated Luminescence Spectroscopy (PSLS), pioneered by Clarke et al. [12-16] and refined by Sohn, Gell, Jordan et al. [17-19] has demonstrated its capability as an NDE technique for TBCs. Specifically, PSLS can provide information regarding the following factors associated with TBC failures:

- Residual stress of $\alpha$-Al$_2$O$_3$ (i.e., TGO structural integrity).
- Polymorphic transformation of Al$_2$O$_3$.
- Formation of other oxides (containing Ni, Co, Y, etc.) in TGO [20].

In PSLS technique, schematically illustrated in Figure 6, a systematic shift in the position of $R_1$ and $R_2$ luminescence doublets can be phenomenologically translated into residual stress in $\alpha$-Al$_2$O$_3$, assuming that the TGO consists of randomly oriented polycrystals. The average biaxial residual stress $\sigma$ in the $\alpha$-Al$_2$O$_3$ scale is generally calculated from the average shift in the position of $R_2$ luminescence $\Delta \omega$ using the relation [12-15]:

\[
\sigma = \frac{\Delta \omega}{C}
\]
where \( \Pi \) is the piezospectroscopic coefficients. Clarke et al. [15,16] as well as Sohn, Gell, Jordan et al. [17,18] have demonstrated that the damage of TGO by cracking during thermal cyclic oxidation results in relief of TGO residual stress. In addition, Figure 7 shows the N, Q and G-luminescences arising from, respectively, a significant \( \text{Cr}_2\text{O}_3 \) concentration in the TGO [21], the presence of metastable \( \theta \), and \( \gamma-\text{Al}_2\text{O}_3 \) in TGO. Intensity of these luminescences can be determined relatively using the relation:

\[
\frac{I_\alpha}{I_T} + \frac{I_N}{I_T} + \frac{I_Q}{I_T} + \frac{I_G}{I_T} = 1
\]

where IR, IN, IQ, IG and IT refer to the integrated luminescence intensities of \( \alpha-\text{Al}_2\text{O}_3 \), N-luminescence, \( \theta-\text{Al}_2\text{O}_3 \), \( \gamma-\text{Al}_2\text{O}_3 \) and total luminescence, respectively. Formation of other constituents in TGO such as Y-rich oxide (e.g., \( \text{YAl}_2\text{O}_{12}, \text{Y}_2\text{O}_3 \)), and Ni/Co-rich oxide (e.g., \( \text{NiO, CoO, (Ni,Co)(Cr,Al)}_2\text{O}_4 \)-spinel) may be detected by the PSLS technique based on theory of photoluminescence [20]. Thus, NDE of these TGO characteristics by PSLS as a function of thermal cyclic oxidation can provide insight into the failure mechanisms of TBCs specifically associated with the factors listed in Table I.

Figure 6. A schematic diagram of photostimulated luminescence spectroscopy, and \( R_1-R_2 \) luminescence doublets from stressed and stress-free \( \alpha-\text{Al}_2\text{O}_3 \).
After specified thermal cycles reported in Table III, TBC specimens will be carefully removed from the CM furnace for NDE by PSLS. NDE by PSLS will be restricted to EB-PVD TBCs, since PSLS cannot be applied to APS TBCs without impregnating APS YSZ coatings with other medium [22] whose effect on TBC lifetime has not been investigated. TGO residual stress, polymorphic transformation of Al₂O₃, formation of Ni/Co rich TGO, and development of sub-critical TGO damage will be carefully monitored using PSLS. Minimum of 30 measurements, randomly over the surface of the specimen coupon will be carried out for each specimen. Spectra will be collected using Renishaw™ 1000B µ-Raman spectrometer and analyzed using GRAMS™ software.

**Electrochemical Impedance Spectroscopy**

Electrochemical impedance spectroscopy (EIS) is a well-established technique in materials engineering related to corrosion. This technique was first employed to examine TBCs by V.H. Desai through a previous AGTSR program (No. 98-01-SR067) [23]. Results from this program indicated that the EIS technique has a good potential to provide information regarding the following factors associated with TBC failure [23,24]:

- Thickness of TGO.
- Adhesion integrity of TGO/bond coat and YSZ/TGO interfaces.
- Microstructure, thickness, sintering and cracking in YSZ.

The IS technique, schematically shown in Figure 8, involves measurement of the multi-layer system response subjected to a small ac signal at various frequencies, and representing it with Nyquist and Bode plots, which represents the changes in impedance and phase angle. With concurrent simulation of equivalent ac circuits, various aspects of TBCs including YSZ microstructure, TGO thickness and TBC structural integrity can be evaluated non-destructively. An EIS ac equivalent circuit employed in this study is presented in Figure 9 for (a) as-coated APS TBCs without significant TGO scale and (b) as-coated EB-PVD TBCs with TGO and thermally cycled TBCs deposited either by APS or EB-PVD. NDE of TBCs by EIS as a function of thermal cyclic oxidation can provide insight to the failure mechanisms, specifically associated with the factors listed in Table I.
Similar to PSLS, after specified thermal cycles reported in Table III, TBC specimens will be carefully removed from the CM furnace for NDE by EIS. TGO thickness, interfacial adhesion and damage, and microstructural evolution of YSZ coatings will be carefully monitored using EIS. Minimum of 3 measurements will be carried out by applying 10mV over a frequency range of 1MHz to 10mHz. EIS set-up employed in this study consist of IM6E BAS Zahner frequency response analyzer and a three-electrode system, namely counter electrode (Pt-mesh), reference electrode (standard calomel) and working electrode (TBC) in contact with K₃Fe(CN)₆/K₄Fe(CN)₆-3H₂O electrolyte solution. The center of the TBC coupons is examined by EIS with a measurement diameter of 1 cm.

![Diagram](image.jpg)

Figure 8. A schematic diagram of a typical set-up for electrochemical impedance spectroscopy.
Microstructural Characterization

During and after thermal cyclic oxidation testing, selected specimens of TBCs are employed for the microstructural and failure analysis as presented in Table III. Development of microstructural features and failure characteristics of TBCs are being examined as a function of thermal cycles. Aforementioned, this task employs state-of-the-art characterization techniques with emphasis on field emission scanning electron microscopy (FE-SEM), energy dispersive spectroscopy (EDS), in-situ focused ion beam (iFIB) lift out and high resolution transmission electron microscopy (HR-STEM; Philips™/Tecnai™ F30 300KeV) equipped with nano-spot-EDS (n-EDS), convergent beam electron diffraction (CEBD), high angle annular dark field (HAADF) imaging and electron energy loss spectroscopy (EELS). In addition, facilities at the Advanced Materials Processing and Analysis Center (AMPAC) at UCF such as X-ray diffraction (XRD), auger electron spectroscopy (AES) with depth profiling, X-ray photoluminescence spectroscopy (XPS), Rutherford backscattering spectroscopy (RBS), and secondary ion mass spectroscopy (SIMS) with depth profiling can be employed if necessary. According to Table III, all intact TBCs (8 specimens for each type) and selected failed TBCs, will be examined by FE-SEM/EDS and HR-STEM on cross-sections prepared by iFIB. For the fracture surfaces of TBC specimens, analysis can be carried out by appropriate techniques that may include FE-SEM, XRD, AES (with depth profiling capability), XPS, and SIMS (with depth profiling capability).
RESULTS AND DISCUSSION

Photostimulated Luminescence Spectroscopy of As-Coated EB-PVD TBCs

Aforementioned, the delivery of type II EB-PVD TBCs is expected by early 2003. NDE by PSLS will be restricted to EB-PVD TBCs (type II, III and IV), since PSLS cannot be applied to APS TBCs (type I and V) without impregnating APS YSZ coatings with other medium [22], whose effect on TBC lifetime may be harmful.

For type III as-coated EB-PVD TBCs with as-coated (i.e., with grain boundary ridges) (Ni,Pt)Al bond coat, PSLS was collected for all 20 specimens. For each specimen, 30 random-spot measurements were carried out. Luminescence from α-, γ- and θ-Al2O3 was observed in all spectra for all specimens. Relative luminescence intensity from α-, γ- and θ-Al2O3 polymorphs is presented in Figure 10. In general, 70~80% of luminescence was from α-Al2O3 while 20~30% luminescence was from γ- and θ-Al2O3 for as-coated type III TBCs. These values do not correspond to the actual volume fraction of Al2O3 polymorphs.

![Figure 10. Relative luminescence intensity from α-, γ- and θ-Al2O3 in TGO for as-coated type III TBCs with as-coated (Ni,Pt)Al bond coat.](image)

Figures 11 and 12 present the shift in the position of R_{2} luminescence \( \Delta \beta \) based on 30 random-spot measurements for type III TBCs. In all cases, bimodal (i.e., two sets of R_{1} and R_{2}) luminescence corresponding to higher (~5 GPa) and lower (~3.5 GPa) compressive residual stress in α-Al2O3 was observed. Evolution of relative luminescence intensity from Al2O3 polymorphs and compressive residual stress in α-Al2O3 will be monitored as a function of thermal cycling as presented in Table III during the next reporting period. These data will then be correlated with microstructural analysis.
PSLS was collected for 16 specimens of type IV as-coated EB-PVD TBCs with grit-blasted (i.e., removal of grain boundary ridges) (Ni,Pt)Al bond coat. No luminescence could be obtained from the remaining 4 specimens; no explanation exists at this time. For 16 specimens with luminescence, 30 random-spot measurements were carried out. Luminescence from α-, γ- and θ-Al₂O₃ was observed in all spectra for all specimens. Relative luminescence intensity from α-, γ- and θ-Al₂O₃ polymorphs is presented in Figure 13. In general, 60~70% of luminescence was from α-Al₂O₃ while 30~40% luminescence was from γ- and θ-Al₂O₃ for as-coated type IV TBCs. These values do not correspond to the actual volume fraction of Al₂O₃ polymorphs. Relative to type III TBCs with as-coated (Ni,Pt)Al bond coat, a slightly stronger γ-Al₂O₃ luminescence than θ-Al₂O₃ was observed.
Figures 14 and 15 represent the shift in the position of R2 luminescence determined based on 30 random-spot measurements for type IV TBCs. In all cases, bimodal (i.e., two sets of R1 and R2) luminescence corresponding to higher (~6 GPa) and lower (~1 GPa) compressive residual stress in α-Al2O3 was observed. Evolution of relative luminescence intensity for polymorphs of Al2O3 and compressive residual stress in α-Al2O3 will be monitored as a function of thermal cycling as presented in Table III during the next reporting period. These data will then be correlated with microstructural analysis.

Figure 14. Higher average compressive residual stress of α-Al2O3 TGO determined from bimodal luminescence for as-coated type IV TBCs.
Electrochemical Impedance Spectroscopy of Thermal Barrier Coatings

As-coated Air Plasma Sprayed Thermal Barrier Coatings

For type I and V APS TBCs, EIS measurement was carried out 3 times for one of each specimen type: typical Nyquist plot for type I and V TBCs are presented in Figure 16. Table IV also reports values of resistance and capacitance of various TBC constituents, which were calculated based on the ac-equivalent circuit in Figure 9. Ceramic top coat resistance, RC and ceramic top coat capacitance, CC of type I TBC is higher and lower, respectively, compared to those of type V TBCs. This observation corresponds to the difference in thickness of the YSZ in type I (600µm-thick) and type V (200µm-thick) TBCs as presented in Table II. While similar pore resistance, RP values may reflect the similar amount of porosity in the APS YSZ coatings, the pore capacitance, CP differs by an order of magnitude, reflecting the difference in the shape of the porosity in the APS YSZ coatings. Indeed, microstructural analysis (section V.3.2) revealed that type I TBC contains spherical pores without splat boundaries, and type V TBC contains many splat boundaries.

Evolution of resistance and capacitance of TBC constituents will be monitored as a function of thermal cycling as presented in Table III during the next reporting period. These data will then be correlated with microstructural analysis.
While EIS offers a potential technique to assess a variety of TBC characteristics, the effect of EIS measurement (i.e., penetration of K$_3$Fe(CN)$_6$/K$_4$Fe(CN)$_6$·3H$_2$O) solution electrolyte into TBCs on lifetime has not been investigated. With the permission from the supplier, 6 specimens of type V TBC were employed to examine the effect, if any, of electrolyte on TBC lifetime. All 6 specimens were thermally cycled together at 1121°C. Each thermal cycling consisted of a 10-minute heat-up, a 40-minute hold at 1121°C and a 10-minute forced-air quench. The 3 designated specimens were non-destructively examined by EIS every 20 cycles, while the other 3 specimens were thermally cycled without EIS measurement. The variation in TBC lifetime of these specimens is presented in Figure 17. Although a more rigorous and statistically-significant lifetime database is needed, it is concluded that, within the scope of this program, EIS can be applied as a NDE technique without significantly influencing the overall lifetime of TBCs. Alternative electrolyte that will not influence TBC lifetime will be sought after.

![Nyquist plots from as-coated type I and V APS TBCs.](image)

Figure 16. Typical Nyquist plots from as-coated type I and V APS TBCs.

<table>
<thead>
<tr>
<th>TBC Type</th>
<th>$R_C$ (kΩ)</th>
<th>$C_C$ (nF)</th>
<th>$R_P$ (kΩ)</th>
<th>$C_P$ (μF)</th>
<th>$R_T$ (kΩ)</th>
<th>$C_T$ (μF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.50 ± 0.04</td>
<td>2.2 ± 0.4</td>
<td>10.6 ± 4.2</td>
<td>377.7 ± 22.0</td>
<td>0.3 ± 0.1</td>
<td>16.5 ± 2.7</td>
</tr>
<tr>
<td>V</td>
<td>0.29 ± 0.02</td>
<td>4.8 ± 0.5</td>
<td>11.8 ± 1.4</td>
<td>38.0 ± 9.3</td>
<td>0.9 ± 0.1</td>
<td>3.9 ± 0.2</td>
</tr>
</tbody>
</table>

Preliminary NDE of Thermally Cycled Type V APS Thermal Barrier Coatings by EIS
During this preliminary evaluation, resistance and capacitance of TBC constituents was also determined as a function of thermal cycles as presented in Figures 18 through 20. Trends and changes in the values of resistance and capacitance were observed as a function of thermal cycling. Ceramic top coat resistance $R_C$ initially increased, then decreased and stabilized till failure with thermal cycling; this perhaps reflects two important microstructural changes, namely sintering and micro-cracking. Based on Figure 18, no significant microstructural changes occur in APS YSZ with prolonged thermal cycling until failure.

While the growth of TGO should intuitively increase the resistance and decrease the capacitance, the opposite results were observed as presented in Figures 19 and 20. As seen in Figure 19, TGO resistance, $R_O$ (not defined for as-coated condition) continuously decreases and TGO capacitance, $C_O$ continuously increases with thermal cycling. In addition, a sharp 2–5X increase in the $C_O$ was observed as presented in Figure 20. These trends are consistent with another type of TBCs (section V.2.4), and may reflect initiation and growth of sub-critical damage in TGO through which electrolyte can penetrate.

From this preliminary data, it is proposed that gradual changes may be expressed in terms of a functional equation to predict the remaining TBC lifetime. Also abrupt changes in values of resistance and capacitance before and near the failure of TBCs can be sought as a “near-failure event”.

Figure 17. Variation in TBC thermal cycling lifetime with and without EIS measurement.
As-coated Electron Beam Physical Vapor Deposition Thermal Barrier Coatings

For type III and IV EB-PVD TBCs, EIS measurement was carried out 3 times for one of each specimen type: typical Nyquist plot for type III and IV TBCs are presented in Figure 21. Table V also reports values of resistance and capacitance of ac-equivalent circuit in Figure 9.
The main difference in the specification of type III and IV TBCs is the surface treatment of (Ni,Pt)Al bond coat by grit blasting as reported in Table II. However, the values of resistance and capacitance in Table V vary significantly between these two types. This observation can be related to the microstructural variation of EB-PVD YSZ coatings from two different suppliers and the thickness and morphological variation of TGO associated with grit blasting (section V.3.3). Evolution of resistance and capacitance of TBC constituents will be monitored as a function of thermal cycling as presented in Table III during the next reporting period. These data will then be correlated with microstructural analysis.

Table V. Resistance and capacitance of various as-coated EB-PVD TBC constituents. Values in parenthesis are standard deviation based on 3 independent measurements.

<table>
<thead>
<tr>
<th>TBC Type</th>
<th>$R_C$ (kΩ)</th>
<th>$C_C$ (μF)</th>
<th>$R_P$ (kΩ)</th>
<th>$C_P$ (μF)</th>
<th>$R_O$ (Ω)</th>
<th>$C_O$ (nF)</th>
<th>$R_T$ (kΩ)</th>
<th>$C_T$ (μF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>III</td>
<td>6.06 (0.87)</td>
<td>0.05 (0.001)</td>
<td>127.1 (44.8)</td>
<td>0.05 (0.004)</td>
<td>35.7 (1.7)</td>
<td>0.21 (0.02)</td>
<td>172.0 (54.8)</td>
<td>1.48 (0.34)</td>
</tr>
<tr>
<td>IV</td>
<td>0.65 (0.05)</td>
<td>20.4 (0.5)</td>
<td>0.29 (0.03)</td>
<td>29.7 (2.8)</td>
<td>62.5 (0.0)</td>
<td>2.50 (0.06)</td>
<td>3.40 (0.56)</td>
<td>0.32 (0.01)</td>
</tr>
</tbody>
</table>

Selected EIS Observations for TBC Applications

Prior to receiving the 20 specimens of five types of TBCs, selected experiments were carried out for EIS independently at UCF and in collaboration with industrial partners. The following summarizes the results from these additional specimens. Detailed information on experimental procedure, results and discussion will be published elsewhere [25,26,27].

Monolithic 7YSZ with Varying Thickness and Density

Monolithic 7YSZ with varying thickness and density, received from Trans-Tech, Adamstown, PA, was examined by EIS. Figure 22 shows an increase in resistance (and a corresponding decrease in capacitance) with increasing thickness. In addition, lower resistance was observed for more porous 7YSZ as seen in Figure 22, reflecting greater conduction via electrolyte penetration through 7YSZ [25].
Electron Beam Physical Vapor Deposited 7YSZ with Varying Thickness

A series of as-coated EB-PVD 7YSZ TBCs with varying thickness, which is controlled by deposition time, was examined by EIS. Specimens were provided by one of the industrial partners. An increase in the ceramic resistance was observed with increasing thickness as presented in Figure 23 [25].

NiAl Disk Specimens as a Function of Thermal Cycling

Hot-extruded NiAl disk specimens, received from NASA-GRC, were thermally cycled at 1121°C using a 10-minute heat-up, a 40-minute hot-time and a 10-minute forced-air-quench. Resistance and capacitance of TGO, $R_O$ and $C_O$ were monitored as a function of thermal cycles as presented in Figure 24. Initial increase and decrease, in the resistance and capacitance, respectively, of TGO correspond to the parabolic growth (thickening) of TGO scale [25]. This trend in the resistance and capacitance of the TGO, changes between 20 and 50 cycles, at which spallation of TGO was observed using optical microscopy [25]. Upon spallation of TGO, localized exposure of NiAl surface to the electrolyte will decrease the resistance, and increase the capacitance.
EB-PVD TBCs with various thermal cycling at 1121°C (40-minute hot-time) were examined by EIS with specimens provided by the University of Connecticut/industrial partner. Resistance and capacitance of YSZ and TGO were monitored as a function of thermal cycles as presented in Figure 25. After prolonged thermal cycling, a sharp decrease and an increase in the resistance and capacitance, respectively, of YSZ was observed [26]. Initial increase and decrease in the resistance and capacitance of TGO, respectively, correspond to the parabolic growth (thickening) of TGO scale [26]. Abrupt changes in the resistance and capacitance of TGO, by orders of magnitude, occurred with the failure [26]. A decrease in the resistance of TGO occurred prior to failure [26]. This observation is consistent with that from the oxidation of NiAl (Figure 24) and type V TBC specimens (Figures 18-20).

A decrease in the resistance and the corresponding increase in the capacitance of insulating oxide (YSZ and TGO) reflect the conduction via penetration of electrolyte. This penetration of electrolyte can occur through porosity, and more importantly, through damages/cracks that develop within YSZ and TGO during thermal cycling.
YSZ and CaTiO3 Air Plasma Sprayed Thermal Barrier Coatings

YSZ and CaTiO3 TBCs with varying thickness, provided by one of the industrial partners, were examined by EIS. There is a decrease in the capacitance of ceramic top coat with increasing thickness as presented in Figure 26 [27]. A decrease in capacitance also corresponds to an increase in resistance as presented in Figure 26 [27]. Variation in thickness was measured on these specimens using scanning electron microscopy. The dielectric constant of CaTiO3 is around 160 while that for YSZ is in the range of 40-60. The resistivity of CaTiO3 is in the order of $10^{14}$ Ω-cm and that of YSZ is approximately $10^9$ Ω-cm. From these values of dielectric constant and resistivity, the resistance and the capacitance of the CaTiO3 must be higher than that of YSZ at similar thickness as presented in Figure 26.

![Figure 25. Evolution in (a,c) resistance and (b,d) capacitance of (a,b) EB-PVD YSZ and (c,d) TGO during thermal cycling at 1121C.](image)

![Figure 26. Ceramic top coat capacitance $C_C$ and resistance $R_C$ of APS YSZ and CaTiO3 as a function of thickness.](image)
Microstructural Analysis of Thermal Barrier Coatings

In-situ Focused Ion Beam Lift Out Specimen Preparation

The focused ion-beam (FIB) technique has been developed for the preparation of TEM specimens containing fragile interfaces such as TBCs, and other traditionally difficult-to-prepare materials [28]. Using the technique, site-specific electron transparent thin (<100nm) specimens suitable for TEM analysis can be prepared with consistency and efficiency. The ex-situ FIB (eFIB) technique has been previously employed with some success in preparing APS and EB-PVD TBC specimens with thermal cycling [29-34]. Recent advances with in-situ FIB (iFIB) lift out method [10] now allow consistent and efficient preparation of TBC specimens regardless of their thermal cycling history or the extent of damage as long as they are intact.

In this program, initial characterization is carried out by SEM/EDS for each type of TBC. Then TEM specimens containing YSZ, TGO, bond coat and all the interfaces in between are prepared using the iFIB lift out technique using an FEI™ 200TEM FIB. The process of in-situ FIB lift out is illustrated in Figure 27 with ion beam images collected during the actual specimen preparation of TBCs. This process takes about 2.5 hours.

During iFIB, a specific site of interest to be prepared is first covered with a ~0.5 µm wide x 30 µm long x 1 µm high Pt layer deposited by ion-assisted chemical vapor deposition (CVD). This is done to prevent spurious sputtering of the top surface of the specimen, and outline the area of interest (Figure 27a). Then, a gradual “stair step” trench milling is performed from either side of the Pt layer.
the sample by tilting the sample back and forth (Figure 27b). The edges of the wedge-shaped specimen are cut by FIB, in-situ probe is welded to the specimen (Figure 27c), and the specimen is lifted out from the bulk (Figure 27d) and transferred to a TEM grid. During and after iFIB process, the specimen can be thinned further to desired thickness at any time; another distinctive advantage of iFIB lift out technique.

_Site-specific and routine (<3 hours) preparation of TBC specimens regardless of thermal exposure for HR-STEM has been achieved during the first reporting period of this program using iFIB lift-out technique_. This achievement now allows a systematic HR-STEM investigation of TBCs as a function of thermal exposure, and will give a detailed understanding of microstructural evolution, and ultimately how TBCs fail.

**As-coated Air Plasma Sprayed Thermal Barrier Coatings**

Figure 28 represents secondary electron micrograph of as-coated type I (600µm-thick) and V (200µm-thick) APS TBCs. Specimens conformed to the specification described in Table II. Using SEM, no significant TGO scale was observed for both types. However, a difference in the microstructure of APS 7YSZ was observed. Type I TBC did not exhibit any splat morphology while type V did as seen in Figure 28. This difference correlated to the NDE results by EIS (section V.2.1): a distinctive difference in pore capacitance \( C_P \) for these two specimens reported in Table IV. Excluded from this first semi-annual report are the detailed micrographs from general microscopy using optical and scanning electron microscopy (OM and SEM) for as-coated TBCs. These will be appropriately presented in the future with evolution in microstructure with thermal cycling.

![Figure 28](image)

*Figure 28. Secondary electron micrograph of (a) type I and (b) type V air plasma sprayed thermal barrier coatings.*

After OM and SEM, a site-specific specimen was prepared for HR-STEM using iFIB. Figure 29 shows an ion beam images from the TEM specimen preparation of APS TBCs by iFIB lift out technique: the specimen has been welded to a micromanipulator and lifted out. In as-coated type I TBC specimen, extensive presence of voids between YSZ and MCrAlY bond coat was observed as presented in Figure 30. TGO that consisted of agglomerated \( \alpha \)-Al\(_2\)O\(_3\) particles ~100
nm in size was also observed. Figure 30 also shows that the microstructure of type I APS YSZ coating does not have the typical columnar grains within splats and splat boundaries. No other types of oxide (e.g., Ni, Cr, Co containing oxides) were found as presented by HAADF image in Figure 31. At localized regions where TGO has fully developed, atomic level bonding was observed at YSZ/TGO and TGO/bond coat interfaces as presented in Figure 32. These microstructural observations indicate that the integrity of type I APS TBCs, at least in as-coated condition, may be maintained significantly by “mechanical interlocking” with some adhesion by “atomic bonding.”

In the as-coated type V TBC sample, interfacial void between YSZ and MCrAlY bond coat was largely filled with carbon (presumably in graphite form) as seen in Figure 33. Also, TGO was completely absent. Figure 33 shows that the microstructure of type V APS YSZ coating consists of typical columnar grains within splats, and spat boundaries.

For both type I and V TBC specimens, extensive microstructural analysis on YSZ and MCrAlY bond coat was also carried out. Other results are excluded from this first semi-annual report, but will be presented appropriately in the future along with microstructural evolution of specimens after thermal cycling.

Figure 29. Ion beam image of iFIB lift out process.
Figure 30. Bright field image of as-coated type I APS TBC exhibiting extensive presence of voids, and TGO that consists of agglomerated $\alpha$-$\text{Al}_2\text{O}_3$ particles (~100 nm in size).

Figure 31. High angle annular dark field (HAADF) image of as-coated type I APS TBC showing the chemical homogeneity within TGO that consists of agglomerated $\alpha$-$\text{Al}_2\text{O}_3$ particles (~100 nm in size).
As-coated Electron Beam Physical Vapor Deposited Thermal Barrier Coatings

Figure 34 presents a secondary electron micrograph of the as-coated type III and IV EB-PVD TBCs. The specimens conformed to the specification described in Table II. Excluded from this first semi-annual report are the detailed micrographs from general microscopy using optical
and scanning microscopy (OM and SEM) for as-coated TBCs. These will be appropriately presented in the future with the evolution of microstructure with thermal cycling.

After OM and SEM, the site-specific specimen was prepared for HR-STEM using iFIB. In as-coated type III TBC, a continuous TGO layer was observed along with patches of “mixed-oxide” layer as seen in Figure 35. Defective voids between the TGO and the as-coated (Ni,Pt)Al bond coat were also locally observed as presented by white spots in Figure 35(a). Regions in TGO with “mixed-oxide” were always thicker (~0.5µm) than those consisting of continuous α-Al2O3 layer (~0.1µm) as presented by Figures 35 and 36(a). Based on n-EDS and EELS, the “mixed-oxide” layer consisted of oxides containing primarily Al, Zr, Y and Ni with traces of Cr, Co and Mo. Presence of metastable γ- and θ-Al2O3, as confirmed by PSLS in Figure 10, particularly within the “mixed-oxide” layer, is currently being investigated. Presence of the “mixed-oxide” layer and defective voids at the TGO/bond coat interface may give rise to the bimodal luminescence reported in Figures 11 and 12. Figures 36(b) and (c) present bright-field lattice images of atomic-level bonding between the TGO and the bond coat as well as YSZ and TGO in regions where defective voids were not found.

Relative to type III TBCs, the microstructure of type IV EB-PVD TBC specimen presented in Figure 37 exhibited many distinctive features including (1) larger intercolumnar voids, (2) more feathery YSZ columns, (3) thinner Al2O3 TGO without a “mixed-oxide” layer, (4) large residual α-Al2O3 particles from grit blasting, and (5) small β-(Ni,Pt)Al grains. Larger intercolumnar voids and more feathery morphology of YSZ columns for type IV TBCs may be responsible for EIS variation reported in Table IV. Microstructural feature of type VI EB-PVD 7YSZ would allow easier paths for electrolyte penetration and conduction than type III. Thus, lower ceramic topcoat and pore resistances, Rc and Rp, and higher ceramic topcoat and pore capacitance, Cc and Cp, for type IV TBC may be observed. Difference in TGO resistance and capacitance may also originate from phase constituents, grit blasting residuals, and effective thickness of TGO, although the relationship between the EIS and TGO microstructure can be better established with thermal cycling.

For both type III and IV TBC specimens, extensive microstructural analysis on EB-PVD YSZ and (Ni,Al)Pt bond coat was also carried out. Results are excluded from this first semi-annual report, but will be presented appropriately in the future along with microstructural evolution of specimens after thermal cycling.
Figure 34. Secondary electron micrograph of as-coated (a) type III and (b) type IV electron beam physical vapor deposited thermal barrier coatings.

Figure 35. (a) Bright field and (b) HAADF images of as-coated type III electron beam physical vapor deposited thermal barrier coatings with as-coated (Ni,Pt)Al bond coat.
Since successful specimen preparation by iFIB for thermally cycled TBC is critical to the success of this program, an EB-PVD TBC sample near failure, after 645, 10-hour thermal cycles at 1038°C, was received from one of the industrial partners for iFIB and HR-STEM.

**Selected Microstructural Analysis for TBCs using iFIB and HR-STEM**

Since successful specimen preparation by iFIB for thermally cycled TBC is critical to the success of this program, an EB-PVD TBC sample near failure, after 645, 10-hour thermal cycles at 1038°C, was received from one of the industrial partners for iFIB and HR-STEM.
investigation. Within 3 hours, an iFIB specimen preparation was successfully completed and is shown by the bright-field image in Figure 38. Significant decohesion (white region) at the YSZ/TGO interface, and within TGO near YSZ/TGO interface was observed. Based on selected area diffraction (SAD) pattern, TGO mainly consisted of $\alpha$-Al$_2$O$_3$. Phase identification by CBED and Fast Fourier Transformed (FFT) diffractogram from lattice images also confirmed that TGO mainly consisted of $\alpha$-Al$_2$O$_3$. A large crack in TGO that extends up to 2 $\mu$m into the TEM specimen at the top of the micrograph presumably is the damage due to cross-sectional mechanical polishing.

The YSZ, TGO, bond coat and all the interfaces in-between were further examined using high-angle annular dark field (HAADF) in scanning transmission electron microscopy (STEM) mode to obtain the diffraction/composition contrast images of the various phases, followed by n-EDS analysis. HAADF micrographs from the cross-section of the TBC are presented in Figure 39(a). Several types of oxide particles containing Zr, Ta, Ti, Cr and Ni were identified within the TGO near the YSZ/TGO interface on both sides of the decohesion as presented in Figure 39(b). Ta-, Ti- and Cr-containing oxide particles were frequently observed at the $\alpha$-Al$_2$O$_3$ grain boundaries as seen in Figure 39(c). Good interfacial adhesion was observed for the TGO/bond coat interface even after 645, 10-hour thermal cycling at 1038°C (1900°F) as seen by Figure 39(d).

![Figure 38. Bright field micrograph of intact EB-PVD TBC specimen after 645, 10-hour thermal cycles at 1038°C.](image-url)
CONCLUSION

This program seeks elucidate the failure mechanisms for TBCs during thermal cyclic oxidation under the HEET-UTSR program. Failure characteristics and mechanisms for five types of commercial production TBCs are being investigated by using two complimentary NDE techniques PSLS and EIS. In addition, microstructural analysis of TBCs is carried out at atomic-micro-macro levels using a variety of characterization techniques including high resolution scanning transmission electron microscopy (HR-STEM) with specimen preparation by iFIB. The results of NDE and microstructural analysis will be correlated to provide a clearer understanding of the failure mechanisms in TBCs and further development/refinement of NDE techniques. Attained knowledge based on fundamental science of thermo-kinetics and thermo-mechanics in this program will lead to durable, reliable and well-maintained service of TBCs by increasing the performance efficiency and reducing the emission of advanced gas turbine engines.

During this first reporting period, the non-destructive evaluation of all received TBCs in the as-coated condition by PSLS and EIS was completed. Microstructural analysis for each type of TBC in the as-coated condition was also completed using SEM equipped with EDS and HR-STEM.
TEM equipped HAADF, CBED, n-EDS, EELS. In particular, a site-specific and routine (<3 hours) preparation of TBC specimens regardless of thermal exposure for electron transparency (HR-STEM ready) was achieved using an iFIB lift out technique. No apparent damage to TBCs was observed during iFIB specimen preparation. This achievement now allows a systematic evaluation of interfacial integrity at atomic resolution and phase identification at nanoscale (~10 nm) resolution by HR-STEM.

In addition to complete NDE of as-coated TBCs, demonstrative and promising results were obtained, particularly for EIS through additional specimens that were selected and provided by industrial partners. Variations in the electrochemical resistance and capacitance of TBC constituents were correlated to the difference in the microstructure, chemistry, and thermal cycling history of TBC. The daily tasks in this program carried out by two graduate (Mr. S. Laxman and Mr. B. Jayaraj) and two undergraduate students (Miss B. Franke and Mr. C. Petorak) with additional assistance from a post-doctoral fellow (Dr. B. Kempshall) and a graduate student (Miss J. Liu). In particular, Miss B. Franke has developed extensive expertise in PSLS and is committed to pursue her graduate degree in Materials Engineering starting fall of 2003 under this current program. Education of these students through this research program will harvest engineers with technical competence and professionalism for gas turbine industry.

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INTRODUCTION

The ultimate objective of this 3-year research effort is the development of a model that will allow the direct assessment of the effect of service time on turbine aerothermodynamics. To achieve this objective will require four essential building blocks: acquisition of relevant data from serviced hardware, experimental and computational modeling of deposition and erosion (the two primary degradation mechanisms), experimental measurement of performance degradation for surfaces with service-related roughness, and finally detailed computational modeling of these performance effects. To accomplish these tasks, we have assembled a highly qualified research team with specific expertise in the required disciplines: BYU/AFRL in the measurement and wind tunnel testing of rough surfaces, Michigan State University in CFD and grid generation, and University of Cincinnati (UC) in erosion experimental and computational studies. We feel that the synergy created by the cooperative efforts of these team members applied to the four tasks listed will ultimately allow the desired objective to be achieved.

During the first six months of this effort, significant progress has been made on all fronts. Initially, representatives from 4 major engine companies were contacted to solicit in-service turbine hardware. These contacts include: Dr. Ron Bunker at General Electric Corporate R&D, Mr. Robert Bruce at General Electric – Evendale, Dr. Hee-Koo Moon at Solar Turbines, Mr. Michael Blair at United Technologies Research Center, and Mr. Ihor Diakunchak and Mr. Ed North at Siemens-Westinghouse. Discussions with several of these participants continued in earnest at the UTSR Aero-Heat Transfer V workshop in November, 2002. Since that time, components have been received from two of these contacts with hardware expected in the very near future from a third. Discussions will continue with all participants. The components delivered for measurement thus far are primarily aircraft engine components. With their much more frequent maintenance schedules, aircraft turbines are much easier to evaluate at different points in their use history than land based turbines. Since the operating environments for the two types of turbines are similar in most respects, surface measurements of roughness tend to be similar as well [1, 2, 3]. As a part of this study, comparisons will continue between the surface condition of aircraft and land-based turbine hardware.

In addition to the serviced hardware supplied thus far, we have solicited material test coupons to be used in laboratory erosion and deposition tests at UC and BYU. Several such coupons have been received thus far and testing has commenced with Dr. Tabakoff’s research group at UC. The test coupons are coated and uncoated samples of typical turbine materials. They have been installed in Dr. Tabakoff’s erosion tunnel and subjected to particulates at engine appropriate temperature, impingement angle, and velocity. The specimens are now undergoing surface evaluation at AFRL. At BYU, preparations are still being made to modify an existing combustion simulator for deposition studies. The facility will operate at appropriate engine conditions and the evolution of deposit formation from various compounds will be evaluated.

Finally, Drs. Shih and Wang at Michigan State University have begun exploring methods for efficient grid generation over surface topologies measured from serviced turbine hardware.
Results thus far suggest that by employing state-of-the-art gridding techniques, sufficiently accurate 3D grids can be generated within acceptable periods of time.

This BYU-led roughness study will provide the power generation community with the tools to predict the surface degradation history of hot section components and their associated performance decrements. This critical information will allow the engine user to establish more economical maintenance schedules and procedures. Operators will have a better idea of the cycle penalties associated with accumulated surface roughness and be able to make informed decisions about when to take their power plant off line for maintenance. At the same time, engine designers will have the ability to estimate the expected performance history of their product for a given operating environment. The combination of these added capabilities will reduce operating costs for the energy producer and prevent possible emergency shut-downs due to unanticipated surface degradation or part failure.

Though this is only the first report in what is hoped to be a very successful research venture, the results are promising. Industrial participation is a critical part of this study, since it insures the relevancy of the findings. We continue to enjoy active participation from a wide range of turbine manufacturers. The study includes both the measurement of actual hardware and the laboratory simulation of degradation mechanisms. By performing the two components in parallel, we hope to insure the relevancy of the laboratory simulations. Because they are performed in a controlled environment, these erosion and deposition studies should provide the framework for semi-empirical roughness evolution models. As these models are incorporated into computational codes, this will in turn provide the engine community with powerful roughness predictive capabilities.

**EXPERIMENTAL**

Turbine materials supplied thus far include aircraft engine components from GE-Evendale and sectioned ground power turbines from GE-Corporate. Target coupons have also been received from GE-Corporate. The precise features of the various articles are not to be divulged in order to respect proprietary concerns of the industry participants. Surface measurements are being made with a Taylor-Hobson Form Talysurf Series 2 contact stylus measurement system at AFRL. Future measurements will also be made using a Hommel contact stylus measurement system at BYU. The specific characteristics of the erosion tunnel employed in UC’s testing are presented in [5]. A schematic of the facility is provided in Figure 1. The facility matches operating turbine temperatures and particle impact velocities over a full range of impingement angles with various target materials and particulates.
RESULTS AND DISCUSSION

Representatives from 4 major engine companies have been contacted to solicit in-service turbine hardware. These contacts include: Dr. Ron Bunker at General Electric Corporate R&D, Mr. Robert Bruce at General Electric – Evendale, Dr. Hee-Koo Moon at Solar Turbines, Mr. Michael Blair at United Technologies Research Center, and Mr. Ihor Diakunchak and Mr. Ed North at Siemens-Westinghouse. Since that time, components have been received from two of these contacts with hardware expected in the very near future from a third. Discussions will continue with all participants. The components delivered for measurement thus far are primarily aircraft engine components. Preliminary surface analyses conducted at AFRL thus far indicate a strong roughness dependency on three operating parameters: service time, operating environment, and turbine user. The first two dependencies were expected based on previous work. The dependency on the operator was not expected and appears to stem from the different maintenance schedules/procedures employed by the various engine operators. A more complete report of these data will be forthcoming in the annual report.

To supplement the data acquired from these industrial sources, we have made contact with 2 engine service facilities: the Air Force’s turbine maintenance facility at Oklahoma City (OC-
Because of its wide array of industry contacts, Standard-Aero has access to a substantial inventory of used turbine parts and will hopefully be an active participant. The expected difficulty in locating land-based turbine hardware with low operating hours (less than 10,000hrs) has led us to also pursue a measurement program with the US Air Force’s aircraft turbine hardware at OC-ALC. We expect to have substantial interaction with these two entities before the next reporting period.

In addition to the serviced hardware supplied thus far, we have solicited material test coupons to be used in laboratory erosion and deposition tests at UC and BYU. Several such coupons have been received thus far and testing has commenced with Dr. Tabakoff’s research group at UC. The test coupons are coated and uncoated samples of typical turbine materials. They have been installed in Dr. Tabakoff’s cold erosion tunnel and subjected to fine sand particulates at 100m/s and 4 different impingement angles (20, 40, 60, & 90). The specimens are now undergoing surface evaluation at AFRL. At BYU, preparations are still being made to modify an existing combustion simulator for deposition studies. The facility will operate at appropriate engine conditions and the evolution of deposit formation from various compounds will be evaluated.

Finally, Drs. Shih and Wang at Michigan State University have begun exploring methods for efficient grid generation over surface topologies measured from serviced turbine hardware. By employing a novel viscous adaptive Cartesian grid method, sufficiently accurate 3D grids can be generated for a standard RANS-type solver. Immediate plans call for the implementation of a low Reynolds number model to the existing code, followed by an LES implementation, and then DES. A sample 2D slice of a 3D grid generated using this adaptive method is shown in Figure 2.

Due to the time-intensive nature of these 3D calculations, MSU researchers are also pursuing lower order roughness models that will provide designers with practical engineering models of roughness effects. As such, intuition gained using RANS and DES solvers will be analyzed with the hope of finding simple but accurate roughness models that could be employed without the
necessity of resolving the precise roughness features. Specific features of interest include both
peaks due to deposits and TBC spallation as well as pits (valleys) created by erosion.

CONCLUSION

Though this is only the first report in a multi-year research effort, the results are promising. Industrial participation has been positive and is expected to accelerate in the next reporting period. Meanwhile erosion and deposition laboratory simulations proceeding on schedule and should provide the framework for semi-empirical roughness evolution models. As these models are incorporated into computational codes developed at MSU, this will in turn provide the engine community with powerful roughness predictive capabilities.

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RFP for Year 2001

Ten university proposals were short-listed by the Industrial Review Board (IRB) during the September IRB meeting. The number of projects that will be funded will depend on the budget for the continuation of the university research program. Awards for 2001 research projects have been awaiting the award by the DOE to SCIES for the university program continuation. The contract was received in late March and is being reviewed by the Clemson University Research Foundation and SCIES before signing.

RFP for Year 2002

Recent DOE emphasis for the developing High Efficiency Engines and Turbine (HEET) program has been directed to coal-based turbine systems. Since coal-fueled turbine applications have not previously been a focus of the university research program, the IRB companies were asked to recommend additional university research topics related to coal-based turbine systems and rank them along with those that were provided by SCIES in January.

Very few coal-related topics were provided the IRB in February with their rankings of RFP topics. Consequently, SCIES has requested information from the DOE on needed coal research from the latest roadmaps that are being developed through meetings in recent months at the HEET Roadmapping Workshop and a HEET Roadmapping meeting at the end of the Turbine Power Systems and Condition Monitoring Workshop. The DOE provided information on material presented at these meetings but, to date, the DOE roadmaps have not been generated and the large number of potential research topics presented at the meetings have not been prioritized by the DOE. It appears uncertain that the DOE Roadmaps and DOE ranking of turbine research for alternate fuels will be ready in time for release of the university RFP in May.

Consequently, the highest ranked topics by the IRB will be expanded to consider coal syngas and alternate fuels to meet the schedule for release of the RFP. Many of the high priority technology issues for natural gas are even more challenging for alternate fuels.

Materials Workshop II

The AGTSR Materials Workshop II was co-hosted with Prof. Maurice Gell of the University of Connecticut and conducted in Greenville, SC. The proceedings on CD were completed and distributed in March.
Workshops for 2002

Contracts for hotel, meeting room, and conference arrangements have been signed for all three workshops in 2002. Workshop dates and venues are:

- Combustion Workshop IX, August 26-28, 2002, Hosted by Penn State University
- Materials Workshop III, October 14-16, 2002, Hosted by the University of Connecticut
- Aero-Heat Transfer Workshop V, November 11-13, Hosted by Louisiana State University

Work has started on draft agendas for two of the workshops.

Progress Reports from AGTSR University Projects

Three semi-annual reports and one final report from AGTSR university projects were received in March. The final report was received from project SR047/Northwestern University.

Membership

Invoices for 2002 IRB membership dues were mailed in February. Payments from two voting members and three associate members were received in March.

Industrial Internships

Graduating seniors, MS and Ph D students from AGTSR Performing Member Universities will be placed as interns for 10-12 weeks at IRB organizations of the AGTSR. Because an insufficient number of internship applications were received by the deadline in February, the application deadline was extended to March 6 and all of performing member universities were contacted again to encourage student applicants. This has resulted in 16 applicants, compared to 12 interns placed in 2001.

However, two non-citizen applicants have applied for, but have not yet received, Permanent Resident Alien (PRA) status required by the DOE. SCIES is awaiting a clear response from the DOE whether these two applicants can be considered, since they might receive PRA status before the end of their proposed internship intervals. Another student indicated on his application that he has work authorization (unspecified) in the US but a further inquiry has shown that he does not have PRA status. Also, one student has withdrawn his application because of other summer plans.

Success Story

Additional Advantages for Catalytic Combustors

Conventional low NOx combustors currently used in gas turbines sustain combustion in regions of large-scale flow re-circulation. This causes large-scale turbulence that propagates into the first stage turbine vanes. The large-scale turbulence produces high rates of heat transfer to the vanes, which consequently must be highly cooled.
Under the Advanced Gas Turbine Systems Research (AGTSR) program, the University of North Dakota (UND) has used experiments and computer analyses to evaluate the effects of flow characteristics representative of catalytic combustors on first stage vane cooling requirements. The research has verified that the relatively small scale and low level turbulence representative of catalytic combustors can reduce heat transfer to vanes by a factor of two compared to turbulence representative of conventional low emission combustors. Consequently, catalytic combustors are capable of not only reducing turbine emissions compared to current low NOx combustors, but UND has also shown they might provide advantages to turbine designers in reducing cooling requirements and the complexity of first stage vanes.

**Miscellaneous**

- SCIES is organizing a regional workshop on the HEET Program, in cooperation with NETL, the US DOE Atlantic Regional Office, Georgia Tech, and the Southern States Energy Board. The location is on the Georgia Tech campus in Atlanta and the dates are May 1 and 2, 2002. The workshop will address Southeast Region power needs and mechanisms of cooperation between region stakeholders and the HEET program.

- In response to a request by Marvin Singer from DOE Headquarters, SCIES prepared a discussion on a combined success story concerning thermal barrier coating advancements in AGTSR projects at the University of Connecticut and Northwestern University.

- Draft Fact Sheets on active AGTSR projects were previously provided to the DOE. The DOE organized these Fact Sheets into a format for publication, which were sent to SCIES for review in March. All reviews were returned to the DOE along with additional figures for the Fact Sheets.
REPORT FOR APRIL

Completed Tasks

- The principal investigators (PIs) of the ten short-listed projects from the year 2001 RFP were notified by telephone of their impending awards. The new and additional reporting requirements for the HEET university research program were also discussed with them. The subcontracts for the new projects will be sent to the universities in early May.
- A draft of the year 2002 RFP was completed. The RFP will be sent in electronic format in May for distribution within their institutions to the points of contact of the 101 AGTSR Performing Member universities.
- SCIES responded to a DOE urgent request to provide descriptions of four university projects for a Vision 21 report to the National Research Council.
- Final arrangements were completed by SCIES for the organization of the May regional workshop on the HEET Program in Atlanta.
- A search for the new position of Manager of Outreach Development was completed. Bill Day, formerly IRB Focal Point to the AGTSR, has accepted this position.

Key Milestone Update

There are no milestone modifications this month.

Discussion Topics

There are no issues that require DOE COR attention or action this month.

Significant Accomplishments – Success Story

Under a continuing AGTSR project, the University of California at Santa Barbara is developing a scientific basis for improving thermal barrier coatings (TBCs) used in gas turbines. One effort is determining how TBCs fail under cyclic conditions and how impending failures might be detected. Determining how TBCs fail will aid in the development of better coatings. Detection before failure will enable turbine parts to be taken out of service before loss of the protective coating.

The project has shown that an early warning of TBC internal damage leading to eventual failure is wrinkling or rumpling at the surface of the TBC that increases with time and the number of thermal cycles. These surface undulations are evidence of separation of the outer ceramic coating layer from an internal thermally grown oxide layer and can be detected using low level magnification and oblique illumination. The project has also shown that use of laser techniques to monitor the change in internal stresses within the TBC combined with monitoring surface rumpling enhances the ability to detect TBC degradation before failures that limit the protection of the underlying metal surface.
Presentations and Publications

- The CDs with 13 AGTSR technical reports for January 1 to March 31, 2002 were sent to the IRB companies for review and comments.
- A presentation “Gas Turbine Research in the AGTSR Program” is being prepared for ASME Turbo Expo in Amsterdam on June 3-5, 2002.

Site Visits

No site visits occurred or were planned with high level corporate or government officials this month.

Travel

SCIES will conduct on May 1 and 2, 2002 the regional workshop in Atlanta on the HEET Program.
REPORT FOR MAY

Completed Tasks

- Subcontracts were awarded for nine of the ten short-listed university projects from the year 2001 RFP. The final subcontract has been delayed because the Principal Investigator (PI) has moved to another university. The university from which the original proposal was issued has agreed to allow the project to be awarded to the institution to which the PI has moved. The PI has prepared an amended proposal with the only the change of university of the PI. The work statement and all facilities and subcontracts remain unchanged.
- The University of Massachusetts at Amherst was added as a new AGTSR-HEET Performing Member University. With this addition, there are now 102 Performing Member Universities in 38 states.
- The RFP for year 2002 was sent in electronic format on May 15 to the points of contact at the AGTSR Performing Member universities for distribution within their institutions. The RFP was also sent to the professors who had previously received AGTSR project awards.
- Eight students from AGTSR-HEET Performing Member Universities were placed as industrial interns for periods of 10 to 12 weeks at AGTSR-HEET Industrial Review Board organizations.
- SCIES worked with Prof. Dom Santavicca to produce a first draft agenda for Combustion Workshop IX on August 26-28, 2002 at Penn State University.
- The contract required Power Point Presentation describing the new AGTSR-HEET university program was prepared and sent to Tom George, the DOE COR.
- The contract required Program Plan for the new AGTSR-HEET university program was prepared and sent to the contract COR.
- Six proposal debriefings were given by telephone to professors who had not received awards from the year 2001 RFP.
- SCIES responded to a DOE urgent request to provide a description of the AGTSR-HEET university program for a Vision 21 report.

Key Milestone Update

There are no milestone modifications this month.

Discussion Topics

There are no issues that require DOE COR attention or action this month.

Significant Accomplishments – Success Story

Under the Advanced Gas Turbine Systems Research (AGTSR) program, Texas A&M is evaluating methods to improve cooling for gas turbine airfoils. The project experimentally and computationally evaluates parameters and design aspects associated with airfoil internal cooling passages with rectangular cross sections and various internal features such as dimples to enhance
cooling effectiveness. Evaluations in the program have shown that dimples on interior surfaces of cooling channels can improve cooling effectiveness by as much as a factor of two compared to smooth cooling channels.

The stationary and rotating experimental and computational results from this project will provide turbine engineers with new data for design of airfoil internal rectangular cooling passages and thereby potentially improve the cooling efficiency and thermal efficiency of gas turbines.

**Presentations and Publications**

- The CDs with 13 AGTSR technical reports for January 1 to March 31, 2002 were sent to the IRB companies for review and comments.
- A presentation “Gas Turbine Research in the AGTSR Program” was completed for ASME Turbo Expo in Amsterdam on June 3-6, 2002.

**Site Visits**

No site visits occurred or were planned with high level corporate or government officials this month.

**Travel**

On May 1 and 2, 2002 SCIES conducted a regional workshop in Atlanta on the HEET Program.
REPORT FOR JUNE

Completed Tasks

- The subcontract was awarded for the tenth and final short-listed university project from the year 2001 RFP.
- The University of Alaska at Fairbanks was added as a new AGTSR-HEET Performing Member University. With this addition, there are now 103 Performing Member Universities in 39 states.
- The RFP for year 2002 was released in electronic format in May. The recipients were notified in June of a modification of the RFP according to a modification of SCIES cooperative agreement with the DOE. This modification allows for up to 10% of the total budget of university research subcontracts for purchase of supplies and equipment.
- SCIES is proposing a change in the scope of university research to achieve linkage between different technical fields (example: coal gasification and gas cleanup in addition to turbines). A draft white paper has been written, and meetings are being set up with key FE executives.
- Proceedings were released for the first HEET Regional Workshop, held in Atlanta on May 1-2.
- The second HEET Regional Workshop will be held back to back with the Combustion Workshop IX on August 26-28, 2002 at Penn State University. This will save cost and facilitate attendance at the Regional Workshop by university people. A preliminary agenda has been prepared, and speakers are being lined up. The registration package and preliminary agenda have been sent to potential attendees specializing in combustion and a later mailing will invite a broader audience.
- For Regional Workshops in the west, arrangements have been made to combine efforts with the National Association of State Energy Officials (NASEO), who are working under a DOE-FE contract to hold regional workshops in Portland, OR, Denver and San Francisco. The purpose is to address the issues, needs and opportunities for collaboration on advanced turbines and hybrid fuel cell systems in the western states. Combining the Regional Workshops with the NASEO meetings will save cost and avoid asking many of the same audience to attend two similar sets of workshops.
- The contract required Fact Sheet describing the new AGTSR-HEET university program was prepared and sent to Tom George, the DOE COR.
- Another proposal debriefing was given by telephone to a professor who had not received an award from the year 2001 RFP.

Key Milestone Update

There are no milestone modifications this month.

Discussion Topics

There are no issues that require DOE COR attention or action this month.
Significant Accomplishments – Success Story (AGTSR Project)

Under the Advanced Gas Turbine Systems Research (AGTSR) program, a University of Connecticut (UCONN) project has the goal of identifying a new thermal barrier coating (TBC) material with improved properties over those for the conventional TBC now used in turbines. Two of those properties are lower thermal conductivity (to better insulate underlying metal surfaces) and no reactivity with the aluminum oxide scale that forms on the interface between the insulation layer and the bond coat layer on the metal turbine part. Experiments at UCONN have previously shown that compositions of gadolinium zirconates (Gd-Zr) have over 30% lower thermal conductivity than the conventional TBC material. Recently reported experiments have shown that Gd-Zr compositions do not react with aluminum oxides even at 500°F higher than turbine temperatures. Consequently, UCONN has identified a material with two important superior properties over those for current TBCs used in turbines.

Presentations and Publications

A presentation “Gas Turbine Research in the AGTSR Program” was given at ASME Turbo Expo in Amsterdam on June 5, 2002.

Site Visits

The IRB Focal Point persons have been asked to confirm their availability for the Industrial Review Board (IRB) Meeting at SCIES on September 24-25. Purposes of the meeting are to short list university proposals and discuss the AGTSR-HEET program.

Travel

Bill Day, AGTSR-HEET Manager of Outreach, traveled to Washington DC to discuss the scope of activities for SCIES during a meeting at DOE Fossil Energy headquarters.
REPORT FOR JULY

Completed Tasks

- Forty-nine (49) university proposals were received in response to RFP HEET 02-01. The proposal distribution among technical areas is:

Combustion……………………………………………………………17
Aero-Heat Transfer…………………………………………………15
Materials……………………………………………………………11
Reliability, Availability, and Maintainability (RAM)……….6

The proposals and ranking forms were sent to the Industrial Review Board (IRB) organizations for evaluation. The IRB rankings are due back at SCIES on August 21.

- A regional meeting on the HEET Program was held in conjunction with the regional Advanced Gas Turbine Opportunities Workshop for the Pacific Northwest region in Portland, OR on July 22, 2002. The conference was hosted by the National Association of State Energy Officials (NASEO) and was funded by DOE - FE. It was the first of three such meetings to be held in the western states this summer. It was decided to combine the HEET Regional meetings for the western states with the NASEO meetings in order to reduce the number of meetings required to gain input on the HEET Program from different regions of the U.S. Attendees included regional representation from installers of combined heat and power (CHP) systems, gas utilities, turbine manufacturers, universities, state and municipal governments, and research institutes.

Principal conclusions were:

a) Hybrid systems are of the most interest among HEET objectives.
b) High efficiency is of interest due to CO2 offset charges and tax credits
c) Low cost hydro power is a detriment to DG; less incentive than in higher cost regions
d) There is no interest in coal in the region, except Montana and Alaska.
e) Most existing capacity is hydro; major new capacity additions are gas turbines fired with natural gas imported from Canada.
f) High efficiency HEET combined cycles (fired with natural gas) are of interest due to CO2 offset charges and tax credits.
g) Reduced capital cost ($/kW) of both large and small systems needs to be emphasized; necessary for widespread deployment and achieving public benefits.

- SCIES provided inputs to two Secretary’s (of Energy) Reports. One concerned a University of Connecticut project to develop advanced thermal barrier coatings and the other concerned the HEET Regional Meeting in Portland.

- Preparations are nearly completed for Combustion IX Workshop on August 26-28 and the HEET Regional Workshop on August 27-28 at Penn State University.
The HEET Regional Workshop for the Philadelphia (Mid-Atlantic) Region is being held in conjunction with the Combustion Workshop at Penn State, in order to reduce the number of separate meetings. Speakers have been arranged for both meetings, the agendas have been set and invitations have been sent out. Over 50 people have registered so far, most of whom will attend both meetings.

- The preparations for the registration mailing for Materials Workshop III at the University of Connecticut in October were nearly completed at the end of July. The preliminary agenda has been completed and the speakers have been arranged.

- The first draft agenda is being refined for Aero-Heat Transfer Workshop V at Louisiana State University in November.

- University project Fact Sheets and Power Point presentations have been received for a Virginia Tech project on improved prediction of turbine blade internal cooling and a University of Central Florida project on assessments of thermal barrier coating failure mechanisms.

Key Milestone Update

There are no milestone modifications this month.

Discussion Topics

There are no issues that require DOE COR attention or action this month.

Significant Accomplishments – Success Story (AGTSR Project)

Under the Advanced Gas Turbine Systems Research (AGTSR) program, a recently completed University of Connecticut (UCONN) project had a goal of advancing a laser fluorescence (LF) technique as a non-destructive evaluation (NDE) technique for anticipating and predicting thermal barrier coating (TBC) failures. TBC life variability is high and NDE approaches are needed to remove turbine parts from service before failure and resulting forced turbine shut down. The LF technique was used to measure internal stresses within three types of TBC coatings on specimens cycled to three high temperatures. The tests showed that TBC failure occurred only over narrow range of measured stresses and it is possible for LF to predict the time of failure to within 7 % of expected life from measurements made prior to half of the coating life. LF was also used to measure stresses in 20 turbine vanes and blades before and after operation in engines. The LF measurements were readily obtained and the measured stresses in the turbine parts decreased in a way consistent with those observed in the laboratory experiments.

Significance: The project has shown that LF can provide predictions of remaining TBC life that are sufficiently reliable for engineering use.
Presentations and Publications

The Technical Quarterly Progress Report for April through June 2002 for Cooperative Agreement DE-FC-21MC29061 was sent to the DOE on July 30.

Site Visits

The dates of September 24-25 have been confirmed for the annual IRB Meeting at Clemson.

Travel

On July 22, SCIES participated in a regional workshop in Portland OR as part of program planning for the HEET Program.
REPORT FOR AUGUST

Completed Tasks

- Forty-nine (49) university proposals have been received in response to RFP HEET 02-01. In July, the proposals and ranking forms were sent for evaluation to the Industrial Review Board (IRB) organizations. Nearly all of the IRB rankings were received at SCIES by the end of August. Work started to compile the proposal scores from the individual IRB organizations to obtain consensus rankings.

- Combustion IX Workshop and a HEET Regional Workshop were conducted at Penn State University on August 26-28. In order to reduce the number of separate events, the two meetings overlapped with combined sessions on the afternoon of August 27 and morning of August 28, followed by a facilitated discussion session to identify the needs and increase public benefits of the HEET Program for the Philadelphia (Mid-Atlantic) Region. Fifty-five people attended the Combustion Workshop, including 39 people who attended both meetings. Nineteen additional people attended only the HEET Regional Meeting.

There was excellent regional representation that included energy consortia, power generators, turbine manufacturers, universities, state governments, DOE – FE and EE, and consultants. Conclusions from the HEET Regional Meeting are being compiled.

- A regional meeting on the HEET Program was held in conjunction with the regional Advanced Gas Turbine Opportunities Workshop for the Mountain States in Denver, CO on Aug. 15, 2002. The conference was hosted by the National Association of State Energy Officials (NASEO) and was funded by DOE - FE. This was the second of three such meetings for the western states this summer. It was decided to combine the HEET Regional meetings for the western states with the NASEO meetings in order to reduce the number of meetings required to gain input on the HEET Program from different regions of the U.S.

Attendees included regional representation from installers of combined heat and power (CHP) systems, gas utilities, turbine manufacturers, universities, state and municipal governments, and research institutes. Principal HEET - related conclusions were: There is interest in coal; the IGCC portion of HEET would be a benefit to the region due to lower emissions in the air management area. The hybrid side of HEET is of interest due to the interest in DG. The use of coal-derived liquids such as methanol would be more practical than coal gasification for DG-size hybrids. Gas turbine research should make the gas turbines compatible with a range of non standard gases, not only coal gas. This is influenced by the wide use of non-standard fuels in the region. At $3M/year, the university research funding is too low to reach enough universities; it should be increased.

- A preliminary agenda and the registration materials were mailed to potential attendees for the Materials Workshop III to be held at the University of Connecticut on October 14-16.
- Nearly all of the speakers have been identified and a preliminary agenda has been completed for the Aero-Heat Transfer Workshop V to be held at Louisiana State University on November 11-13.

- At DOE request, SCIES provided input descriptions of nine university projects and other program activities for a Techline report.

- University project Fact Sheets and Power Point presentations have been received for a Georgia Tech project on improved understanding and control of turbine combustor instabilities and a Brigham Young project on effects of service on turbine airfoil surface degradation.

Key Milestone Update

There are no milestone modifications this month.

Discussion Topics

There are no issues that require DOE COR attention or action this month.

Significant Accomplishments – Success Story (AGTSR Project)

The analysis techniques to design natural gas fired, low emissions turbine combustors have been insufficient to predict and completely eliminate instabilities which cause unacceptable noise, structural damage, and removal of turbines from service. Available analysis techniques in this area are even less capable for liquid turbine fuels.

Under the Advanced Gas Turbine Systems Research (AGTSR) program, a recently completed Pennsylvania State University (PSU) project conducted experiments with a variety of liquid fuels in a low emissions combustor to evaluate effects of operating conditions and fuel characteristics on stability and emissions performance.

Significance: The experiments have provided a database obtained under well-defined and controlled conditions to aid in the development of computational models for predicting instabilities and designing gas turbine combustors. General Electric and CFD Research Corporation are currently using this database to validate new combustor design computational models.

Presentations and Publications

A White Paper on gas turbine research needs to facilitate operation with alternate fuels (including syngas) was provided to the DOE. Co-authored by persons from SCIES and Oak Ridge National Labs, this White Paper was produced for a DOE/Navy workshop on alternate fuels for gas turbines at Colorado School of Mines to be held in October.
Site Visits

The dates of September 24-25 are planned for the annual IRB Meeting at Clemson.

Travel

SCIES personnel participated in the workshops described above in Denver, CO on Aug. 15, and Penn State (State College, PA) on Aug. 26-28.
REPORT FOR SEPTEMBER

Completed Tasks

- Forty-nine (49) university proposals have been received in response to RFP HEET 02-01. A short list of nine proposals was selected and ranked at the IRB Meeting at SCIES on September 24-25. Three proposals were in the area of combustion and two proposals were in each of the areas of materials, aero-heat transfer, and RAM. Five of the top six proposals have synfuel content. The number of proposals to be funded will depend on the level of DOE funding for the UTSR in 2002.

- SCIES prepared and sent to the DOE summary descriptions of 31 active AGTSR and UTSR university projects. These descriptions included principal investigator contact information, contract information (e.g., cost, duration), and a brief description of each project.

- Boston University was added as a new UTSR Performing Member University. With this addition, there are now 105 Performing Member Universities.

- Final preparations and agenda modifications were in progress this month for the Materials Workshop III to be held at the University of Connecticut on October 14-16.

- A preliminary agenda and the registration materials were mailed to potential attendees for the Aero-Heat Transfer Workshop V to be held at Louisiana State University on November 11-13.

- At DOE request, SCIES provided input to a table of technical issues for transitioning UTSR research from natural gas to syngas fuels.

- University project Fact Sheets and Power Point presentations have been received for a LSU project on improved cooling of turbine passage endwalls, a University of Connecticut project on a simplified life prediction method for thermal barrier coatings, and a University of Pittsburgh project on testing methodology for improved coatings for gas turbines.

- Agreement was reached with the Vic de Biasi, publisher of Gas Turbine World Magazine, to work together on an article to be published in GTW on the UTSR Program. Fact Sheets on four university projects were sent to Vic.

- NASEO - HEET Regional Workshop in Palo Alto:
  A regional meeting on the HEET Program was held in conjunction with the regional Advanced Gas Turbine Opportunities meeting in Palo Alto, CA on Sept. 5, 2002. The conference was hosted by the National Association of State Energy Officials (NASEO) and was funded by DOE - FE. This was the third of three such meetings, which were held in the western states this summer. It was decided to combine the HEET Regional meetings for the western states with the NASEO meetings in order to reduce the
number of meetings required to gain input on the HEET Program from different regions of the U.S.

Attendees included regional representation from utilities, universities, manufacturers, state governments, and research institutes. Principal HEET-related conclusions were:

There is no interest in using coal in California. They burn coal in other states and import the power by wire.

There is interest in coal in Nevada, but not in coal gasification because the Pinion Pines IGCC project in Nevada is considered to be a big failure.

The hybrid side of HEET is of interest due to the interest in DG.

Gas turbine research should make the GT's compatible with a range of non-standard gases, not only coal gas. This is influenced by the increasing use of renewable fuels in the region.

At $3M/year, the university research funding is too low to accomplish enough; it should be increased.

- For the remaining two regional meetings to get input on the HEET Program, it has been decided to have brief meetings in Boston and Chicago. We will get the assistance of the National Association of State Energy Officials (NASEO) to reach stakeholders in those regions.

- Work has begun on connecting with stakeholders in the coal industry, including coal gasification combined cycle interests, to educate them and get input from them on the HEET Program. Doug Todd (Gasification Technologies Council) and Jeff Abboud (Gas Turbine Association) have provided information on IGCC (emissions and economics) and contact information in the coal industry, which will be used in developing a message to the coal interests.

Key Milestone Update

There are no milestone modifications this month.

Discussion Topics

There are no issues that require DOE COR attention or action this month.
**Significant Accomplishments – Success Story (AGTSR Project)**

The premixer of gas turbine combustors is a critical component. Thorough mixing must be accomplished in very short time intervals under fuel lean conditions to achieve low emissions without damaging flashback into the premixer. Combustion instability oscillations resulting from operation near lean blowout limits must be controlled since such pressure oscillation can cause unacceptable noise and fatigue induced structural damage and failure of the turbine combustor.

Under the Advanced Gas Turbine Systems Research (AGTSR) program, a Purdue University (PU) project is conducting experiments to measure the flow fields and pressure oscillations in a Solar Turbines premixer and a General Electric turbine premixer for a range of operating conditions.

**Significance:** The experiments have provided insights on the effects of operating conditions and flow field characteristics on instabilities for low emissions turbine premixers. Such insights can enable turbine designers to improve stability performance of turbine combustors.

**Presentations and Publications**

A presentation on gas turbine research needs to facilitate operation with alternate fuels (including syngas) was initiated. Two versions of this presentation will be delivered, one at the UTSR Materials Workshop III at the University of Connecticut on October 14-16 and the second at a DOE/Navy workshop on alternate fuels for gas turbines at Colorado School of Mines on October 22-24.

**Site Visits**

The Industrial Review Board visited SCIES for the annual IRB Meeting described above.

**Travel**

Bill Day traveled to Palo Alto for the NASEO-HEET Regional meeting described above.
REPORT FOR OCTOBER

Completed Tasks

- Materials Workshop III was held at the University of Connecticut on October 14-16. Forty-eight people from academia, industry and government attended the workshop. The agenda included presentations by universities on current HEET-UTSR materials projects and presentations by industry on needed materials research applicable to universities. New activities were described associated with the DOE transition from the previous ATS program to the HEET program.

- The final agenda was completed for the Aero-Heat Transfer Workshop V to be held at Louisiana State University on November 11-13.

- Forty-nine (49) university proposals were received in response to RFP HEET 02-01. A short list of nine proposals was selected and ranked at the IRB Meeting at SCIES on September 24-25. Three proposals were in the area of combustion and two proposals were in each of the areas of materials, aero-heat transfer, and RAM. Five of the top six proposals have synfuel content. The principal investigators of the nine highest ranked proposals were notified that their proposals are on the short list and were asked to examine their budgets to determine if a 5 to 10 % budget reduction is possible. The goal is to reduce costs so as to increase the number of projects on the short list that might receive awards. Also, the principal investigators for proposals not on the short list were notified that they would not receive awards.

- Honeywell has inquired about possible participation on the Industrial Review Board (IRB) of the UTSR program. Information was sent to Honeywell that describes the activities, membership benefits, and Industrial Review Board membership dues for the UTSR consortium.

- A mini Regional Meeting on the HEET Program was held at UCONN immediately after the Materials III Workshop, for stakeholders from the State of Connecticut. Attending were a representative from the Energy Section of the Office of Policy and Management, a consultant suggested by the latter who formerly held that job and now consults on State matters, Vic de Biasi, the publisher of Gas Turbine World and Dick Tuthill of P&W, Chair of the IRB. Some HEET-related comments:

  The hybrid portion of HEET would fit very well with the needs of CT. Distributed generation is of interest, due in part to transmission line constraints. There is agreement that to the extent coal-derived fuels are required for the hybrids, an on-site coal gasifier does not make sense, but coal-derived methanol does. The state has a presence of fuel cell manufacturers and small gas turbine manufacturers, which adds to the attractiveness. The IGCC end of HEET would benefit CT by widespread deployment in the Midwest, which would reduce the considerable pollution coming to CT via air transport from the Midwest. It
is questionable whether IGCC’s would be built in CT, but if they were, the goal of making them as clean as NGCC’s (e.g. 3 PPM NOx) would be necessary. An issue is the perception among environmentalists that Clean Coal is an oxymoron. HEET would gain increased public support if it included gasification of biomass fuels, including municipal solid waste, not just coal. This supports the idea of getting EERE and FE sides of DOE to work closely together during the HEET Program, and to promote both efforts together.

- An action which came out of the Mid Atlantic Regional Meeting at Penn State in August was that we need to connect with the coal industry in order to enhance support for the HEET Program. Contact is now established with the Gasification Technologies Council and the Center for Energy and Economic Development, both of which are influential with the coal industry. This was done via Jeff Abboud of the Gas Turbine Association and Doug Todd, former head of IGCC’s at GE and now a consultant in the IGCC field. These contacts will be the basis for work with the coal industry to advocate full government support for the HEET Program.

- Based on suggestions from the University panel at the Penn State meeting, we have developed a set of enhancements to the industrial internship program, with worthwhile input from Karen Thole of VA Tech. These are now being circulated to the IRB for comment. The intent is to improve the value of the program to the students so we attract more of the best and brightest to the gas turbine industry.

- R. Wenglarz represented SCIES at a DOE/Navy workshop on alternate fuels for gas turbines at the Colorado School of Mines on October 22-24. He had previously prepared a White Paper “Alternate Fuels for Land-Based Turbines” with Ian Wright of Oak Ridge National Laboratories which describes past turbine and laboratory test experience using alternate fuels and recommends needed technology development to enable future turbines to operate with syngas and biomass fuels. This White Paper, and others related to turbine corrosion, were reviewed by workshop participants. The revised White Papers that incorporate comments from workshop participants will be published in a book of the workshop proceedings.

Key Milestone Update

There are no milestone modifications this month.

Discussion Topics

There are no issues that require DOE COR attention or action this month.

Significant Accomplishments – Success Story (AGTSR Project)

Low emission turbine combustors operate near their lean blowout limits where combustion temperatures and resulting NOx emissions are low. However, this has caused combustion pressure oscillations and instabilities with accompanying noise and vibrations. In a number of
cases, such pressure oscillations have resulted in unacceptable noise, vibration induced fatigue structural failures in engines, and removal of commercial turbines from service for repair.

Under the Advanced Gas Turbine Systems Research (AGTSR) program, a Georgia Tech (GT) project has developed a new experimental technique for determining the stability margin of combustors, which is a measure of how close they are to becoming unstable.

**Significance:** Turbine operators have little warning of how close the combustors is to becoming unstable, unless an actual instability occurs. Since the GT approach can determine combustor stability margins, operators could avoid combustor instabilities and resulting excessive noise, structural failures, and forced shutdowns.

**Presentations and Publications**

Presentations on gas turbine research needs to facilitate operation with alternate fuels (including syngas) were delivered at the UTSR Materials Workshop III at the University of Connecticut on October 14-16 and at a DOE/Navy workshop on alternate fuels for gas turbines at Colorado School of Mines on October 22-24.

**Site Visits**

No site visits occurred or were planned with high level corporate or government officials this month.

**Travel**

For the workshops described above, SCIES staff (Larry Golan, Bill Day, Rich Wenglarz, Donna Partain) traveled to the Materials III Workshop and Rich Wenglarz traveled to DOE/Navy Workshop on alternate fuels for gas turbines.
REPORT FOR NOVEMBER

Completed Tasks

- Aero-Heat Transfer Workshop V was held at Louisiana State University on November 11-13. Thirty-five people from academia, industry and government attended the workshop. The agenda included presentations by universities on current AGTSR/UTSR aerodynamics and heat transfer projects and presentations by industry on needed research in those technology areas that would be applicable to universities. New activities were described associated with the DOE transition from the previous ATS program to the HEET program.

- During the Aero-Heat Transfer Workshop V, a UTSR outreach meeting was held with Mike French, Director of Technology Assessment at the Louisiana DNR. Also attending the meeting were Ting Wang (U of New Orleans) and Sumanta Acharya (LSU). It is expected by mid January that the UTSR should receive an “outreach” proposal from the Louisiana DNR.

- The principal investigators of the nine highest ranked proposals at the IRB Meeting had been notified in October that their proposals are on the short list and were asked to examine their budgets to determine if a 5 to 10% budget reduction is possible. The goal is to reduce costs so as to increase the number of projects on the short list that might receive awards. Most of the universities have responded with budget reductions ranging from 4.5% up to about 9%.

- Fellowship Program: The brochure on the new Gas Turbine Industrial Fellowship Program, containing enhancements to attract more students, has been sent to both the UTSR university contacts and the graduate school offices at those universities.

- Connecting with the coal industry: At the recommendation of Doug Todd, formerly of GE and an industry expert on IGCC, SCIES participated in the annual Gasification Technologies Conference (GTC). Todd and Jeff Abboud (Gas Turbine Ass'n) also recommended that we enlist the help of the Center for Energy & Economic Development (CEED), who is influential in coal matters in DC. Steve Miller, their CEO, recommended that we meet with Terry Ross, VP of CEED's Western Region, at the GTC; Terry is CEED's most knowledgeable person on IGCC. Following the meeting, Terry arranged for SCIES to be an Associate Member of CEED at no cost. Terry has also passed on our needs to advocate the HEET Program to those at CEED who lobby and to Steve Miller.

- Also at the GTC, SCIES met with Dale Simbeck (SFA Pacific, a speaker on the market for coal who is an advocate of IGCC). Based on his comments we have contacted David Hawkins of the Natural Resources Defense Council (NRDC), who says he was responsible for earmarking funding for gasification in the Senate energy bill. He has been educated on the HEET Program and the kind of money we'd like to see in it, and has been asked for help in advocating HEET.

- The Association of State Energy Research and Technology Transfer Institutions
(ASERTTTI) has been reorganized. Jack White has retired as President, and they decided to replace him with two people: Mark Hansen for State Relations and Bob Kripowicz for Federal relations. Bob was Deputy Assistant Secretary for Fossil Energy at DOE. He retired from DOE in June '02 and remained in the DC area. Bob has been asked for his help in advocating HEET.

- As part of advocating HEET (and SCIES), Vic de Biasi of Gas Turbine World agreed to do an article on HEET, including SCIES. He provided a draft, which has been edited and finalized for publication in the January / February issue of GTW.

- Working with EERE: We recommended to Rich Dennis that FE encourage joint effort with EERE on synfuels work. In HEET, we are developing the turbine technology necessary for V21, which includes biomass fuels as well as coal - and EERE has the scope for the biomass. From a technical point of view it makes sense that biomass-based syngas capability in gas turbines be developed in the same program as coal-based syngas capability. This applies to both the work done by universities (UTSR) and the component development work done by the manufacturers. Rich subsequently met with Debbie Haught and recommended that we work together, and that EERE contribute $1M / year to the UTSR effort. Debbie said that it's too late for FY03 funding, but something may be possible in FY04.

- During the International Energy Conference in Reno, NV, where SCIES provided a presentation on HEET, Richard Moorer of EERE was the keynote speaker; he had just been promoted to be Deputy Assistant Secretary for Technology Development. We took the opportunity to urge him to help facilitate the working together of FE and EERE on HEET; he seemed receptive.

**Key Milestone Update**

There are no milestone modifications this month.

**Discussion Topics**

SCIES recommended to the DOE a research effort to address research needs for turbine flow path protection for use of syngas and other alternate fuels. This effort would provide research topics for UTSR RFP's and would also provide foundational work and a basis for future university and industry development of turbine protection approaches for adequate lifetimes.

**Significant Accomplishments – Success Story (AGTSR Project)**

Turbine vane and blade airfoil surfaces experience surface roughening during service due to deposition, erosion, corrosion, and coating spallation. Surface roughening significantly increases aerodynamic losses and heat loading of the airfoils. Consequently, engineers must represent the roughening effects of turbine service in the aerodynamic and cooling design of vanes and blades. However, past methods of representing turbine surface roughening due to service have not been adequate for turbine design.
Under the Advanced Gas Turbine Systems Research (AGTSR) program, an Air Force Institute of Technology (AFIT) and Mississippi State University (MSU) project has analyzed over 100 parts that had experienced turbine service and has developed new methods to analytically represent roughening for aerodynamic and cooling design of airfoils.

**Significance:** The new MSU model for turbine surface roughness was shown to represent laboratory measured aerodynamic roughness effects to within 7% and heat transfer roughness effects to within 16%. This accuracy was demonstrated for surfaces representing both deposit buildup and erosive removal and is significantly improved over that of previous models used by turbine manufacturers for vane and blade design. The MSU student that developed the model has received his Ph.D. degree, accepted an Assistant Professorship at the University of Alabama, and is now pursuing research to develop even more accurate representations of service roughening of airfoil surfaces for turbine design.

**Presentations and Publications**

The Proceedings for UTSR Combustion Workshop IX were released and distributed in November.

**Site Visits**

No site visits occurred or were planned with high level corporate or government officials this month.

**Travel**

SCIES staff (Larry Golan, Bill Day, Rich Wenglarz, Donna Partain) traveled to the Aero-Heat Transfer V Workshop and Bill Day traveled to the Gasification Technologies Conference and the International Energy Conference, as described above.
REPORT FOR DECEMBER

Completed Tasks

- SCIES submitted to the DOE the Continuation Request for year 2003. The yearly Program Plan, required by the UTSR Cooperative Agreement, was included in the Continuation Request.

- Work has started to define university research topics for the next RFP of the UTSR Program. The significant challenge is to define topics that emphasize the syngas turbine research needs of the DOE HEET Program while also addressing the interests of the Industrial Review Board (IRB) companies of the UTSR Program. DOE input on combustion research topics has already been obtained from Geo Richards. Other DOE sources being compiled for research needs include the documents from the DOE HEET Roadmapping Workshop in Reston, VA and HEET roadmapping meetings that immediately proceeded and followed the DOE Power Systems Conference in Galveston, TX. Research needs of the turbine industry are being compiled from presentations by IRB technical representatives at the three UTSR workshops in 2002.

- A request has been received from David Pollard of Alstom inviting UTSR participation in a joint EU/US gas turbine conference in Europe, which he has been discussing with Rich Dennis of the DOE. SCIES called Rich Dennis who indicated that, assuming DOE upper management approves DOE participation, he would like the UTSR to provide up to three, or perhaps four, presentations at the conference. However, there is an issue how travel costs might be covered, since the AGTSR/UTSR university contracts do not allow reimbursement for foreign travel.

- Fellowship Program: In order to get more publicity for the Fellowship Program, SCIES contacted Lee Langston, who is well connected with IGTI (former IGTI Board member and now Editor of the ASME Journal of Engineering for Gas Turbines and Power) to see what could be done to increase awareness of the program. Lee suggested some contacts at IGTI, and SCIES now has a request in to Judy Osborn of IGTI Headquarters, who handles the Global Gas Turbine News, for publicity on the program.

- Connecting with the Coal Industry: Contact has been made with Andy Robart, who is the new President of the Washington Coal Club. Andy is known to SCIES; he is a Washington rep for Siemens Westinghouse and is their member on the Gas Turbine Association's Government Affairs Committee. Andy is active in working with the government on funding for coal-based gas turbine systems. We agreed to compare notes after the holidays and decide what we can do together to advocate the HEET Program.

- With the Coal Utilization Research Council (CURC), we found that Siemens
Westinghouse has been pushing hard on them to move their position from advocating only coal combustion technologies (PC, PFB, etc.) which benefit the boiler makers, to also advocating IGCC. After talking to Frank Bevc and Harry Morehead of S-W, SCIES will be part of a conference call in January including Jeff Abboud (GTA) and Ben Yamagata (CURC) to establish a mutually agreeable position of recommendations to the government from CURC.

- Gas Turbine Association: GTA had a Board meeting in Orlando in conjunction with the Power Gen conference, and SCIES made a presentation to the GTA Board on the efforts underway to advocate the HEET Program. Among the interchange came comments about CURC which led to the actions in the previous paragraph.

- The Association of State Energy Research and Technology Transfer Institutions (ASERTTI): The lead people on two of the six newly formed planning teams of the State Technology Advancement Collaborative (STAC) are from SCIES; Dave Stubblefield for the Buildings and Bill Day for Fossil Energy. STAC is a program in which DOE funding supplements the state funds to do projects which are of interest to the states. The program was started with $2M last year from EERE and has been renewed with a Memorandum of Understanding between ASERTTI and DOE which was signed in November. A request has been made for $6M each from EERE and FE for this year. Marv Singer is the FE point of contact. Marv doesn't know yet how much if any money will make it through the budget process, but in the meantime planning will get underway with the objective of having programs planned by mid February in the event that money becomes available.

- Article in Gas Turbine World: Just prior to the holidays Vic de Biasi contacted SCIES with the desire to add more information to the article which had been written with input from SCIES and NETL. We provided him with several of the success stories from the AGTSR and UTSR programs, and after several rounds of clarification Vic felt that the article was ready to go to press. He is still trying to make the January / February issue.

- Working with EERE: At the Power Gen conference in Orlando, SCIES and Rich Dennis of NETL met with Debbie Haught of EERE on the subject of funding from EERE to work on university research projects which would be of interest to EERE. It was agreed that SCIES would provide copies of proposals in materials and combustion which didn't quite make the short list in the September '02 meeting of the IRB but which were considered worthy proposals. Debbie may be able to provide enough funding for one of them, which would test the system of working together. We provided the proposals on a confidential basis; Debbie will have them evaluated and get back to us with a decision.
Key Milestone Update

There are no milestone modifications this month.

Discussion Topics

SCIES is awaiting DOE response on a research effort recommended in November to address research needs for turbine flow path protection for use of syngas and other alternate fuels. This effort would provide research topics for UTSR RFP's and would also provide foundational work and a basis for future university and industry development of turbine protection approaches for adequate lifetimes.

Significant Accomplishments – Success Story (AGTSR Project)

Hot streaks in turbine expander flow paths substantially affect vane and blade lifetimes and stage aerodynamic performance. These hot streaks are located in circumferential positions related to the location of the upstream combustor fuel injectors.

Under the Advanced Gas Turbine Systems Research (AGTSR) program, a Virginia Commonwealth University (VCU) project has conducted computational analyses to improve airfoil temperatures and stage aerodynamic performance by selecting the circumferential positions of first and second stage vanes with respect to the hot streaks (i.e., fuel nozzles). The analyses previously showed that locating the circumferential position of the second stage vanes with respect to the first stage vanes could affect stage efficiency by as much as 0.5%. The analyses have recently indicated that selective circumferential positioning the first stage vanes with respect to the hot streaks can significantly reduce the time average surface temperature of the downstream first rotor blades and second stator vanes.

Significance: A 55 degree centigrade increase in time average surface temperature can reduce the lifetime of turbine rotor blades by a factor of ten. The VCU project showed the potential of significantly increasing turbine component lifetimes or reducing cooling (and associated performance penalties) by selective circumferential positioning of first stage vanes.

Presentations and Publications

SCIES reviewed a paper from GE that was submitted for the 2003 Turbo Expo conference.

Site Visits

No site visits occurred or were planned with high level corporate or government officials this month.

Travel

Bill Day traveled to the Power Gen conference in Orlando, Dec. 9-11.
ATTACHMENT B

OUTREACH FOR YEAR 2002

Regional Meetings: In addition to the technical workshops described above, a series of Regional Outreach meetings were held to determine differences in regional energy needs and to gain regional input on the HEET program. The meetings held include the following:

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<tr>
<th>Organization</th>
<th>Region/Office</th>
<th>Date</th>
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<tbody>
<tr>
<td>DOE/EERE</td>
<td>Atlanta Regional Office</td>
<td>May 1 and 2</td>
</tr>
<tr>
<td>DOE/EERE</td>
<td>Philadelphia Regional Office</td>
<td>August 28</td>
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<tr>
<td>NASEO</td>
<td>Pacific northwest Region, Portland</td>
<td>July 22</td>
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<tr>
<td>NASEO</td>
<td>Denver Region</td>
<td>August 15</td>
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<tr>
<td>NASEO</td>
<td>San Francisco Region</td>
<td>September 5</td>
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<tr>
<td>Connecticut Energy</td>
<td>Energy Sector, Office of Policy</td>
<td>October 16</td>
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<tr>
<td>Louisiana Energy</td>
<td>Department of Natural Resource</td>
<td>November 12</td>
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The meetings at the Philadelphia Region, Connecticut and Louisiana were held in conjunction with technical workshops at Penn State, University of Connecticut and Louisiana State University respectively. The meetings with NASEO (National Association of State Energy Officials) were held in conjunction with meetings which NASEO was already having on a separate contract with NETL. The process of combining meetings reduced costs considerably and reduced the burden on the attendees of attending multiple meetings. Summary reports of each of these outreach meetings have been released. Attendees at these outreach meetings included representatives from installers of combined heat and power systems, state and local government agencies, manufacturers, power generators, consultants, and research institutes. In all, 35 states have been contacted. During January of 2003 plans are to contact the remaining states with the assistance of NASEO – for the Boston and Chicago regions. A final report addressing all regions will be drafted when all states have been contacted. A summary of what we learned from the meetings held in 2002 is as follows:

- **Need to educate state and federal governments on the public benefits of HEET**
  - Better define the scope and structure of HEET
  - Get the importance of HEET understood so it gets full funding

- **IGCC plants are worthwhile in states which use coal**
  - Must have low capital cost ($/kW) to compete with pulverized coal plants
  - Develop turbines for a wide range of non standard fuels in addition to coal gas.
  - Reduce pollution transported to other states

- **Small hybrid systems, with natural gas or coal-derived liquids, fit with state and regional DG plans**
Advocating the HEET Program: One suggestion that came from the regional meeting at Penn State was that in order to get funding support for the HEET Program, we should connect with the coal industry. To that end, the following has been done:

Contact was made with Doug Todd, formerly of GE and an industry expert on IGCC. Doug recommended that SCIES attend the annual Gasification Technologies Conference (GTC) for networking, which was done. He and Jeff Abboud (Gas Turbine Association) also recommended enlisting the help of the Center for Energy & Economic Development (CEED), who is influential in coal matters in DC. Steve Miller, their CEO, recommended meeting at the GTC with Terry Ross, VP of CEED’s Western Region; Terry is CEED’s most knowledgeable person on IGCC. This was done, and Terry arranged for SCIES to be an Associate Member of CEED at no cost. Terry has also passed on our needs to advocate the HEET Program to those at CEED who lobby and to Steve Miller.

Also at the GTC a meeting was held with Dale Simbeck (SFA Pacific, a speaker on the market for coal and who is an advocate of IGCC). Based on his comments SCIES contacted David Hawkins of the natural resources Defense Council (NRDC), who was reportedly responsible for earmarking funding for gasification in the Senate energy bill in FY 2002. David has now been educated on the HEET Program has been asked for help in advocating HEET.

SCIES attended the semi annual meeting of ASERTTI (Association of State Energy Research and Technology Transfer Institutions, of which SCIES is a member) and learned that they have reorganized. Jack White has retired as President, and they have replaced him with two people: Mark Hansen for State Relations and Bob Kripowicz for Federal relations. Bob was Deputy Assistant Secretary for Fossil Energy at DOE. He retired from DOE in June '02 and has remained in the DC area. A meeting was held with Bob, and he has been asked for help in advocating HEET.

The Coal Utilization Research Council (CURC) in the past has advocated funding of pulverized coal technology without also advocating IGCC (their major benefactors are boiler makers). This is starting to change thanks to the efforts of Siemens Westinghouse, who has been doing considerable advocating with CURC to add IGCC to their advocacy. SCIES contacted Siemens Westinghouse on this subject, and a conference call is being arranged with S-W, SCIES and Ben Yamagata of CURC to discuss recommendations.

Contact has been made with Andy Robart, who is the new President of the Washington Coal Club. Andy is known to SCIES; he is a Washington rep for Siemens Westinghouse and is their member on the Gas Turbine Association’s Government Affairs Committee. Andy is active in working with the government on funding for coal-based gas turbine systems. Andy is interested in helping with the CEED connection (see above), particularly to help advocate the HEET Program to the Administration side of the government. SCIES will hold a follow-up meeting with Andy in February.

As part of advocating HEET (and SCIES) a suggestion was made to Vic de Biasi, publisher of Gas Turbine World magazine to do an article on HEET with including a description of SCIES.
He obliged, and SCIES provided edits to the draft. The article is expected to be published in the December / January issue.

**Working with EERE:** SCIES recommended to NETL that FE encourage joint effort with EERE on synfuels work. In HEET, we are developing the turbine technology necessary for Vision 21, which includes biomass fuels as well as coal - and EERE has the scope for the biomass. From a technical point of view it makes sense that biomass-based syngas capability in gas turbines be developed in the same program as coal-based syngas capability. This applies to both the work done by universities (UTSR) and the component development work done by the manufacturers. NETL subsequently met with EERE and recommended that FE and EERE work together, and that EERE contribute to the UTSR effort.

During the Power Gen conference in December SCIES and NETL met with EERE to discuss working together. It was left that EERE would consider funding one of the proposed university research efforts in combustion or materials from the most recent round of proposals – one which didn’t make the short list but which SCIES and the IRB would have wanted to fund if the money were available. SCIES then sent copies of those proposals to EERE, who is now evaluating the proposals. They are considering one of the combustion proposals and will decide when they know their FY 2003 budget.

During the International Energy Conference in Reno, NV, where SCIES gave a presentation on HEET, Richard Moorer of EERE was the keynote speaker; he had just been promoted to be Deputy Assistant Secretary for Technology Development. SCIES took the opportunity to recommend that he help facilitate the working together of FE and EERE on HEET.

**Creating Linked University Research Programs:** SCIES wrote a white paper recommending that the university research be linked between the gasification and cleanup work and the turbine work, due to the physical linkage between the two. The recommendations included having one combined workshop with multiple tracks instead of separate workshops. This would enable input from the gasification / cleanup side and give the opportunity for cross-fertilization. Also recommended was consolidation of the university research under SCIES. SCIES met with FE people in Washington DC and at NETL. Following the NETL meeting it was decided that the idea of the combined workshops, with input from the gasification / cleanup side, will be pursued, starting with the combined workshop which is planned for October 2003.

**Gas Turbine Industrial Fellowship:** SCIES worked with Karen Thole of VA Tech to develop a set of changes to the Internship Program: 1) Changing the name to Gas Turbine Industrial Fellowship Program, 2) Increasing the monthly stipends to be more competitive with similar programs, 3) Having the interns make presentations at the new combined UTSR Workshop to get in front of potential employers and 4) In special cases combine the work at the company location with the thesis topic. The brochures for this new program were developed and distributed, to a wider audience than the previous distribution to the university points of contact. Additional distribution included the university Principal Investigators of present and former contracts and to Graduate Offices of the universities.

SCIES also contacted Lee Langston, former IGTI Board member and now Editor of the ASME Journal of Engineering for Gas Turbines and Power, to see what could be done to increase
awareness of the program. Lee suggested some contacts at IGTI, and at SCIES’ request the IGTI website has publicized the Program on their website and provided links to both SCIES and an application form for the Fellowship Program.