UNIVERSITY TURBINE SYSTEMS RESEARCH PROGRAM

FINAL REPORT

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EXECUTIVE SUMMARY

UTSR Organization

The University Turbine Systems Research (UTSR) program involved a consortium of 111 Performing Member Universities (Appendix A) in 42 states and 17 gas turbine industry partners (Appendix B). Research that supported DOE advanced power system goals and met the needs of the US gas turbine industry was defined jointly by the DOE, industry (via an Industrial Review Board (IRB)) and academia (via an Academic Advisory Board (AAB)). The Performing Member Universities conducted the research, with IRB members providing technical review and comments. The activities of the UTSR consortium were coordinated and managed by the South Carolina Institute for Energy Studies (SCIES) at Clemson University.

UTSR Research Projects

Thirty-nine research projects at Performing Member Universities throughout the US were funded by the UTSR program from March 2002 through December 2010. Summaries of the research results and their significance are given in the University Research section of this report. Peer reviewed publications resulting from the university projects are listed in the Reports and Publications section. Final reports from the projects are provided in Appendix C.

Six of the university projects were previously awarded in 2001 and were carried from the earlier Advanced Gas Turbine Systems Research (AGTSR) program and completed under the UTSR Program. These projects addressed research needs for turbines operating with natural gas fuels. The DOE Turbine Program (which funded the UTSR), and consequently the remaining university projects, shifted emphasis to turbines operating with high hydrogen and syngas fuels derived from coal.

The primary areas of university research were combustion, aerodynamics/heat transfer, and materials, with a few projects in the area of instrumentation, sensors and life (ISL). Research topics in these areas were defined with input from the DOE and member organizations of the Industrial Review Board (IRB). Through 2007, SCIES released a yearly RFP for university research on those topics. Research projects, usually of three years duration, were awarded based on an IRB evaluation and recommendation process. Research results were reported semi-annually to SCIES, who compiled the information into quarterly reports to the DOE and IRB companies, providing an immediate transfer of new technology developments. Project evaluation forms were also provided to the IRB companies for return to SCIES to enable industry input for increasing the relevance of the university projects.

Nine UTSR workshops were conducted by SCIES. These provided the DOE and IRB companies with opportunities to hear presentations and discuss with principal investigators the results of current university research projects. IRB companies also provided presentations on their technology needs so the university researchers could focus future research towards those needs.

UTSR Interns/Fellows

The UTSR program also sponsored and coordinated an Industrial Fellowship Program, which placed and supported upper level undergraduate and graduate students for periods of 10 to 12 weeks at IRB companies. A total of 145 students participated in this program from 2002 through 2010. Most of these students have taken permanent positions in the energy industry or academia after graduation.

Research Results

The research results from the 39 university research projects are summarized in the Research Projects section. Only a few representative results are provided in this section. In summary, the university projects produced data, analyses and understanding to aid gas turbine engineers with the design of combustors, internal/film cooling, and materials selection for turbines operating with high hydrogen fuels produced from coal syngas.

Examples of combustion results include determining a parameter to capture the effect of fuel composition on blowout propensity for lean-premixed, low NO_x combustors operating with high hydrogen fuels with a range of compositions of H₂, CO, H₂O and other gases. A methodology was demonstrated and licensed to a turbine monitoring instrumentation company that interrogates engine operation data to determine when a combustor should be taken out of service for maintenance to prevent emergency shutdowns due to instability. Ignition delay data needed for premixer design for low NO_x combustors was extended to H₂/CO blends representative of syngas. An improved ignition delay computer model was developed to replace previous models which had completely unacceptable accuracies for combustor design.

Examples of aero/heat transfer results include the development and verification of computer techniques for designing internal cooling passages of turbine airfoils with an order of magnitude less computer computation time and corresponding reduced design costs. This should facilitate improved cooling designs to accommodate the higher heat loading to airfoils for combustion products of high hydrogen fuels from syngas. Also to reduce the cooling penalty due to higher heat loads, another university project identified flow structures for internally cooled airfoils that increase cooling performance and decrease cooling air requirements. Concerning deposition that has occurred in syngas turbines, university projects developed a deposition rig and explored factors that aggravate deposition, along with effects of deposition on airfoil cooling and effects of film cooling to alleviate deposition. Another project identified a film cooling approach that not only improves airfoil cooling for turbines that experience roughened surfaces representative of fuels that cause deposition but also improves airfoil cooling for fuels that do not produce deposition.

Materials results included verification of a novel process to produce ultra thick (3 mm) thermal barrier coatings (TBCs) that provide improved insulation of airfoils from high heat loads and resistance to spallation from thermal cycling. This process also has the potential for producing layered TBCs to reduce deposit induced spallation that has decreased TBC life in IGCC turbines. A UTSR project identified turbine alloy properties that alleviate degradation due to high water vapor levels as in the combustion products from high hydrogen fuels derived from coal syngas. Another project exposed a range of airfoil alloys and coatings to environments with high water

vapor levels and contaminants representative of syngas impurities. Impurities and conditions were identified that produce the greatest materials attack and the relative resistance of various candidate turbine materials to attack were determined. A four page article in the January-February 2003 issue of the gas turbine trade magazine *Gas Turbine World* described several UTSR projects to improve the performance and reliability of thermal barrier coatings for gas turbine components and to accurately predict remaining TBC life once in service. Quoting the summary heading of the article, “DOE-university research has already paid off in terms of more durable bonding, ability to predict service lifetime of installed coatings, and portable TBC evaluation probe for use by gas turbine builders, repair service suppliers and operators.”

Effectiveness and Benefits

In 2007, the ASME conducted at DOE’s request a peer review of projects within the DOE Advanced Power Systems (APS) Program. The Peer Review Panel members rated the UTSR Program highest of the 21 APS Projects evaluated and in their written comments stated that the UTSR was a benchmark project and an excellent use of government resources.

The UTSR has produced fundamental data and understanding for the development by industry of advanced turbines operating with a range of gaseous fuels derived from coal. Through funded university research projects and internships at the IRB companies, the program has also provided training for many of a new generation of higher degreed engineers and scientists who will lead future advancements to meet the energy needs of the US.

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Due to file size limitations, the University final reports have been removed from this uploaded version of the final report. Copies of this final report delivered to NETL and the Industrial Review Board on CD include all of the University final reports.

SR089: *Internal Cooling in Leading and Trailing Edge Passages with Rotational and Buoyancy*, Sumanta Acharya, Louisiana State University

SR090: *Optimization of the Injector Fuel Distribution for Stable, Low Emissions Combustion in Lean Premixed Gas Turbine Combustors*, Domenic Santavicca, Pennsylvania State University

SR091: *"Thermal Barrier Coatings and Metallic Coatings with Improved Durability"*, Maurice Gell, University of Connecticut

SR092: *"Attenuation of Hot Streaks and Interaction of Hot Streaks with the Nozzle Guide Vane and End Wall"*, David G. Bogard, University of Texas

SR093: *"A Science-Based Approach to Enhanced Zirconia-Based Thermal Barrier Coatings for Advanced Gas Turbine Applications"*, David R. Clarke, University of California-Santa Barbara

SR094: *"Rotating Heat Transfer in High Aspect Ratio Rectangular Cooling Passages with Shaped Turbulators"*, Je-Chin Han, Texas A&M University

SR095: *"Understanding and Control of Combustion Dynamics in Gas Turbine Combustors"*, Ben Zinn, Georgia Institute of Technology

SR096: *"Aerothermal Effects of Interfacial Leakage and Film Cooling Schemes with End Wall and Leading Edge Contouring"*, Terrence Simon, University of Minnesota

SR097: *"Measurement of Three Critical Parameters as a Basis for a Simple Life Prediction Method"*, Eric Jordan, University of Connecticut

SR098: *"Experiments and Computations on Film-Cooled End Walls with Contouring"*, Sumanta Acharya, Louisiana State University

SR099: *"Modeling and Control of Ultra-Lean Premixed Combustion Dynamics for Gas Turbines"*, Uri Vandsburger, Virginia Institute of Technology

SR100: *"Enhanced Prediction Techniques Based on Time-Accurate Simulations for Turbine Blade Internal Cooling"*, Danesh Tafti, Virginia Institute of Technology

- SR101:** "*Mechanism-Based Testing Methodology for Improving the Oxidation, Hot Corrosion and Impact Resistance of High-Temperature Coatings for Advanced Gas Turbines*", Gerald Meier, University of Pittsburgh
- SR102:** "*Advanced Sensor Approaches for Monitoring and Control of Gas Turbine Combustors*", Principle Investigator: Jerry Seitzman, Georgia Institute of Technology
- SR103:** "*Assessment of Failure Mechanisms for Thermal Barrier Coatings by Photoluminescence, Electrochemical Impedance and Focused Ion Beam*", Yong-ho Sohn, University of Central Florida
- SR104:** "*Turbine Surface Degradation with Service and Its Effects on Performance*", Jeffrey Bons, Brigham Young University
- SR105:** "*Advanced Optical Sensor for Monitoring and Control of Multiple Gas and Turbine Blade Properties*", Scott Sanders, University of Wisconsin
- SR106:** "*Spectroscopic In-Situ Non-Destructive Evaluation to Monitor the Health of Thermal Barrier Coatings*", Kang Lee, Cleveland State University
- SR107:** "*Superior Thermal Barrier Coatings for Industrial Gas turbines Using a Novel Solution Plasma Spray*", Nitin Padture, University of Connecticut
- SR108:** "*An Advanced Diagnostic and Prognostic System for Gas Turbine Generator Sets with Experimental Validation*", John Wagner, Clemson University
- SR109:** "*The Effects of Fuel Distribution, Velocity Distribution, and Fuel Composition on Static and Dynamic Instabilities and NO_x*", Domenic Santavica, Pennsylvania State University
- SR110:** "*Improved Film Cooling Performance for Turbine Vanes and Endwalls with Realistic Surface Conditions*", Karen Thole, Virginia Institute of Technology
- SR111:** "*Combustion Instability and Blowout Characteristics of Fuel Flexible Combustors*", Timothy Lieuwen, Georgia Institute of Technology
- SR112:** "*Correlation of Ignition Delay with IGCC Type Fuels*", Scott Samuelsen, University of California-Irvine
- SR113:** "*Heat Transfer from Rotating Blade Platforms With and Without Film Cooling*", J. C. Han, Texas A&M University
- SR114:** "*Combustion Characterization and Modeling of Fuel Blends for Power Generation Gas Turbines*", Eric Petersen, University of Central Florida
- SR115:** "*Effects of Coating Blockage and Deposits on Film Cooling Effectiveness and Heat Transfer*", M. Chyu, University of Pittsburgh
- SR116:** "*Investigation of Materials Performance in High Moisture Environments Including Corrosive Contaminants Typical of Those Arising by Using Alternate Fuels in Gas Turbines*", F. S. Pettit, University of Pittsburgh
- SR117:** "*Autoignition Studies of Syngas and Hydrogen (SGH) Fuels*", Robert Santoro, Pennsylvania State University

- SR118:** *"Degradation of Thermal Barrier Coatings with Syngas Combustion"*, Yongho Sohn, University of Central Florida
- SR119:** *"Aero Losses, Heat Transfer, Discharge Coefficients for Different Vane Trailing Edge Configurations for Syn Gas Fired Turbines"*, Forrest Ames, University of North Dakota
- SR120:** *"Deposition of Alternative (Syngas) Fuels on Turbine Blades with Film Cooling"*, Thomas Fletcher, Brigham Young University
- SR121:** *"Fundamental Studies in Syngas Premixed Combustion Dynamics"*, Ahmed Ghoniem, Massachusetts Institute of Technology
- SR122:** *"Turbulent Flame Speed Measurements and Modeling of Syngas Fuels"*, Jerry Seitzman, Georgia Institute of Technology
- SR123:** *"Syngas Particulate Deposition and Erosion at the Leading Edge of a Turbine Blade with Film Cooling"*, Danesh Tafti, Virginia Institute of Technology
- SR124:** *"Materials for Oxy-Fuel Turbomachine Conditions"*, Gerry Meier, University of Pittsburgh
- SR125:** *"Evaluating Coatings for Current and Future Service with Thermal Property Measurements"*, Ted Bennett, University of California-Santa Barbara
- SR126:** *"High Pressure Kinetics of Syngas and Nearly Pure Hydrogen Fuels"*, John Daily, University of Colorado
- SR127:** *"Simulating Particle Deposition and Mitigating Deposition Degradation Effects in Film Cooled Turbine Sections"*, David Bogard, University of Texas

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1. INTRODUCTION

1.1. Cooperative Agreement

Cooperative agreement DE-FC26-02NT41431 was established on March 20, 2002 between the U.S. Department of Energy/National Energy Technology Laboratory (DOE/NETL) and the Clemson University Research Foundation/South Carolina Institute for Energy Studies (SCIES). This cooperative agreement, which continued through December 31, 2010, established a basic and applied research program as a conduit for university support of the DOE's Fossil Energy (FE) Turbine Program. To emphasize the university role, the program was renamed the University Turbine Systems Research Program (UTSR) in late 2002.

The major activities specified in the Scope of Work for the UTSR Program were related to the establishment and oversight of university research projects pertinent to the goals of the DOE Turbine Program. The research was also to be of high importance to long-term health of the U.S. energy (especially gas turbine) industry. The research emphasis at the start of the cooperative agreement was for turbines operating with natural gas fuels. Within a year, the emphasis of the DOE Turbine Program, and consequently the UTSR Program, started to shift from turbines operating with natural gas fuels to turbines operating with coal derived syngas and syngas-derived hydrogen fuels.

In 2005, the DOE launched several programs with industry to develop turbine technologies for advanced power systems that operate with high hydrogen fuels produced from coal (coal syngas and nearly pure hydrogen from gasified coal). The UTSR Program provided fundamental research for turbine technologies that support development of coal based power systems with increasing efficiency and emissions performance and decreased capital cost per kW output. The hydrogen fuel technologies are leading to FutureGen type power plants that can capture CO₂ and produce hydrogen. These advancements involve a transition from turbines operating with syngas typical of that produced at current IGCC plants, to very high hydrogen content fuels derived from syngas, to syngas burned in nearly pure oxygen using steam to control temperatures (oxy-fuel systems). The transition requires development of turbine combustion technologies for this variety of fuels and turbine hot section flow path aero/heat transfer and materials technologies to accommodate expansion gases that are not only increasingly hotter but also contain trace amounts of coal ash impurities and increasing levels of water vapor.

The UTSR Program was directed to provide fundamental data and analyses to aid in the development of the DOE advanced coal based turbine power systems and advance these technologies. The emphasis was to understand the issues and underlying factors affecting combustion, aero/heat transfer and materials experience for syngas used in current IGCC turbines and use that knowledge to design and conduct experiments and analyses to aid in turbine technology development for transition from coal syngas with current properties to nearly pure hydrogen fuels derived from coal syngas to syngas burned in oxygen. Some of these evaluations involved obtaining an understanding of effects on the turbine hot section flow path of trace coal impurities that pass the syngas cleanup systems. This knowledge assists in determining how clean these various fuels must be for acceptable protection of the turbine flow path and minimal

emissions, without unduly incurring the capital cost and pressure drop efficiency penalties of more extensive gas cleanup systems than are needed.

1.2. Technology Issues

Syngas and high hydrogen fuels derived from coal gasification present challenges because they have different and more variable combustible components (and combustion/emission characteristics) than natural gas. Even after passing cold gas cleaning systems, these fuels contain limited levels of impurities (e.g., up to 100 ppm sulfur, 0.1 to 1 ppm particulate) considered to be detrimental to components in the turbine flow path due to deposition, erosion, and corrosion. Consequently, the UTSR program conducted research to help define and address issues expected to impact the goal of designing future robust turbines for syngas and high hydrogen fuels derived from coal. Because of higher performance and emission requirements for these advanced turbines, these issues are increased or are in addition to those for turbines of current Integrated Gasification Combined Cycle (IGCC) plants.

Combustion Issues – Turbines that have operated with coal syngas at IGCC plants use diffusion flame combustors with diluent (e.g., steam, nitrogen, or both) injection to lower combustion temperatures and thereby reduce NO_x to a typical guaranteed range of 15 to 25 ppmv. For natural gas fuels, lean premixed combustors have been developed to produce guaranteed NO_x emissions down to the about 9 ppmv. Similar developments are needed to advance lean premixed combustion approaches to achieve low level emissions using high hydrogen fuels derived from syngas.

Formidable challenges to the development of lean premixed combustors for high hydrogen fuels derived from syngas result from their unique properties (e.g., high flame speed, high diffusivity, short ignition delay time, and wide explosion limits) and range of compositions (e.g., H₂, CO, H₂O). Also, the DOE goal for turbines using high hydrogen fuels (less than 2 ppmv NO_x at 15% O₂) is significantly lower than guaranteed for turbines operating lean premixed combustors with conventional fuels. Consequently, additional fundamental combustion experiments and modeling research were needed to advance lean premixed combustion approaches to produce guaranteed lower NO_x emissions than achieved in the past with conventional fuels but using syngas-derived fuels with more difficult and variable properties. For that purpose, the UTSR program research addressed the combustion and operability issues (blowout, flashback, dynamic stability, etc.) to achieve fundamental capabilities needed for the design of low single digit NO_x emission combustors that use high hydrogen fuels derived from coal syngas. The UTSR program research was directed toward providing insight and data for design of very low emission (NO_x under 2 ppmv at 15% O₂), stable combustors that could function with the expected variety of syngas-derived fuel compositions and operating conditions expected for future turbines.

Aero/Heat Transfer Issues – Low heating values typical of syngas and injection of diluents (to control combustion temperatures and therefore thermal NO_x) have resulted in higher (up to 14% higher) mass flows through the turbine hot section of IGCC turbines than for the same model turbines operated with natural gas. This produces 20-25% higher turbine output power compared to natural gas but also increases the heat load to the hot section vanes and blades. Where steam is used as a diluent to control NO_x, the higher heat transfer properties for steam compared to air additionally increase the heat load to hot section components. Accordingly, current IGCC

turbines have been operated at reduced firing temperatures to maintain hot gas stream parts at temperatures similar to those of the same model turbines operating with natural gas. The progression from current syngas to high hydrogen fuels produced from coal syngas and oxy-fuels, along with the usual increase in turbine inlet temperature through time to increase performance (power and efficiency), will tend to produce additional heat loads and aero/cooling requirements for hot section components. Also, turbine operational experience and past rig tests with alternate fuels containing ash impurities have shown that corrosion and deposition can be drastically higher for increased inlet temperatures because of higher levels of molten ash phases in the flow stream. Although increased gas cleanup in future plants may significantly reduce impurities entering the turbine, current experience has shown that even highly filtered ambient air can produce significant deposition (fouling) in compressors when molten phases exist at flow path conditions. Consequently, UTSR research was directed toward defining the aero/heat transfer environments and investigating cooling approaches to accommodate higher heat loads under potential deposition and corrosion conditions in the hot sections of turbines operating with coal syngas, future high hydrogen fuels derived from syngas, and oxy-fuels.

Materials Issues – Even though limited IGCC plant data on measured syngas impurities has indicated lower levels of critical ash constituents (e.g., Na, K, Ca) than limits from turbine fuel specifications, greater materials degradation (corrosion, erosion, and deposition) has occurred in some IGCC plant turbines to date than for the same model turbines operating with conventional fuels such as natural gas. At least in some cases, hot section coatings, vanes, and blades have needed replacement during routine maintenance shutdowns at more frequent intervals than for natural gas fired turbines. For example, analyses of IGCC turbine first rotor blades have shown that, at some locations, surface reactions were radically different in nature and more severe than typically observed in turbines operating with conventional fuels. These areas appeared to experience a combination of sulfidation and oxidation. However, the mechanisms leading to this attack are uncertain because partial pressures of sulfur containing gases in the syngas combustion products do not appear to be as high as required to produce materials sulfidation.

Also, TBC's in IGCC turbines have experienced deposition and spallation and sometimes needed replacement at more frequent intervals than for natural gas fired turbines. Analyses have indicated that iron oxides (e.g., Fe_2O_3) have been primary constituents of deposits on the TBC's, which also penetrated into the TBC porosity. The presence of other ash elements (e.g., Si, Al, Ca, Mg, Na, K and sulfate ions) has also been detected. These deposits are different in composition than deposits consisting of calcium, magnesium, aluminum, and silicon (CMAS) that have caused past degradation of TBC's in airborne turbines.

Consequently, UTSR materials research was directed to first understanding the nature of degradations to date in IGCC turbines, identifying approaches to alleviate these degradations, and then using these insights as a starting knowledge base for evaluations of materials for turbines using higher hydrogen fuels derived from coal gasification and oxy-fuels.

2. UNIVERSITY RESEARCH

Table 1 summarizes the 39 university research projects. The first six projects were carried to completion from awards in the previous Advanced Gas Turbine Systems Research (AGTSR) university program. They were directed to research needs for turbines operating with natural gas fuels, but also had implications for turbines operating with alternate fuels. The remaining 33 projects were awarded under the UTSR cooperative agreement and the research transitioned from needs for natural gas fuels to addressing needs for advanced turbines operating with coal syngas and high hydrogen fuels derived from syngas. Appendix C provides detailed final reports for the 39 research projects. The experimental and analytical methods used for the research in each project are described in that Appendix. Details about materials and special equipment used in the projects are also given. Publications resulting from the research are listed in the following Reports and Publications section.

Table 1 – University Research Projects Summary

Subcontract # Applicant Award Date	Principal Investigator	\$ DOE, Months	Area of Research (Combustion; Materials; Aero-Heat Transfer; Instrumentation, Sensors and Life), Project Title, Goal
01-01-SR089; Louisiana State University, Baton Rouge, LA 3/1/01	Sumanta Acharya 225.578.5809 acharya@alpha2.eng.LSU.edu	\$228,873 24 months Under UTSR	AHT: "Internal Cooling in Leading and Trailing Edge Passages With Rotational and Buoyancy." For parameter ranges pertinent to gas turbines, provide data that will increase the understanding of turbine engineers to design cooling channels for rotor blades.
01-01-SR090; Pennsylvania State University; University Park, PA 2/1/01	Domenic Santavicca 814.863.1863 das8@psu.edu	\$259,392 24 months Under UTSR	C: "Optimization of the Injector Fuel Distribution for Stable, Low Emissions Combustion in Lean Premixed Gas Turbine Combustors." Identify approaches to position and time fuel injection to control stability and emissions in lean premixed turbine combustors.
01-01-SR091; University of Connecticut; Storrs, CT 2/1/01	Maurice Gell 860.486.3514 mgell@mail.ims. uconn.edu	\$319,918 24 months Under UTSR	M: "Thermal Barrier Coatings and Metallic Coatings With Improved Durability." Evaluate bond coat compositions and TBC processing to improve coating lifetimes by a factor of at least three times.
01-01-SR092; University of Texas at Austin; Austin, TX 3/1/01	David G. Bogard 512.471.3128 dbogard@mail.utexas.edu	\$324,900 24 months Under UTSR	AHT: "Attenuation of Hot Streaks and Interaction of Hot Streaks With the Nozzle Guide Vane and Endwall." Provide a database to turbine engineers describing interactions of hot streaks and vane/endwall heat transfer for cooling design and materials selection.

01-01-SR093; University of California at Santa Barbara; Santa Barbara, CA 2/1/01	David R. Clarke 805.893.8275 clarke@engineering.ucsb.edu	\$399,253 24 months Under UTSR	M: "A Science-Based Approach to Enhanced Zirconia-Based Thermal Barrier Coatings for Advanced Gas Turbine Applications." Establish a scientific basis to enable the development of zirconia based TBCs with improved high temperature properties (reduced conductivity, sintering, and destabilization) compared to current commercial TBCs.
01-01-SR094; Texas A&M University; College Station, TX 3/1/01	Je-Chin Han 409.845.3738 jchan@mengr.tamu.edu	\$189,248 24 months Under UTSR	AHT: "Rotating Heat Transfer in High Aspect Ratio Rectangular Cooling Passages With Shaped Turbulators." Provide turbine engineers with new data for designing turbulators to improve internal cooling and thereby increase turbine performance and fuel efficiency.
02-01-SR095; Georgia Institute of Technology; Atlanta, GA 5/1/02	Ben Zinn 404.894.3033 ben.zinn@aerospace.gatech.edu	\$452,700 36 months	C: "Understanding and Control of Combustion Dynamics in Gas Turbine Combustors." Experimentally evaluate factors that cause and sustain combustion instabilities and develop models to analytically predict the occurrence and amplitude of oscillations.
02-01-SR096; University of Minnesota; Minneapolis, MN 5/1/02	Terrence Simon 612.625.5831 tsimon@mc.umn.edu	\$430,620 36 months	AHT: "Aerothermal Effects of Interfacial Leakage and Film Cooling Schemes with Endwall and Leading Edge Contouring." Evaluate the use of cooling flows, cavity flows, and end wall contouring to reduce aerodynamic losses and improve cooling heat transfer for turbine flow passages.
02-01-SR097; University of Connecticut; Storrs, CT 5/1/02	Eric Jordan 860.486.2371 jordan@engr.uconn.edu	\$478,490 36 months	M: "Measurement of Three Critical Parameters as a Basis for a Simple Life Prediction Method." 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.
02-01-SR098; Louisiana State University; Baton Rouge, LA 5/1/02	Sumanta Acharya 225.578.5809 acharya@alpha2.eng.LSU.edu	\$302,370 36 months	AHT: "Experiments and Computations on Film-Cooled End Walls with Contouring." 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 more effective end wall cooling.
02-01-SR099; Virginia Polytechnic Institute; Blacksburg, VA 5/1/02	Uri Vandsburger 540.231.4459 uri@shakti.me.vt.edu	\$603,690 36 months	C: "Modeling and Control of Ultra-Lean Premixed Combustion Dynamics for Gas Turbines." Develop and use design-oriented modeling capabilities for determining passive energy absorption strategies or active control approaches that reduce the occurrence and level of instabilities and extend lean blowout limits for combustors.

02-01-SR100; Virginia Polytechnic Institute; Blacksburg, VA 5/1/02	Danesh Tafti 540.231.9975 dtafti@vt.edu	\$331,430 36 months	AHT: "Enhanced Prediction Techniques Based on Time-Accurate Simulations for Turbine Blade Internal Cooling." Evaluate alternate techniques for predicting flows in internal cooling passages of turbine blades and then validate those techniques in an experimental facility.
02-01-SR101; University of Pittsburgh; Pittsburgh, PA 5/1/02	Gerald Meier 412.624.9741 ghmeier@engr.pitt.edu	\$412,700 36 months	M: "Mechanism-Based Testing Methodology for Improving the Oxidation, Hot Corrosion and Impact Resistance of High-Temperature Coatings for Advanced Gas Turbines." Develop a mechanism-based non destructive testing methodology to assess metallic coating and TBC degradation resulting from cyclic oxidation, hot corrosion, and foreign object impact damage.
02-01-SR102; Georgia Institute of Technology; Atlanta, GA 5/1/02	Jerry Seitzman 404.894.0013 jerry.seitzman@ae.gatech.edu	\$317,500 36 months	ISL: "Advanced Sensor Approaches for Monitoring and Control of Gas Turbine Combustors." Develop sensing strategies to monitor turbine combustor health and performance and also enable control systems to actively manage engine condition to compensate for changes in ambient conditions and system degradation (e.g., wear).
02-01-SR103; University of Central Florida; Orlando, FL 5/1/02	Yong-ho Sohn 407.882.1181 ysohn@mail.ucf.edu	\$208,230 36 months	M: "Assessment of Failure Mechanisms for Thermal Barrier Coatings by Photoluminescence, Electrochemical Impedance and Focused Ion Beam." Use multiple types of measurement techniques to determine causes of TBC failures and refine non destructive evaluation methods for TBC coatings.
02-01-SR104; Brigham Young University; Provo, UT 6/1/02	Jeffrey Bons 801.422.8036 jbons@byu.edu	\$563,700 36 months	AHT: "Turbine Surface Degradation With Service and Its Effects on Performance." Establish the groundwork for a model to assess the effect of turbine service time on engine performance degradation due to factors such as erosion, deposition and coating spallation from airfoils.
03-01-SR105; University of Wisconsin; Madison, WI 7/1/03	Scott Sanders 608.262.3540 sanders@engr.wisc.edu	\$418,960 36 months	ISL: "Advanced Optical Sensor for Monitoring and Control of Multiple Gas and Turbine Blade Properties" , Evaluate the potential of fiber optic sensors for monitoring and active control input for gas turbines. Sensed parameters include strain and temperature of gas turbine components and gas temperature and composition.

03-01-SR106; Cleveland State University; Cleveland, OH 7/1/03	Kang Lee 216.433.5634 kang.n.lee@lerc.nasa.gov	\$391,615 36 months	M: "Spectroscopic In-Situ Non-Destructive Evaluation to Monitor the Health of Thermal Barrier Coatings" , Evaluate an approach based on optically monitoring turbine exhaust composition for detection of thermal barrier coating degradation and impending failure.
03-01-SR107; University of Connecticut; Storrs, CT 7/1/03	Nitin Padture 860.486.4206 nitin.padture@uconn.edu	\$540,000 36 months	M: "Superior Thermal Barrier Coatings for Industrial Gas turbines Using a Novel Solution Plasma Spray" , Evaluate a new Solution Plasma Spray (SPS) process to produce improved thermal barrier coatings. At representative syngas turbine conditions, determine the hot corrosion performance of SPS TBCs compared to conventional TBCs.
03-01-SR108; Clemson University; Clemson, SC 7/1/03	John Wagner 864.656.7376 jwagner@clemson.edu	\$319,480 36 months	ISL: "An Advanced Diagnostic and Prognostic System for Gas Turbine Generator Sets with Experimental Validation" , Develop a real-time conditioning monitoring and prediction program for gas turbine engines to diagnose and predict short term health and readiness. Use behavior models, sensor fusion strategies, neural networks, and extensive statistical analyses in the program along with a prognostic model to predict onset of faults, degraded operation, and to facilitate maintenance scheduling.
03-01-SR109; Pennsylvania State University; University Park, PA 7/1/03	Domenic Santavicca 814.863.1863 das8@psu.edu	\$382,540 36 months	C: "The Effects of Fuel distribution, Velocity Distribution, and Fuel Composition on Static and Dynamic Instabilities and NOx" , Investigate the effects of fuel-air profile and velocity profile on lean blowout, combustion dynamics, and NOx emissions under conditions representative of lean premixed combustors operating with coal syngas and natural gas.
03-01-SR110; Virginia Polytechnic Institute; Blacksburg, VA; 7/1/03	Karen Thole 540.231.7192 thole@vt.edu	\$572,385 36 months	AHT: "Improved Film Cooling Performance for Turbine Vanes and Endwalls with Realistic Surface Conditions" , Investigate the effects on airfoil cooling performance of surface roughness and cooling hole partial blockage, such as caused by deposits in syngas turbines. Evaluate cooling hole traverse slots to improve cooling effectiveness and alleviate effects of partial blockage of cooling holes by deposits.

03-01-SR111; Georgia Institute of Technology; Atlanta, GA 7/1/03	Timothy Lieuwen 404.894.3041 tim.lieuwen@aerospace.gatech. edu	\$376,720 36 months	C: "Combustion Instability and Blowout Characteristics of Fuel Flexible Combustors" , Use experiments and analyses to improve understanding and develop modeling capabilities for effects of fuel variability on a combustor's static stability (lean blowout) and dynamic stability characteristics. Tests and analyses consider gas compositions representative of coal syngas.
03-01-SR112; University of California, Irvine; Irvine, CA 7/1/03	Scott Samuelsen 949.824.5468 gss@uci.edu	\$172,650 24 months	C: "Correlation of Ignition Delay with IGCC Type Fuels" , Using simulated coal synfuels, conduct ignition delay experiments to identify design rules for avoiding autoignition in lean premixed combustion systems.
03-01-SR113; Texas A&M University; College Station, TX 7/1/03	J. C. Han 979.845.3738 jchan@mengr.tamu.edu	\$361,020 36 months	AHT: "Heat Transfer from Rotating Blade Platforms With and Without Film Cooling" , Obtain experimental data and numerical predictions to enable turbine designers to improve the cooling efficiency of rotating blades and thereby increase turbine power and efficiency.
04-01-SR114; University of Central Florida; Orlando, FL 8/1/04	E. Petersen 407.823.6123 Petersen@mail.ucf.edu	\$405,990 36 months	C: "Combustion Characterization and Modeling of Fuel Blends for Power Generation Gas Turbines" , Measure combustion characteristics (flame speed, autoignition, kinetics, NO _x) over a wide range of fuel compositions and conditions representative of syngas turbines.
04-01-SR115; University of Pittsburgh; Pittsburgh, PA 8/1/04	M. Chyu 412.624.9783 mkchyu@engr.pitt.edu	\$399,707 36 months	AHT: "Effects of Coating Blockage and Deposits on Film Cooling Effectiveness and Heat Transfer" , Experiments and computations to explore transport processes and effects on cooling performance associated with film cooling hole blockage and surface deposits.
04-01-SR116; University of Pittsburgh; Pittsburgh, PA 8/1/04	F. S. Pettit 412.624.9730 pettit@engrng.pitt.edu	\$340,206 36 months	M: "Investigation of Materials Performance in High Moisture Environments Including Corrosive Contaminants Typical of Those Arising by Using Alternate Fuels in Gas Turbines" , Experiments and data analyses to develop a fundamental understanding of corrosion of typical turbine alloys and coatings due to deposits and moisture environments under conditions representative of operation with alternate fuels, including syngas.

05-01-SR117 Penn State University; University Park, PA 8/1/05	Robert Santoro 814.863.1285 rjs2@psu.edu	\$419,036 36 months	C: "Autoignition Studies of Syngas and Hydrogen (SGH) Fuels" , Experiments to characterize the autoignition of syngas and hydrogen (SGH) fuels at high pressures and temperatures typical of lean premixed gas turbine engine conditions. Autoignition delay times determined in the first two years for CO/H ₂ mixtures representing syngas (CO+3H ₂) to pure hydrogen (H ₂). For the third year, autoignition characteristics of CO/H ₂ /H ₂ O mixtures are evaluated.
05-01-SR118 University of Central Florida; Orlando, FL 8/1/05	Yongho Sohn 407.882.1181 ysohn@mail.ucf.edu	\$246,599 24 months	M: "Degradation of Thermal Barrier Coatings with Syngas Combustion" , Advanced microstructural analyses techniques (such as advanced electron microscopy) used for the first time to evaluate degradation mechanisms of TBCs in realistic syngas combustion environments.
05-01-SR119 University of North Dakota; Grand Forks, ND 8/1/05	Forrest Ames 701.777.2095 forrest.ames@mail.und.nodak.edu	\$342,552 36 months	AHT: "Aero Losses, Heat Transfer, Discharge Coefficients for Different Vane Trailing Edge Configurations for Syn Gas Fired Turbines" , Performance characteristics of five different approaches for cooling trailing edges of turbine airfoils are experimentally evaluated in this project. Experiments include representation of the effects of airfoil surface roughness caused by deposition in syngas turbines.
05-01-SR120 Brigham Young University; Provo, UT 8/1/05	Thomas Fletcher 801.422.6236 tom_fletcher@byu.edu	\$399,422 36 months	AHT: "Deposition of Alternative (Syngas) Fuels on Turbine Blades with Film Cooling" , A natural gas combustion stream is seeded with coal and biomass products of combustion particulate and accelerated to turbine flow velocities in a simulator where specimens of turbine materials are exposed. Phase 1 of the project explores the possibility of increased cooling of specimens (and turbine surfaces) to mitigate deposition. Phase 2 evaluates the influence of deposit formation on film cooling.
05-01-SR121 Massachusetts Institute of Technology; Cambridge, MA 8/1/05	Ahmed Ghoniem 617.253.2295 ghoniem@mit.edu	\$455,820 36 months	C: "Fundamental Studies in Syngas Premixed Combustion Dynamics" , The fundamental characteristics of syngas combustion are experimentally evaluated over a wide range of conditions representative of syngas turbines. Data on flammability limits, stability characteristics, laminar and turbulent flame propagation, flame anchoring mechanisms, burning conditions, and syngas composition are collected experimentally and synthesized into models.

07-01-SR122 Georgia Tech; Atlanta, GA 5/15/07	Jerry Seitzman 404.894.0013 jerry.seitzman@ae.gatech.edu	\$322,890 36 months	C: "Turbulent Flame Speed Measurements and Modeling of Syngas Fuels" , After preparation of the facility to handle syngas compositions, experiments are conducted to measure turbulent combustion flame speeds over the range of conditions relevant to recuperated microturbines, mid-size simple cycle turbines, and heavy duty large gas turbines. The data and analyses are used to produce predictive models that could be used by gas turbine manufacturers to develop combustors that operate with syngas and hydrogen derived from syngas.
07-01-SR123 Virginia Tech; Blacksburg, VA 8/1/07	Danesh Tafti 540.231.9975 dtafti@vt.edu	\$507,286 36 months	AHT: "Syngas Particulate Deposition and Erosion at the Leading Edge of a Turbine Blade with Film Cooling" , Experimental and advanced computation approaches are used to provide design data and tools for turbine engineers to evaluate deposition and erosion at the leading edges of turbine blades with film cooling. Evaluations are conducted over a range of flow and thermal conditions and particle dynamics applicable to turbines operating with syngas and hydrogen derived from syngas.
07-01-SR124 University of Pittsburgh; Pittsburgh, PA 7/15/07	Gerry Meier 412.624.9741 ghmeier@engr.pitt.edu	\$338,640 36 months	M: "Materials for Oxy-Fuel Turbomachine Conditions" , Oxidation and ductility performance of candidate alloys and coatings are evaluated for conditions of Oxy-fuel turbines. Steam, O ₂ , and CO ₂ levels are varied to represent the anticipated range in the flow path of Oxy-fuel turbines. Alloys and coatings with the highest performance in these environments are indentified and then further tested under conditions when trace levels of SO _x and alkali are present.
07-01-SR125 University of California, SB; Santa Barbara, CA 5/15/07	Ted Bennett 805.893.8115 bennett@engineering.ucsb.edu	\$186,502 24 months	M: "Evaluating Coatings for Current and Future Service with Thermal Property Measurements" , A non-destructive procedure is advanced to take thermal property measurements on thermal barrier coatings (TBC) that have experienced service in turbines to assess and track coating performance deterioration. The procedure uses harmonic laser heating of the coating and measurements that interrogate the phase of the resulting temperature field to determine coating properties. The procedure is applied to TBC that have experienced deposits, such as in syngas turbines, to asses the effects of deposits on coating properties and life.

07-01-SR126 University of Colorado; Boulder, CO 5/15/07	John Daily 303.492.6221 john.daily@colorado.edu	\$340,102 36 months	C: "High Pressure Kinetics of Syngas and Nearly Pure Hydrogen Fuels" , Kinetics related to combustion of syngas and high hydrogen fuels are explored through detailed composition measurements of combustion intermediaries and products in a high pressure flow reactor. The data are then compared with calculations using existing mechanisms. Comparisons are used to modify reaction rate parameters and modify existing mechanisms to provide more accurate kinetics models for the design of turbine combustors that operate with syngas and nearly pure hydrogen fuels.
07-01-SR127 University of Texas; Austin, TX 7/ 1/07	David Bogard 512.271.3128 dbogard@mail.utexas.edu	\$555,400 36 months	AHT: "Simulating Particle Deposition and Mitigating Deposition Degradation Effects in Film Cooled Turbine Sections" , A new film cooling technique is evaluated that not only improves cooling performance compared to standard approaches used in conventional turbines but also maintains cooling performance for conditions of deposits on turbine surfaces, such as those that can occur in syngas turbines.

2.1. Results and Discussion

This section provides brief summaries of each project, conclusions, logical implications, and relevancy of results to advanced turbines operating with high hydrogen fuels produced from coal syngas. The university final reports in Appendix C and publications from the university projects listed in the Reports and Publications section include data from each of the projects with explanations of how the data was interpreted, how the data relate to the research goals and how the data verified the conclusions and accomplished the objectives of the research.

SR089: *Internal Cooling in Leading and Trailing Edge Passages with Rotational and Buoyancy*, Principal Investigator: Sumanta Acharya, Louisiana State University

This Louisiana State University (LSU) project investigated rotation effects on cooling of turbine blades. Experimental data were acquired in a rotating test facility for smooth and ribbed rectangular cooling passages with two aspect ratios (4:1 and 1:4) and two orientations with respect to the rotation axis. The figure below shows one of the cooling channel setups used in the rotating cooling flow experiments.

Figure 1 – Experimental Setup

Computational analyses using both Large Eddy Simulations (LES) and Reynolds Averaged Navier–Stokes (RANS) techniques were validated with experimental data. RANS computer analyses were then used to obtain simulations for cooled rotating passages over an extended range of Reynolds numbers, rotation numbers, and buoyancy parameters pertinent to gas turbines.

Significance: This project expanded the data base for turbine engineers to design internally cooled rotating airfoils. The research explored cooling channel configurations and Reynolds Numbers beyond those previously reported in the literature.

SR090: Optimization of the Injector Fuel Distribution for Stable, Low Emissions Combustion in Lean Premixed Gas Turbine Combustors, Principal Investigator: Domenic Santavicca, Pennsylvania State University

This Penn State University (PSU) project conducted experiments in an optically accessible premixed combustor to evaluate the effects of combustor inlet fuel injection distributions on combustion stability, NO_x emissions, and flame structure. Stability and emissions maps were experimentally obtained for five fuel injection locations and a range of combustor configurations, flow velocities, temperatures, and equivalence ratios. Flame structure images were obtained using chemiluminescence techniques. The following figure shows an example Rayleigh Index color map illustrating stable damping (negative regions) and unstable damping (positive regions) in the combustor flow stream.

Figure 2 - Rayleigh Index Color Map of Combustor Flow Stream

The project determined that inlet fuel distribution significantly affects both combustion stability and emissions. Interactions of combustor configuration and operating conditions on stability and emissions were also quantified.

Significance: Because lean premixed turbine combustors operate near lean blowout limits, achieving low NO_x emissions with stable operation under lean premixed fuel conditions present design challenges for turbine combustor engineers. The PSU project produced an extensive data base of operating parameters and provided insights for design of low NO_x turbine combustors.

SR091: "Thermal Barrier Coatings and Metallic Coatings with Improved Durability",
Principal Investigator: Maurice Gell, University of Connecticut

This University of Connecticut (UConn) project also involved the University of Pittsburgh and the University of Central Florida which conducted experiments and analyses to evaluate thermal barrier coating (TBC) manufacturing processes to improve life. Six industrial companies also participated in the project.

The figure below shows project experimental data on spallation life measured in thermal cycles for various TBC processing methods: 1) Preoxidation, 2) Without preoxidation, 3) Barrel finished with preoxidation, 4) Barrel finished without preoxidation, 5) Hand finished with preoxidation, and 6) Hand finished without preoxidation.

Figure 3 – Spallation Life for Various TBC Processing Methods

The project demonstrated that substantially increased TBC spallation life can be achieved by i) media finishing the TBC bond coat to make it as smooth as possible, ii) pre-oxidizing the smooth bond coat to form a thin, continuous alpha alumina layer prior to depositing the outer ceramic layer, and iii) using bond coats containing silicon and hafnium for improved long term adherence of the bond coat.

Significance: TBCs insulate turbine metal surfaces to reduce part cooling requirements and thereby improve turbine power and efficiency. Originally developed for aircraft turbines, TBC use in utility and industrial turbines with much longer life requirements than aircraft turbines has been hindered because of a lack of long term service durability and reliability. The combined efforts of three universities and six industrial participants in this project identified TBC manufacturing specifications that can increase lifetimes by a factor of four times. A gas turbine manufacturer has implemented and refined the UCONN findings and has achieved even greater improvements in TBC lifetimes.

A four page article in the January-February 2003 issue of the gas turbine trade magazine *Gas Turbine World* focused mainly on this research (along with other UTSR research projects on TBCs). Commenting on the project results, the article noted "...significant progress to improve the performance and reliability of thermal barrier coatings for gas turbine components—and to accurately predict remaining TBC life once in service."

SR092: "Attenuation of Hot Streaks and Interaction of Hot Streaks with the Nozzle Guide Vane and End Wall", Principal Investigator: David G. Bogard, University of Texas

This University of Texas (UT) project with Virginia Tech (VT) used experiments and computer analyses to improve cooling and thereby protect first row vanes in turbines from burnout due to hot streaks from the turbine combustor. First vane end walls are typically protected from burnout by injecting cooling air through holes in the end walls and/or through circumferential

slots between the combustor and vane platforms. The research in this project evaluated the cooling effectiveness of slot cooling alone, end wall cooling alone, and combined slot and end wall cooling. The figure illustrates the UT experimental cascade and hot streak generator.

Figure 4 – Experimental Cascade and Hot Streak Generator

The evaluations showed that slot cooling alone is not adequate because vane secondary flows prevent full coolant coverage of the end walls. End wall cooling alone was found deficient in protecting the end wall regions near the interface between adjacent vanes. The combination of slot cooling and end wall cooling provided the best protection of end walls from burnout but a certain minimum level of end wall cooling is needed to prevent a high temperature ring that extends along the entire vane convex surface. The experiments also showed that the cooling flows interacted with the vane passage secondary flow vortex to produce a temperature environment that would not be predicted by superposition such that superposition would under predict end wall life.

Significance: Determination of appropriate cooling flow rates and placement of cooling holes is a difficult challenge for turbine engineers because of the complicated flow and heat transfer interactions between slot and end wall cooling flows, combustor hot streaks, and the secondary flows that develop through vane passages. The UT and VT project results provide guidance to turbine designers to enable more efficient cooling of first stage vane end walls, thereby increasing component life and decreasing turbine power and efficiency losses due to cooling.

SR093: "A Science-Based Approach to Enhanced Zirconia-Based Thermal Barrier Coatings for Advanced Gas Turbine Applications", Principal Investigator: David R. Clarke, University of California-Santa Barbara

The University of California at Santa Barbara (UCSB) project conducted experiments to determine how TBCs fail under cyclic conditions and how impending failure might be detected. The project showed that an early warning of TBC internal damage is wrinkling or rumpling at the surface of the TBC that increases with time and number of thermal cycles. These surface undulations (illustrated below) are evidence of separation of the outer ceramic coating layer from an internal thermally grown oxide layer. The undulations can be detected using low level magnification and oblique illumination.

Figure 5 – TBC Surface Undulations Due to Thermal Cycling

The research demonstrated 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 structure. The project also characterized sintering of the TBC ceramic (YSZ) which reduces insulation benefits.

Significance: The UCSB project advanced the scientific-basis for improving thermal barrier coatings (TBCs) used to insulate gas turbines metal surfaces from very high temperatures. Fundamental understanding and information from the project on how TBCs fail will aid in the development of coatings with longer lifetimes and detection of degradation so turbine parts can be taken out of service before loss of their protective coating.

SR094: "Rotating Heat Transfer in High Aspect Ratio Rectangular Cooling Passages with Shaped Turbulators", Principal Investigator: Je-Chin Han, Texas A&M University

This Texas A&M (TAM) project explored six candidate rib configurations (illustrated in the following figure) for use within internal cooling passages of turbine airfoils to increase flow turbulence and thereby improve air cooling efficiency for both stationary and rotating turbine airfoils. The project developed improved computer models to provide much better flow and heat transfer predictions than the standard turbulence model for rotating cooling channels with angled ribs. The project identified V and W shaped rib configurations that produce up to 24% better cooling performance than configurations previously used for airfoils.

Figure 6 – Candidate Rib Configurations for Turbine Airfoil Internal Cooling Passages

Significance: TAM obtained information on the best performing internal rib configurations for airfoil cooling passages that will enable turbine engineers to refine cooling designs for improved performance. The research also provided advanced computational tools for improved cooling design of stationary vanes and rotating blades. These project results offer the potential to reduce the penalties of cooling on turbine power output and efficiency, which supports the improved efficiency goals of the DOE Turbine Program for syngas and high hydrogen fuels from syngas.

SR095: "Understanding and Control of Combustion Dynamics in Gas Turbine Combustors",
Principal Investigator: Ben Zinn, Georgia Institute of Technology

This Georgia Tech (GT) project conducted experiments and analyses to evaluate pressure oscillations in turbine combustors. The project characterized combustion process non-linearities that determine the amplitude of instabilities, developed and validated models of turbulent flame/acoustic wave interactions that occur during screeching instabilities, and showed practical control approaches for preventing instabilities. Two promising instability control approaches were demonstrated in the project. The first provides open loop control of combustion instabilities by fuel injection rate modulation at non-resonant frequencies. The second approach demonstrated that instabilities can be inhibited by adjusting the inner and outer swirler air flow ratio for the combustor fuel injector. The following figure shows project data indicating the benefit of using fuel injection control to reduce the amplitude of combustor pressure oscillations.

Figure 7 – Impact of Fuel Injector Control on Combustor Oscillations

Significance: Results from the GT project have provided the gas turbine industry with improved understanding and methods to control processes that produce combustion instabilities which have resulted in removal of turbines from service due to excessive noise and structural damage.

SR096: "Aerothermal Effects of Interfacial Leakage and Film Cooling Schemes with End Wall and Leading Edge Contouring", Principal Investigator: Terrence Simon, University of Minnesota

This University of Minnesota (UM) project evaluated contouring of the end wall of transition passages between the turbine combustor and first stage stator vanes for improved end wall cooling and reduced aerodynamic losses in the passage. Cascade tests and computational codes were also used to identify the aerodynamic and cooling effects of factors such as leakage flows, misalignments that produce steps in the flow boundary, and the slash face gap in the platforms between adjacent vanes. Schematics of the experimental facility are shown below.

The project evaluations showed that convex curvature of the end wall stabilizes the boundary layer and reduces the strength of secondary passage flows, thereby reducing aerodynamic losses. Flow leakage through the slash face produces the largest effect (up to 20%) on passage losses of all the passage features that were evaluated. Next in importance was a step in the transition section gap, where a step-up on the contoured end wall results in a decrease in passage losses.

Figure 8 – Schematic of the Experimental Facility

Significance: The UM project evaluated effects of transition passage features on aerodynamic performance. The data and analyses provide turbine engineers with information needed to improve transition passage designs for increased engine performance through reduced aerodynamic losses.

SR097: "Measurement of Three Critical Parameters as a Basis for a Simple Life Prediction Method", Principal Investigator: Eric Jordan, University of Connecticut

This University of Connecticut (UConn) project investigated alternative non-destructive methods to detect internal damage and predict remaining life of thermal barrier coatings used to insulate turbine parts from high temperatures. The project used photo-stimulated luminescence piezo spectroscopy (PLPS) to measure stresses within TBCs produced by the electron beam physical vapor deposition process. Coated specimens were exposed to thermal cycling at turbine temperatures and remaining lifetimes were correlated with the measured internal stress level. The project showed that remaining coating life for TBCs with Pt modified NiAl bond coats correlates with stress level measured by PLPS and is nearly independent of cycle temperature.

The time duration of thermal cycles only moderately affected the relationship between remaining coating life and measured stress levels. As indicated in the following figure, the data showed that the measured stress level at failure was consistent to within 7% for all temperatures and thermal cycle times.

Figure 9 – Relationship Between Remaining TBC Life and Stress Level

The prediction of remaining life of TBCs with MCrAlY bond coats required AC potential drop measurements of thickness of the thermally grown oxide at the bond coat interface and 3-D laser interferometric surface profiler measurements of the bond coat surface geometry in addition to PLPS measurements of stresses. The three parameter measurement approach proved highly useful in making remaining life predictions for five TBC systems.

Significance: The development of advanced non-destructive methods to determine remaining life of TBCs during turbine inspections will reduce unplanned shutdowns due to coating failures or needlessly removing parts with acceptable remaining lifetimes on a statistical basis to prevent failures. UConn showed that the PLPS method of measuring stresses within TBCs with Pt modified NiAl bond coats offers promise for a relatively simple non-destructive approach to determining remaining life while requiring little or no knowledge or monitoring of the histories of turbine part temperatures or thermal cycling.

SR098: "Experiments and Computations on Film-Cooled End Walls with Contouring",
Principal Investigator: Sumanta Acharya, Louisiana State University

This Louisiana State University (LSU) project evaluated the potential benefits of contouring the end walls of turbine airfoil passages and using airfoil fillet shaping to control secondary flows and heat transfer to end walls. Experiments and analyses identified an end wall contour that reduces airfoil passage total pressure losses (illustrated in the figures below) and end wall heat transfer coefficients compared to a baseline case.

Figure 10 – Effect of End Wall Contouring on Pressure Losses

Significance: The LSU project has provided turbine engineers with data and analyses for developing strategies to improve aerodynamic efficiency of turbine airfoil passages and reducing the heat load to passage end walls. The resulting designs offer the potential for reduced aerodynamic losses and lower end wall cooling air requirements, with resulting improved fuel efficiency and reliability of gas turbines.

SR099: "Modeling and Control of Ultra-Lean Premixed Combustion Dynamics for Gas Turbines", Principal Investigator: Uri Vandsburger, Virginia Polytechnic Institute and State University

The objective of this Virginia Tech (VT) project was to develop and use design-oriented modeling capabilities for determining passive energy absorption strategies or active control approaches that reduce the occurrence and level of instabilities and extend lean blowout limits for combustors. The researchers pursued a systems level methodology with analyses and experiments directed to obtaining a fundamental understanding of each combustion sub-process. The laboratory scale combustor used for experiments is shown in the following figure. A goal was reduced-order tools to efficiently aid the design phase of a turbine combustor to eliminate instabilities.

Figure 11 – Laboratory Combustor Rig

Significance: The extensive final report (170 pages) for the project has provided the gas turbine industry with a broad compilation of information and understanding concerning combustion dynamics. The development of simplified reduced order models to capture the essential features of instabilities for a range of combustors would have enabled engineers to design turbine combustors more efficiently and at lower cost. However, although the project advanced the knowledge of combustion processes, it did not appear to develop accurate enough reduced order models for design of complex commercial gas turbine combustors.

SR100: "Enhanced Prediction Techniques Based on Time-Accurate Simulations for Turbine Blade Internal Cooling", Principal Investigator: Danesh Tafti, Virginia Polytechnic Institute and State University

This Virginia Tech (VT) project evaluated various computer simulation algorithms to predict the complex flows and heat transfer for internal cooling channels of turbine airfoils. The project established that the Large Eddy Simulation (LES) approach can be used for robust, repeatable, and accurate predictions of heat transfer in ribbed cooling channels, such as those used in gas turbines. LES was successfully applied for the first time to capture the flow and heat transfer characteristics at the entrance and within a 180 degree bend. The figure below illustrates the test facility used to verify the computational results.

Figure 12 – Internal Cooling Channel Test Facility

Detached eddy simulations (DES) were, for the first time, applied to adequately predict heat transfer in a ribbed channel and showed favorable comparisons with LES but at a much lower computation cost. The computational advancements achieved in this project were recognized in an article appearing in the Fall 2004 issue of ACCESS, the publication of the National Center for Supercomputer Applications.

Significance: The VT project analyzed, developed, and verified advanced computational techniques for use in improving the cooling design of turbine airfoils. The project has enabled new advances in prediction capabilities for internal cooling flows. This technology should result in more cost effective design and more efficient cooling of turbines, with corresponding benefits in turbine efficiency and power. Since higher efficiency for operation with high hydrogen fuels is a major goal of the DOE Turbine Program, the VT project facilitated this goal.

SR101: "Mechanism-Based Testing Methodology for Improving the Oxidation, Hot Corrosion and Impact Resistance of High-Temperature Coatings for Advanced Gas Turbines", Principal Investigator: Gerald Meier, University of Pittsburgh

This University of Pittsburgh (Pitt) project comprised a collaborative University/National Laboratory/Industry effort to develop a mechanism-based testing methodology that could lead to improving thermal barrier coatings and the oxidation resistance of high temperature metallic coatings. A number of nondestructive test approaches were investigated to assess and better understand coating degradation and damage accumulation. The test results were also used to advance a life prediction protocol. Pitt led the effort and performed corrosion studies, acoustic emission assessments and x-ray diffraction evaluations. The acoustic emission testing apparatus used at Pitt is illustrated below.

Figure 13 – Acoustic Emission Testing Apparatus

Carnegie Mellon University (CMU) performed indentation and impact evaluations and fracture mechanics analyses. Oak Ridge National Laboratories (ORNL) performed piezospectroscopic stress analyses and Argonne National Laboratories (ANL) performed optical backscatter measurements. Specimens were prepared by Praxair and Howmet. GE provided input on testing conditions for the various degradation modes that were investigated.

The specimen analyses were used as a basis to model the degradation mechanisms of the coatings and to extend the experimental results in a predictive manner. The project also developed a modified cyclic oxidation model to incorporate stress measurements in predictions. Acoustic emission measurements were used to obtain spall parameters. Good agreement between model predictions and measured lives were obtained. The project then evaluated process and compositional modifications for TBCs for improved resistance to cyclic oxidation, hot corrosion, and impact/erosion.

Significance: The project showed progress in non-destructive evaluation (NDE) of TBCs involving modifications of a NASA life prediction model using acoustic emissions data as input. NDE tests and lifetime prediction models were improved for assessing the condition of TBCs before failure. The close collaboration between Pitt, other universities, national laboratories, industrial coating manufacturers and users in this project should advance the identification and development of more durable TBCs operating in harsh environments such as in syngas turbines.

SR102: "Advanced Sensor Approaches for Monitoring and Control of Gas Turbine Combustors", Principal Investigator: Jerry Seitzman, Georgia Institute of Technology

This Georgia Tech (GT) project explored the monitoring of natural optical and acoustic radiation (light and sound) emitted by combustion processes and characterizing these emissions from a number of combustors to correlate measurements with performance and stability. The goal was to develop real-time sensor methodologies to identify combustor stability margins and performance using transient flame holding event sensors, flame zone sensors and combustion dynamics stability margin sensors. Measurements of acoustic and optical signatures were performed in a variety of combustors to assure general applicability of the sensing approach.

The project identified acoustic and optical monitoring methods that give information on proximity to blow off in a range of combustors. These methods were demonstrated in a gas turbine type combustor using a variety of fuels. As indicated in the figure below, a large increase in precursor events near the lean blowout equivalence ratio of 0.33 (indicated by the dashed vertical line) were detected in the optical and acoustic signatures for a swirl stabilized combustor operated with a H₂-CO fuel mixture.

Figure 14 – Increase in Precursor Events Near the Lean Blowout Equivalence Ratio

A sensing approach to detect the combustion dynamics stability margin was also identified. The method involves measurements of combustor damping while operating stably. Research also explored extending the technique to the unstable (nonlinear) regime to provide a control system with information needed to return the combustor to stable operation.

Flame sensing using chemiluminescence was also developed to detect local variations in fuel to air ratios and heat release (spatial or temporal) in the flame zone. The method was demonstrated in a range of natural gas combustors and for combustion product compositions representative of syngas fuels.

Significance: The GT project advanced sensing methods for power plant operators to detect impending combustor malfunctions (blow out or pressure oscillations that can cause excessive noise and structural damage) so preventative measures can be taken before they happen. GT worked with three gas turbine suppliers to develop the combustor monitoring techniques. The sensing methodology for combustion oscillations was licensed to Alta Solutions which conducted field tests of the methodology on four Calpine gas turbines in Texas.

SR103: *"Assessment of Failure Mechanisms for Thermal Barrier Coatings by Photoluminescence, Electrochemical Impedance and Focused Ion Beam"*, Principal Investigator: Yong-ho Sohn, University of Central Florida

This University of Central Florida (UCF) project evaluated and compared two non-destructive evaluation (NDE) techniques (photostimulated luminescence spectroscopy and electrochemical impedance spectroscopy) to investigate sources of failure for thermal barrier coatings. A range of microstructural analytical techniques was also developed and used to better understand failure mechanisms of TBCs and develop/refine the NDE techniques. These evaluation approaches were applied to five types of TBCs tested under high temperature thermal cycle conditions and analyzed at 10%, 50% and 70% lifetimes. The figure below shows a shift in photostimulated luminescence spectra from an EB-PVB TBC coating indicating an impending failure due to thermal cycles. The coating failed at 350 cycles.

Figure 15 – Photostimulated Luminescence Spectra from an EB-PVB Coating

Significance: Thermal barrier coatings (TBCs), along with advanced cooling techniques, have been the two most important technologies that have enabled turbines to operate at increased temperatures and resulting increased performance (power and efficiency). TBCs, originally developed for aircraft turbines with relatively frequent maintenance intervals, have needed durability improvements for the much longer life requirements of land-based turbines. The testing and analyses in this program of a range of TBC types with a wide variety of NDE and analyses techniques developed a comprehensive set of data and knowledge concerning the fundamental science of thermo-kinetics and thermo-mechanics as a basis for improving TBC durability and reliability.

SR104: "Turbine Surface Degradation with Service and Its Effects on Performance",
Principal Investigator: Jeffrey Bons, Brigham Young University

This Brigham Young University (BYU) project with participants from Iowa State (ISU) University, University of Cincinnati (UC), and the Air Force Research Laboratory (AFRL) measured and analyzed surface roughness on airfoils that had operated in turbines and on specimens from deposition tests (BYU) and erosion tests (UC) using representative airborne particulate and fuel ash. The project also developed 2D and 3D representations of measured roughness maps and performed computational analyses (ISU) of the micro flow fields near

roughened surfaces. Additional experiments and analyses of the measured roughness features were conducted using a wind tunnel at BYU to determine flow shear and heat transfer coefficients for surfaces representative of turbines operating under conditions that produce surface roughening, such as those produced by deposition and erosion from syngas fuels. The following figure shows the evolving surface roughness and corresponding increase in Stanton Number (measure of heat transfer) for a deposit that had grown with increasing time (increasing burn #) in deposition experiments.

Figure 16 – Surface Roughness Evolution with Increasing Burn Number

The roughness correlations also used surface measurements from turbine components (AFRL) that had experienced service and which were provided by GE, Siemens Power Generation (SPG), P&W, Solar, Honeywell, Praxair and Standard-Aero.

Significance: Surface roughness on turbine airfoils affects both aerodynamic performance and effectiveness of airfoil cooling. Consequently, turbine engineers need to realistically represent surface roughness in their airfoil design methodologies. The BYU led research team showed that previous correlations of aerodynamic performance versus surface degradation that were developed over half a century ago are inaccurate. GE, SPG, P&W and Praxair solicited the new project results for potential use.

This research has moved the industry toward a better representation of roughness as it occurs in turbine engines compared to previous approximations. The semi-empirical correlations for roughness evolution with time provide gas turbine manufacturers with improved models to incorporate into aerodynamic and cooling design codes for turbines operating with conventional and alternate fuels, such as syngas derived from coal.

SR105: "Advanced Optical Sensor for Monitoring and Control of Multiple Gas and Turbine Blade Properties", Principal Investigator: Scott Sanders, University of Wisconsin

This University of Wisconsin (UW) project developed a fiber-optic sensing methodology for monitoring gas temperatures and airfoil material temperatures in the harsh and difficult to access regions of turbine hot sections. Assisted by interactions with gas turbine manufacturers, UW refined a strategy for obtaining and maintaining fiber-optic access to combustor/hot section regions of turbines. The following photos illustrate the placement of optical fiber sensing probes in the project for sensing at a Wright-Patterson Air Force Base experimental facility.

Figure 17 – Fiber Optic Monitoring of Turbine Hot Sections

A computer code was produced to optimize optical designs for use in non-ideal laser light propagation environments, such as combustion gases, and showed a three-fold improvement in collection performance. A sensing strategy was refined that distributes light to up to 64 locations using a single laser, a single detector, and no moving parts. A computer algorithm was enhanced to infer gas properties from the measured laser spectra and is now able to process water vapor spectra in gas turbine combustors in near real time.

The cover article in the May 2005 Magazine of the Optical Society of America (trade journal) was authored by the UW principal investigator and highlighted the wavelength agile laser techniques developed in the UTSR project. An Invention Disclosure concerning these techniques was filed by UW in November 2005.

Significance: Turbine inlet gas temperature is the main determinant of engine performance (power output and efficiency). The combustor gas temperature profile and airfoil surface temperatures are important factors affecting vane and blade lifetimes. Designs for laser optical sensing equipment and software were developed in the UW project for monitoring gas and turbine blade properties at multiple measurement stations in turbine engine systems. Gas temperature sensing using the UW approach can be used in engine test facilities to determine and possibly optimize the combustor temperature profile entering the turbine. The sensor might also be used to simultaneously monitor many engine parameters in order to evaluate new engine designs. For example, the effects on combustor pattern, local water vapor levels, and possibly airfoil surface temperatures due to operating a turbine on syngas might be monitored.

SR106: "Spectroscopic In-Situ Non-Destructive Evaluation to Monitor the Health of Thermal Barrier Coatings", Principal Investigator: Kang Lee, Cleveland State University

This Cleveland State University (CSU) project evaluated methods for in-situ, real time monitoring of the deterioration of thermal barrier coatings operating in gas turbines. CSU doped the TBC with marker materials that are released as the TBC degrades to be monitored optically in the combustion stream or turbine exhaust. Measurements of the gas stream concentrations of the marker materials are used to infer the mechanical condition and deterioration of the TBC. The CSU research identified lithium oxide as a potential marker material for TBCs. Lithium oxide was determined to be chemically compatible with the primary TBC components. Laboratory experiments (including tests in a burner rig illustrated below) showed that the extent of cracking and spallation of a lithium oxide doped coating were correlated with lithium spectral density measurements. Examination of lithium spectra obtained from the Li₂O mixed at concentrations of 5, 3, 1, and 0.3 wt% in YSZ showed that a two layer design with doped layer underneath the TBC would be optimum.

Figure 18 – Burner Test Rig for Doped TBCs

Significance: The project showed that emission spectroscopy can be used as an in situ non destructive tool to monitor the health of thermal barrier coatings *provided the TBC top coat layer is not pervious* to the dopant gaseous species. Since TBC top ceramic layers are porous and release the dopant gaseous species to the gas stream regardless of whether or not the TBC had deteriorated, final experiments in the project were conducted with the top ceramic layer covered with a glass layer that was intended to prevent escape of gaseous lithium species before TBC deterioration (cracking or spallation). However, insufficient time was available before the project was completed to verify whether this approach might be effective while retaining acceptable life and insulation properties of the TBC.

SR107: "Superior Thermal Barrier Coatings for Industrial Gas turbines Using a Novel Solution Plasma Spray", Principal Investigator: Nitin Padture, University of Connecticut

This University of Connecticut (UConn) project explored a novel method to produce improved thermal barrier coatings on turbine superalloys. Since thermal cycle spallation limits TBC

coating lifetimes, the project compared thermal cycle lifetimes for SPPS TBC coatings versus TBC coatings of the same composition produced by a conventional APS process. For coatings of conventional thicknesses (about 250 microns), the measured thermal cycle (one hour cycles at 1121°C) lifetime for the SPPS coating was about a factor of 2.5x greater than for the APS coating. For ultra thick 3.3 mm coatings, the SPPS TBC lifetime was a factor of 20 times greater (820 cycles versus 40 cycles) than for the ultra thick TBC produced by the conventional APS process, as shown in the figure below. The ultra thick (3.3 mm) SPPS TBC coating thermal cycle lifetime was also more than 2X greater than that for the APS TBC with conventional thickness (250 microns).

Figure 19 – Performance of SPPS versus APS TBCs

Significance. The UConn project showed the potential for the SPPS process to provide longer lifetime TBCs on turbine parts. More importantly, the project showed the possibility of using the SPPS process to produce durable ultra-thick TBCs. Since TBCs are used to insulate turbine alloys and thereby reduce engine power and efficiency penalties associated with cooling of parts, durable ultra thick TBCs could potentially significantly improve the performance of future gas turbines. A goal of the DOE Turbine Program was increased turbine performance.

SR108: "An Advanced Diagnostic and Prognostic System for Gas Turbine Generator Sets with Experimental Validation", Principal Investigator: John Wagner, Clemson University

This Clemson University (CU) project conducted research to develop condition monitoring and predicting algorithms capable of detecting and isolating the occurrence of gas turbine failures, as well as predicting impending failures and/or possible anomalies for maintenance scheduling. The illustration below indicates the wide range of approaches explored in the project along with the Mercury 50 gas turbine to which some the approaches were applied.

Figure 20 – Gas Turbine Prognostic and Diagnostic System

The project analytically and experimentally demonstrated the following monitoring, analyses, and diagnostic approaches:

- Developed a model-free trend checking diagnostic algorithm
- Demonstrated real-time data streaming between the Mercury 50 gas turbine and the Energy Systems Laboratory at Clemson
- Established a sensory architecture of 28 signals for diagnostics/prognostics
- Developed a dynamic (transient) model for the gas turbine incorporating thermodynamic features
- Verified and validated the dynamic model with experimental data
- Achieved a model-based fault detection algorithm based on Kalman filtering validated with an experimental fault
- Created a prognostic technique based on statistical regression principles for parameters behavior forecast
- Developed a novel multivariate signal comparison technique for diagnostics with validation with the real fault

Significance: The Clemson project identified real-time diagnostic, modeling, and prognostic system monitoring approaches and verified some of these approaches with a gas turbine. The approaches offer the potential for producing increased turbine reliability, safety, and efficiency along with detection of impending issues to be corrected before operational failures occur.

SR109: "The Effects of Fuel Distribution, Velocity Distribution, and Fuel Composition on Static and Dynamic Instabilities and NO_x ", Principal Investigator: Domenic Santavicca, Pennsylvania State University

This Pennsylvania State University (PSU) project conducted experiments in a laboratory scale combustor to characterize and understand the effects of operating conditions (including fuel composition) on the static stability (blowout) and dynamic stability (combustion oscillations) of

lean-premixed combustors. Experiments explored the role of flame-vortex interactions on instabilities using a variable length combustor illustrated below.

Figure 21 – Variable Length Combustor Test Apparatus

A comprehensive set of data was obtained at 40 different operating conditions and 28 different combustor lengths, for a total of more than 1000 test conditions. Unstable combustion occurred only for operating conditions where the ratio of vortex travel time to acoustic period (a function of combustor length) was in the range from about 0.2 to 0.4. Stable operation also occurred at some conditions within this range.

Significance: Gas turbine combustors are designed for lean-premixed operation which results in relatively low flame temperatures that limit NO_x emissions. However, these operating conditions are also near the limits for lean blowout where damaging oscillations and excess combustor noise have caused forced shut downs of turbines in the field. Although turbine manufacturers have been developing combustor design approaches to alleviate blowout and instabilities, additional research was needed to improve design methods, especially for the variability and different composition of syngas compared to conventional turbine fuels. The extensive data gathered in the PSU project identified stable/unstable boundaries for design parameters that should aid engineers in producing more stable, high performance low emission turbine combustors.

SR110: "Improved Film Cooling Performance for Turbine Vanes and Endwalls with Realistic Surface Conditions", Principal Investigator: Karen Thole, Virginia Polytechnic Institute and State University

This Virginia Tech (VT) project used airfoil cascade experiments to evaluate film cooling effectiveness for various surface roughness features and cooling hole blockage structures associated with deposition on cooled surfaces. Cooling performance was compared for trenched holes, trenched slots, and bumps near film-cooling holes along the leading edge end wall region. Another focus of the research was effects of film cooling and end wall gaps between adjacent vanes and at the intersection between the combustor transition sections and first stage vane

segments. Measurements were obtained for film cooling performance at the leading edge region of the end wall with trenches and bumps for a range of blowing ratios and geometries. The project determined the degradation effects of obstructions representative of deposits adjacent to coolant holes using obstructions of various shapes, sizes, and positions.

As shown in the cascade data plot below of cooling effectiveness versus cooling blowing ratio M , the placement of rows of film cooling holes in a trench transverse to the passage flow improved cooling effectiveness of the test airfoils both for smooth airfoil surfaces and for roughened surfaces representing deposition conditions. The trench configuration counteracted degradation due to roughness.

Figure 22 – Cooling Efficiency Improvements from Bumps and Trenches

Significance: The project provided data for turbine design engineers concerning the effects on component film cooling for surface features that might be associated with deposition. The cooling trench design showed a potential to improve film cooling of turbine airfoils for both conventional fuels and also fuels with ash impurities that cause deposition such as syngas derived from coal. The research also identified a specific design configuration for end wall gaps between adjacent hot section parts that provides more favorable cooling benefits from gap flows than other configurations.

SR111: "Combustion Instability and Blowout Characteristics of Fuel Flexible Combustors",
Principal Investigator: Timothy Lieuwen, Georgia Institute of Technology

This Georgia Tech (GT) project evaluated effects of high hydrogen compositions of fuels representative of syngas on combustor oscillations and blowout under lean premixed conditions (low fuel to air ratios) needed to reduce NO_x emissions. Oscillations due to instabilities have caused combustor damage in turbines. For fuel mixtures containing H_2 , CO , and other components, the levels of H_2 were found to dominate blowout characteristics. Flame dynamics at near blowout conditions were determined to fundamentally change with fuel composition. GT identified a parameter (modified Damkohler number with diffusive correction scaling) that describes effects of fuel composition variability on combustor blowout. The following figure

shows very good agreement between the predicted (based on modified Damkoler number) versus measured equivalence ratio at combustor blowout.

Figure 23 – Predicted Versus Measured Equivalence Ratio at Combustor Blowout

Significance: GT has verified for turbine engineers a parameter to identify blowout limits for design of low emissions combustors operating with high hydrogen fuels. The project also provided improved understanding of high hydrogen fuel composition effects on combustor dynamic instability characteristics.

SR112: "Correlation of Ignition Delay with IGCC Type Fuels", Principal Investigator: Scott Samuelsen, University of California-Irvine

This University of California, Irvine (UCI) project conducted chemical kinetic computer calculations and experiments to determine ignition delay times for fuel compositions representative of syngas and high hydrogen fuel derived from coal syngas. An experimental facility was upgraded with the intention of simulating conditions (up to 18 atmospheres pressure and 850 to 1400°F temperatures) representative of turbine premixers and was used to provide autoignition data for the project. Although the upgrades were completed, commissioning of the facility at the highest temperatures and pressures was not. Consequently, measurements of ignition delay times were conducted for H₂ and H₂/CO mixtures at moderate temperatures (850 to 1000F) and pressures (5 atm). The numerical studies used a variety of recently developed detailed kinetic mechanisms for H₂ and H₂/CO mixtures and yielded numerical predictions for ignition delay time which were 2-3 orders of magnitude longer than experimental data from this project and past data from other researchers, as indicated by comparing the curves for numerical predictions (circular symbols) and the experimental data points in the figure below. This showed

that some key deficiencies exist in all of the current kinetic mechanisms for H₂ ignition delay for temperatures below 1000F.

Figure 24 – Effect of Temperature, Pressure and Gas Mixture on Ignition Delay

Significance: The UCI project upgraded an existing continuous flow facility that could in the future provide ignition delay data at appropriate temperatures and pressures for turbine engineers to design combustors for operation with syngas and high hydrogen fuels from syngas. Experimental data obtained in the project was consistent with past data obtained by other researchers in other facilities. This provides confidence in the capabilities of the facility when applied in the future to high pressure conditions beyond the capabilities of most university facilities.

SR113: "Heat Transfer from Rotating Blade Platforms With and Without Film Cooling",
Principal Investigator: J. C. Han, Texas A&M University

This Texas A&M (TAM) project conducted experiments in a three stage experimental unfired turbine and measured pressures, heat transfer coefficients, and film cooling effectiveness distributions on rotating blade platforms with stator-rotor seal ejection and film cooling. The turbine facility is illustrated below. Detailed flow measurements were also taken. Numerical predictions were completed for the film cooling effectiveness and heat transfer coefficients on the rotating platform with stator-rotor seal ejection. Numerical predictions of film effectiveness and heat transfer were also conducted for the cascade end wall and the rotating platform with seal ejection.

Figure 25 – Rotating Unfired Turbine Test Facility

Significance: Using a rotating three-stage turbine, Texas A&M produced a comprehensive aerodynamics and heat transfer data base. This can be used by industry to calibrate and refine fluid dynamic and heat transfer computer codes used for aerodynamic and cooling design of gas turbines.

SR114: "Combustion Characterization and Modeling of Fuel Blends for Power Generation Gas Turbines", Principal Investigator: Eric Petersen, University of Central Florida

This University of Central Florida (UCF) project experimentally evaluated the effects of H₂/CO fuel blends typical of syngas on ignition delay at high pressures (up to 20 atmospheres) representative of turbine combustors. Data from the project confirmed past ignition delay data which are not predicted within an order of magnitude by existing theoretical models for turbine combustor inlet temperatures. UCF then developed a much more accurate ignition delay model that better predicted the experimental data, as shown in the following figure.

Figure 26 – Effect of Temperature on Ignition Delay at High Pressure

Significance. The much improved ignition delay model developed by UCF can be used by turbine engineers to design lean premixed, low NO_x emission combustors operating with high hydrogen fuels. Accurate knowledge of ignition delay time is needed to establish sufficiently long residence times (determined by flow velocities and premixer lengths) for the premixer to produce adequate fuel/air mixing (needed for NO_x control) but not so long as to result in premature ignition.

SR115: "Effects of Coating Blockage and Deposits on Film Cooling Effectiveness and Heat Transfer", Principal Investigator: M. Chyu, University of Pittsburgh

This University of Pittsburgh (Pitt) project (with a subcontract to Iowa State University (ISU)) investigated the effects of thermal barrier coating and deposit partial blockage on film cooling performance and explored innovative design concepts for film cooling based on realistic TBC topology and deposition geometries. The work at Pitt experimentally evaluated and compared both local film cooling effectiveness and heat transfer coefficients for several alternative film cooling concepts including (1) ramp upstream of cooling holes, (2) flow aligned blockers downstream of cooling holes, (3) trench-embedded cooling holes, and 4) a new w-shaped cooling hole configuration. Among concepts 1) to 3), the transverse trench approach achieved the most uniform enhancement in film cooling performance. Computational analysis at ISU and comparison of the w-shaped hole with a conventional cooling hole approach showed that new the w-shaped offers promise for improved cooling performance for turbine components. Evaluations for round and shaped cooling holes showed that simulated partial hole blockage consistently increased heat flux (q) to surfaces downstream (measured by the distance x divided by hole diameter D) as illustrated in the plots below for a cooling flow momentum ratio of 1.69.

Figure 27 – Effect of Cooling Hole Blockage on Downstream Heat Flux

Significance: The project evaluations showed that deposits (such as produced from syngas fuels) could degrade film cooling benefits. The project also identified a w-shaped film cooling hole configuration that could potentially enhance film cooling of turbine components.

SR116: "Investigation of Materials Performance in High Moisture Environments Including Corrosive Contaminants Typical of Those Arising by Using Alternate Fuels in Gas Turbines", Principal Investigator: F. S. Pettit, University of Pittsburgh

This University of Pittsburgh (Pitt) project conducted cyclic high temperature tests of turbine alloys and coatings in water vapor environments with contaminants (e.g., Na_2SO_4 , CaSO_4 , CaO , etc.) potentially representative of syngas turbines. For most alloys and coatings, water vapor environments increased materials degradation in the presence of contaminants compared to exposure to the contaminants without water vapor. Rather unexpectedly, CaO produced greater degradation than Na_2SO_4 , which is recognized as one the most corrosive turbine contaminants. The figures below illustrate the substantial weight losses of NiCrAlY coated specimens on various turbine alloys both for dry and wet air environments under thermal cycle conditions due to CaO deposits. The experiments showed that CaO impurities react with and produce less protective oxide scales than scales (Al_2O_3 , Cr_2O_3) normally formed on alloys and coatings and which normally inhibit excessive oxidation and corrosion.

Figure 28 – Effect of Water Vapor and Contaminants on Turbine Alloys and Coatings

Significance. Since the Pitt project compared materials degradation for a range of candidate alloys and coatings, the project data provides information for metallurgists at gas turbine companies to select materials for future turbines that operate with syngas and high hydrogen fuels produced from syngas. The project also indicates the potentially aggressive role of CaO in materials degradation which may need to be considered in turbine alloy and coating selection for operation with these fuels.

SR117: "Autoignition Studies of Syngas and Hydrogen (SGH) Fuels", Principal Investigator: Robert Santoro, Pennsylvania State University

This Penn State University (PSU) project conducted experiments in a flow reactor to determine autoignition delay times for $H_2/CO/H_2O$ compositions and conditions (pressures up to 3.0 MPa (30 atm) and 950°K (1250°F)) representative of gas turbines operating with high hydrogen fuels. Measurements at pressures of 9 and 16 atmospheres and a fuel composition of 75% H_2 /25% CO at temperatures up to 800°K showed a wide variability of autoignition locations in the flow reactor tube. Autoignition times were 2 to 4 times greater than observed in other shock tube and flow reactor studies at similar temperatures. PSU analyzed past autoignition data from various other experimental facilities to explain major discrepancies between the data and model predictions. Modifying the data analysis to take into account the effects introduced by chemical induction time using a “volume as a function of time” approach brought the data and modeling predictions into agreement. This is illustrated by the following figures showing comparisons of experimental data with theory for previous assumptions (figure on left) and for taking into account “volume as a function of time” (figure on the right).

Figure 29 – Effect of “Volume as a Function of Time” on Ignition Delay Estimates

Significance: The design of low emission turbine combustors requires quantification of ignition delay times to prevent premature autoignition before the fuel and air are thoroughly mixed. For high hydrogen fuels and turbine operating conditions, there has been uncertainty concerning ignition delay times due to greatly different values determined experimentally and through modeling. The PSU research identified a potential cause of the discrepancies between experiments and modeling. However, uncertainties remain since the PSU experiments showed that the autoignition process for fuel compositions representative of syngas was intrinsically variable in terms of the observed ignition delay time for operating conditions at which the studies were conducted. The source of this unexpected variability was not clearly determined and presents an uncertainty with respect to operation with syngas and high hydrogen fuels under lean premixed conditions used to control NO_x emissions from gas turbine combustors.

SR118: "Degradation of Thermal Barrier Coatings with Syngas Combustion", Principal Investigator: Yongho Sohn, University of Central Florida

This University of Central Florida (UCF) project conducted laboratory testing for hot corrosion of thermal barrier coatings due to potential fuel impurities for turbines operating with syngas and high hydrogen fuels derived from coal syngas. Advanced microstructural techniques were also applied to analyze parts that had operated in an IGCC turbine. The TBC degradation

mechanisms for IGCC turbine TBCs were YSZ destabilization, deposit penetration, and reaction with syngas deposits, as illustrated in the figures below. The advanced microstructure techniques were also applied to specimens that had been exposed to Na (sodium), V (vanadium), P (phosphorous) and CMAS (calcium, magnesium, aluminum, silicon) impurities in laboratory experiments. Specific corrosion reactions were identified for the alloys and coatings exposed in the laboratory experiments.

Figure 30 – TBC Degradation Mechanisms

Significance: The UCF project provided one of the first analyses reported in the literature that identified modes of degradation of turbine alloys and TBC coatings that had experienced operation in turbines at IGCC plants. Corrosion characteristics and resistance to impurities that might cause attack in the future were also determined for candidate turbine alloys and coatings.

SR119: *"Aero Losses, Heat Transfer, Discharge Coefficients for Different Vane Trailing Edge Configurations for Syn Gas Fired Turbines"*, Principal Investigator: Forrest Ames, University of North Dakota

This University of North Dakota (UND) project conducted scaled cascade experiments to:

- Determine the effect of different first stator vane trailing edge cooling approaches on aerodynamic and thermal performance, and
- Identify the incremental impact of deposition representative of syngas fuels on aero/thermal performance for different trailing edge cooling approaches

The project evaluated four turbine trailing edge cooling concepts (gill slot, letterbox, covered trailing edge and pressure side holes) in addition to three internal cooling geometries consistent with the trailing edge cooling concepts. Cascade experiments were used to characterize 1) internal heat transfer and discharge pressure drop and 2) external heat transfer and aerodynamics for first stage vane configurations representing these cooling concepts and internal cooling geometries. The experiments also investigated the effect of vane surface roughness representative of deposits from syngas fuels on passage total pressure loss, turning angle, and exit loss. The following figure illustrates the increase due to roughness (data points designated by Ro in the caption table) on heat transfer (measured by Stanton Number) over the concave surface (positive values) and convex surface (negative values) of the cascade airfoil for various levels of turbulence and a Reynolds number of about 2 million.

Figure 31 – Effect of Surface Roughness on Heat Transfer

Significance: The UND research produced a heat transfer and aero database to aid gas turbine designers in choosing between candidate airfoil cooling configurations. Experimental results were also obtained to provide designers with information to help them understand degradation in aerodynamic performance for syngas turbine airfoils due to roughness caused by deposits.

SR120: "Deposition of Alternative (Syngas) Fuels on Turbine Blades with Film Cooling",
Principal Investigator: Thomas Fletcher, Brigham Young University

This Brigham Young University (BYU) project with participation from Ohio State University (OSU) developed a new accelerated deposition test facility designed to produce operating parameters representing the gas temperatures, gas velocities, alloys and coatings, and particle size distributions and compositions for turbines operating with fuels (such as syngas) containing particulate impurities. Deposition experiments conducted with the facility were accelerated by increasing the ash loading into the test section such that the experimental high ash loading multiplied by a relatively short time (a few hours or less) equaled turbine low ash loadings multiplied by long turbine operation time (thousands of hours). Consequently, a large amount of deposition data exploring effects of many parameters was produced in the duration of the project. Experiments in the project seeded combustion products entering the deposition rig with coal ash (and other types of ash) particles and showed an ash composition dependent transition temperature below which deposition rates are low and above which deposition rates drastically increase with gas temperature. The project explored the effects of film cooling design features on deposition. Shaped versus round cooling holes, cooling hole spacing, and cooling hole trenches were evaluated along with deposition effects on film cooled surfaces with thermal barrier coatings. As shown in the figures below, increased film cooling air flow (measured by blowing ratio M) reduced deposition due to lowering surface temperatures and deflecting gas stream particulate from impacting surfaces downstream of the cooling holes.

Figure 32 – Effect of Cooling Air Flow Rate on Particulate Deposition

Shaped cooling holes produced a broader area of deposition reduction than round cooling holes. Larger particle sizes and greater spacing between cooling holes resulted in higher deposition. Deposition on TBC surfaces was higher than on non-coated alloy surfaces. This was attributed to higher surface roughness for TBCs. Deposition was similar in extent with and without the cooling holes located in a trench.

Significance: The project verified an accelerated deposition facility that produced a large amount of data in a relatively short time which could assist turbine engineers in designing cooling approaches for high temperature flow path components in turbines operating with syngas derived from coal and other fuels containing impurities. Test results demonstrated the transition temperature effect previously experienced in turbines and rig tests operated with ash bearing fuels. Since intolerable deposition conditions occur if turbine flow path temperatures are above the transition temperature, the BYU facility might be used to determine whether ashes of various candidate turbine fuels would produce acceptable levels of flow path deposition for the firing temperatures of a turbine of concern.

SR121: "Fundamental Studies in Syngas Premixed Combustion Dynamics", Principal Investigator: Ahmed Ghoniem, Massachusetts Institute of Technology

This Massachusetts Institute of Technology (MIT) project used experiments with hydrogen-carbon monoxide fuel mixtures in two types of combustors to obtain a fundamental understanding of high hydrogen fuel combustion dynamics and stability in swirl stabilized flows and recirculation stabilized flows established by sudden expansion. The experiments focused on dynamics observed as the equivalence ratio was reduced towards the lean blowout limit and flow velocity was increased. The experiments explored how fuel composition and other factors affected the blowout limits of the combustor. Stability maps, optical diagnostics of the time dependent flame shape and heat release profiles, and other mechanistic characteristics were recorded. Time-resolved particle imaging velocimetry was used to investigate the interaction between the flame and flow field.

The experiments showed that increased hydrogen concentration in the fuel enables leaner operation and the corresponding possibility that reduced thermal NO_x emissions might be produced at lower pressure oscillations. Experimental insights were used to develop models linking combustor dynamics to fundamental properties (fuel composition, equivalence ratio, and inlet temperature) of the high hydrogen fuel mixture, along with the acoustic environment. The models showed that the transitions between stable and unstable dynamics are correlated with changes in the flame speed of equivalent strained laminar flames and collapsed the multiple plots of experimental data results to a narrower range when plotted against model parameters, as shown in the following figure.

Figure 33 – Correlation of Sound Pressure Data with Consumption Speed

Significance: The MIT project provided a better understanding of the mechanics underlying combustion stability for various fuel compositions which is necessary to develop and improve low emission turbine combustors operating with high hydrogen fuels derived from coal syngas. A method was also identified to increase flame stability using air injection into the flame anchoring region. A patent disclosure (*Method of using microjet air injection in a swirl-counter-swirl configuration to mitigate thermoacoustic instabilities in a lean premixed swirl stabilized combustor*, Z. A. LaBry, S. J. Shanbhogue, R. L. Speth, and A. F. Ghoniem) concerning this

method was filed in January, 2010. The patent describes a potential approach for improving the stability of combustors operating with high hydrogen fuels.

SR122: "Turbulent Flame Speed Measurements and Modeling of Syngas Fuels", Principal Investigator: Jerry Seitzman, Georgia Institute of Technology

This Georgia Tech (GT) project investigated turbulent flame speed characteristics of fuels with compositions of syngas. Turbulent flame speed is a key parameter affecting the performance (e.g., pollutant emissions, flashback, flame stability, and operability) for low emission combustion systems. Experiments in the project represented the range of H₂/CO compositions, temperatures and high pressures (up to 30 atmospheres) pertinent to gas turbines operating with syngas derived from coal gasification. Experiments confirmed a significant sensitivity of turbulent flame speed (characterized by the global consumption speed) to fuel composition (e.g., H₂/CO ratio). An inequality was developed that bounded the turbulent flame speed data versus normalized turbulence intensity. Analyses showed that the data points for H₂/CO mixtures (but not for high mean flow velocity methane (CH₄)) could be reasonably collapsed to approach a single curve (see figure below) by normalizing the global consumption speed with the maximum stretched laminar flame speed, instead of using the unstrained laminar flame speed to normalize the flame speed data as is commonly done.

Figure 34 – Variation of Normalized Turbulent Flame Speed with Turbulence Intensity

Significance: Essentially no data were previously available for turbulent flame speeds for H₂/CO compositions and pressure/temperature conditions pertinent to low emission operation with syngas in gas turbine combustors. Previous measurements were primarily at atmospheric conditions and consequently of extremely limited usefulness for gas turbine operation. The GT project has provided the needed data and a validated model to facilitate design by industry of gas turbine combustors to operate stably with low emissions over the range of syngas compositions anticipated for future advanced power plants that operate with high hydrogen fuels from coal

gasification. The data and model from the project might also facilitate prediction of combustor operation changes that may be needed to handle new fuels with varied compositions.

SR123: "Syngas Particulate Deposition and Erosion at the Leading Edge of a Turbine Blade with Film Cooling", Principal Investigator: Danesh Tafti, Virginia Polytechnic Institute and State University

This Virginia Tech (VT) project conducted experiments and computational analyses to investigate deposition and erosion conditions for leading edge regions of turbine vanes with film cooling and examined the effect of deposition on hydrodynamics, heat transfer, and cooling effectiveness. The work used the method of time-accurate LES as an analytical tool for simulating particle delivery to surfaces in conjunction with models to calculate the sticking fraction of delivered particles that result in deposit buildup. The sticking model compared the calculated temperatures of the particles to the local gas temperature to assess whether an arriving particle sticks. The delivery and sticking models were applied to compare the analytically predicted deposition with that previously measured on flat plate specimens oriented at a 45 degree angle used in deposition tests with coal ash at Brigham Young University (BYU). Comparisons are shown in the figure below. The results from the VT computational approach reasonably matched the BYU experimental data for temperatures up to 1350 K but increasing diverged from the data for higher increasing temperatures.

Figure 35 - Comparison of LES Model with Experimental Data

VT also applied their modeling approach to calculate the delivery of particles to leading edge regions of a blade with a cylindrical leading edge and a flat after body in a linear cascade and compared the results with an experimental blade with the same configuration. The temperature of the free stream was varied near the melting point of the four micron polyvinyl chloride particles (533 K). The leading edge was film cooled and the cooling blowing ratio was varied from values of one to three to investigate the effect of blowing on deposit accumulation. Particle capture efficiency varied between 10 to 25% and increased with an increase in the free stream temperature. The capture efficiency decreased somewhat as the blowing ratio increased to 3.

Significance: The VT research provided data and insights for turbine designers concerning the effects of fuel ash particle size and film cooling jet momentum ratio on deposition and erosion at leading edges of turbine airfoils. Carefully derived similarity parameters combined with analytical tools were developed with the intent of using the university facility as an inexpensive and effective testing environment to estimate deposition effects in turbines. Although the project showed good results for predicting particle delivery to film cooled surfaces under the conditions tested, there remains uncertainty whether the use of PVC particles adequately represents particle sticking behavior and deposit physical properties (e.g., roughness and insulation effects on heat transfer) associated with turbine fuel ash such as from IGCC plants.

SR124: "Materials for Oxy-Fuel Turbomachine Conditions", Principal Investigator: Gerry Meier, University of Pittsburgh

This University of Pittsburgh (Pitt) project conducted laboratory experiments to evaluate the high temperature (700 to 1100 C) durability of turbine materials at the high steam and CO₂ conditions expected in future coal based oxy-fuel turbines. Performance of candidate alloys (IN738, Rene N5, GTD111, and simple model alloys) and coatings (NiCoCrAlY, Pt-modified Aluminide, and TBCs) were determined in environments starting with 85% steam and 15% CO₂ (by volume). Experiments were then conducted for reduced levels of steam to accommodate up to 5% O₂, which may represent excess oxygen that might be needed to assure complete oxy-fuel combustion. The following figure provides data from the project on oxidation weight gains for a number of alloys and coatings in H₂O-CO₂ environments at 900 C.

Superalloys and Coatings in 85% H₂O-15%CO₂ – 900°C

Figure 36 – Oxidation Weight Gains of Various Turbine Materials

Significance: Turbine materials have not operated in the high steam and CO₂ environments that will be produced in the flow paths of future oxy-fuel turbines. Combined with low oxygen levels, these environments may affect the formation of oxide scales which normally protect turbine materials from excessive oxidation and corrosion. The Pitt project showed that alloys and coatings with sufficient Cr/Al concentrations which are good chromia and alumina oxide scale formers in air are not significantly more degraded in H₂O/CO₂ than in dry air. However,

alloys which are borderline chromia and alumina oxide scale formers in air are severely degraded in H₂O/CO₂ atmospheres. Also, excess oxygen tends to alleviate the detrimental carburization effects of exposure in CO₂. The failure of TBCs in cyclic experiments at 1100 C in H₂O-CO₂ environments was not affected by the presence of H₂O.

SR125: "Evaluating Coatings for Current and Future Service with Thermal Property Measurements", Principal Investigator: Ted Bennett, University of California-Santa Barbara

This University of California at Santa Barbara (UCSB) project evaluated the use of a novel Phase of Photo-Thermal Emission Analysis (PoPTEA) for non-destructive measurement of thermal barrier coating insulation properties. The PoPTEA technique exposes a TBC coated turbine part to a frequency modulated CO₂ laser beam that locally heats the part. The frequency phases of the thermal radiation emitted from the heated part are dependent on heat transport properties of the TBC so interrogation of the emitted radiation provides data on the thermal insulation protection capabilities of the coating. UCSB first validated the technique using a 185 μ m thick Corning 0211 micro-sheet with well-known properties bonded to a superalloy and then with comparisons of properties of a several TBCs measured using thermal imaging at Argonne National Laboratories. Both validations showed that the PoPTEA technique produced good agreement with the comparison measurements. Comparisons of coating diffusivity, conductivity, and heat capacity for the Corning 0211 material are shown in the following figure.

Corning 0211 thermal properties			
	PopTea (at 70 °C)	Ref [*] (at 70 °C)	Manufacturer
α (mm ² /s)	0.418	0.426	---
k (W/m/K)	0.938	0.90	0.96
ρC_p (J/cm ³ /K)	2.25	2.1	---

[*] Ikkawi, R., et. al. 2008, Journal of Nanoelectronics and Optoelectronics Vol. 3, pp. 44–54.

Figure 37 – Comparison of PoPTEA Thermal Properties with Reference Data

The PoPTEA technique was then applied to 7YSZ EB-PVD TBCs deposited on platinum-modified, nickel-aluminide coated single crystal superalloy specimens that were exposed to one hour, ten minute thermal cycles until coating failure. Catastrophic spallation of the coating was preceded by a small (apparent) drop in the coating conductivity/diffusivity. Other experiments showed that the effect of the CMAS (calcium, magnesium, aluminum, silicon) deposit infiltration can be measured on thermal barrier coatings using the PoPTEA technique as indicated by more than doubled thermal conductivity and more than 20% increased heat capacity.

Significance: Prior to this research, the quantitative nondestructive measurement of the thermal protection offered by a TBC was not available for serviceable turbine parts. The project demonstrated the utility of quantitative thermal property measurements for the assessment of thermal barrier coating performance and condition by using the PoPTEA technique. Since neither special preparation nor physical penetration of a TBC coated turbine part is needed to

evaluate the condition of the TBC, the UCSB PoPTEA technique would be particularly suited for quality control of TBC coating processes and also evaluations during scheduled turbine maintenance of whether coatings on turbine parts have degraded and need to be removed from service. Use of PoPTEA coating evaluations during scheduled maintenance could thereby reduce the cost and lost service from forced turbine outages due to part burn-out.

SR126: "High Pressure Kinetics of Syngas and Nearly Pure Hydrogen Fuels", Principal Investigator: John Daily, University of Colorado

This University of Colorado (UC) project conducted experiments and analyses to explain the major discrepancy between measured and theoretically predicted ignition delay at gas turbine combustor inlet conditions in the range from 600-800 K and 10-20 bar for high hydrogen fuel mixtures. The approach used to address the discrepancy between past experiments and theory involved:

- Exploring high-pressure kinetics by making detailed composition measurements of combustion intermediates and products in a flow reactor using molecular beam/mass spectrometry (MB/MS) and matrix isolation spectroscopy (MIS)
- Comparing experimental data with calculations using existing mechanisms
- Using theoretical methods to improve the predictability of existing mechanisms

After exploring a full range of possible mechanisms for the experimental/theoretical discrepancies, UC determined that none of those mechanisms can realistically explain the large departures observed at 700K and 20 bar. Consequently, UC hypothesized that surface catalyzed reactions occurring on suspended particles or reactor walls might be causing much faster hydrogen reaction kinetics than predicted by kinetic theory.

To conduct combustor wall catalytic experiments, UC constructed a pulsed high temperature micro nozzle reactor and used matrix isolation infrared spectroscopy diagnostics for hydrogen kinetics. The reactor was utilized to explore early time surface reaction chemistry when varying wall surface materials and temperature.

Figure 38 – High Temperature Micro Nozzle Reactor

CFD simulations were developed to assist in data interpretation. Initial results demonstrated that nickel and an Inconel alloy do have a catalytic effect for hydrogen oxidation and that the nickel results are roughly predicted using an existing surface reaction mechanism.

Significance: Gas turbine engineers must have accurate ignition delay information for high hydrogen fuel compositions in order to design future low emission combustors that operate with hydrogen rich fuels produced from gasified coal. Uncertainties in ignition delay could result in excessively conservative designs or safety and reliability issues. Although the project showed that at least one high nickel material (Inconel) did show some degree of catalytic activity, the catalytic effects observed in the experiments were much less than needed to explain the differences between ignition delay determined experimentally and by kinetics theory. Other possible mechanisms combined with catalytic effects were suggested in the final report to explain the differences but these were not quantified.

SR127: "Simulating Particle Deposition and Mitigating Deposition Degradation Effects in Film Cooled Turbine Sections", Principal Investigator: David Bogard, University of Texas

This University of Texas (UT) project with Pennsylvania State University (PSU) as subcontractor developed techniques for evaluating deposition effects of contaminant particles on turbine cooling using wind tunnel cascade facilities. Injected molten wax particles simulated deposition on turbine components from fuel ash contaminants. The evaluations at UT were used to evaluate performance of the film cooling configurations for turbine airfoils when subjected to deposition conditions. The evaluations at PSU were used to evaluate performance of film cooling configurations for end walls of airfoil passages when subjected to deposition conditions. Various trench and other film cooling configurations were explored to maximize film cooling performance under contaminated conditions and reduce the deposition of contaminants.

Cascade experiments were conducted at UT with a film cooled leading edge model to simulate the effects of film cooling on deposition at the nose regions of turbine airfoils. Leading edge film cooling jets were found to reduce deposition. Deposition decreased for increased blowing ratio. Later experiments used a cascade facility to evaluate deposition over an entire airfoil. Initial experiments using internally cooled cascade vanes (without film cooling) showed that vane surface temperature had a significant effect on deposit formation, with colder surface temperatures reducing deposition thicknesses.

Cascade experiments were conducted at PSU with leading edge region end wall film cooling to show the effects of film-cooling hole placement and momentum flux on cooling effectiveness of an end wall. PSU cascade experiments also explored the cooling effectiveness of embedding end wall film cooling holes in trenches. As shown in the figure below, the trenched configuration improved cooling effectiveness relative to no trench for a wide range of cooling momentum flux ratios. The best cooling performance occurred when the depth of the trench was 0.8 the diameter of the cooling holes under conditions of deposition and no deposition. Particle deposition reduced cooling effectiveness by 15% with trenched cooling holes compared to 30% for cooling holes not located in a trench.

Figure 39 – Effectiveness of Different Film Cooling Configurations

Significance: Deposits have formed on airfoils and end walls of turbines operating with coal-derived syngas. Deposits from residual oil fuels have substantially reduced commercial turbine performance (power output and efficiency) so syngas deposits probably also affected IGCC turbine performance. A major goal of the DOE Turbine Program is to improve turbine performance which will involve increasing turbine inlet temperatures and therefore deposition potential compared to past IGCC turbines operating with syngas. The UTSR project at UT and PSU identified design features for turbine airfoil and end wall film cooling under deposition conditions to improve cooling effectiveness. Experiments with trenched cooling hole configurations showed the potential for improved airfoil cooling performance both for turbines operating with clean fuels and ash bearing fuels which produce deposition conditions. This could reduce cooling penalties on power and efficiency of future turbines using high hydrogen fuels produced from syngas.

The use of wax particles in the experiments (with matching appropriate dimensionless parameters (e.g., Stokes Number) appeared to adequately represent the effects of ash particle delivery to surfaces and aerodynamic interactions with film cooling typical of turbines operating with ash bearing fuels. However, adequate verification is still needed for wax replication of the sticking properties and effects of deposit physical properties (e.g., roughness and insulation effects) associated with turbines operating with ingested ash or airborne particulate.

2.2. Reports and Publications

The following reports and publications were produced from UTSR funded projects.

SR089

Louisiana State University

Principal Investigator: Sumanta Acharya

Project Title: *Internal Cooling in Leading and Trailing Edge Passages With Rotational and Buoyancy*

- Large Eddy Simulations of Flow and Heat Transfer in a Ribbed Coolant Passage With Rotation and Buoyancy Effects
- LES of Flow and Heat Transfer in a Rotating Ribbed Duct: Flow Physic
- Aspects Ratio Effects in Rotating Ribbed Ducts

SR090

Pennsylvania State University

Principal Investigator: Domenic Santavicca

Project Title: *Optimization of the Injector Fuel Distribution for Stable, Low Emissions Combustion in Lean Premixed Gas Turbine Combustors*

- no publications reported

SR091

University of Connecticut

Principal Investigator: Maurice Gell

Project Title: *Thermal Barrier Coatings and Metallic Coatings with Improved Durability*

- Failure Mechanisms of Dense Vertically Cracked Thermal Barrier Coatings and Damaged Evolution in an Electron Beam Physical Vapor Deposited Thermal Barrier Coatings as a Function of Cycle Temperature and Time - Journal Publication
- Photoluminescence Piezospectroscopy: A Multi-Purpose Quality Control And NDI Technique For Thermal Barrier Coatings - Journal Publication

SR092

University of Texas, Austin

Principal Investigator: David Bogard

Project Title: *Attenuation of Hot Streaks With the Nozzle Guide Vane and Endwall*

- Effects of Coolant Density Ratio on Film Cooling Performance on a Vane - Submitted for Presentation at the 2003 ASME Turbo Conference in Atlanta, June 2003
- The Effects of High Turbulence and Turbine Vane Film Cooling on the Dispersion of a Simulated Hot Streak - Submitted for Presentation at the 2003 ASME Turbo Conference in Atlanta, June 2003
- Computational Predictions of Endwall Film-Cooling for a First Stage Vane - Submitted for Presentation at the 2003 ASME Turbo Conference in Atlanta, June 2003
- Effects of Hot Streaks on Adiabatic Effectiveness for a Film Cooled Turbine Vane - Submitted for Approval for Conference Presentation at IGTI 2004, Vienna
- The Effects of the Vane and Mainstream Turbulence Level on Hot Streak Attenuation - Submitted for Approval for Conference Presentation at IGTI 2004, Vienna

SR093

University of California, Santa Barbara

Principal Investigator: David R. Clarke

Project Title: *A Science Based Approach to Enhanced Zirconia Based Coatings for Advanced Gas Turbine Application*

- no publications reported

SR094

Texas A&M University

Principal Investigator: J.C. Han

Project Title: *Rotating Heat Transfer in High Aspect Ratio Rectangular Cooling Passages with Shaped Turbulators*

- Computation of Flow and Heat Transfer in Rotating Rectangular Channels (AR=4) With V-Shaped Ribs by Reynolds Stress Turbulence Model - Submitted for Presentation at the 2003 ASME Turbo Conference in Atlanta, June 2003
- Heat Transfer and Pressure Drop in Two-Pass Rotation of Rectangular Channel (AR=2) With Discrete Angled Rib Turbulators - Submitted for Presentation at the 2003 ASME Turbo Conference in Atlanta, June 2003
- Heat Transfer in Rotating Rectangular Channels (AR=4:1) with V-shaped and Angled Rib Turbulators With and Without Gaps - Submitted for Presentation at the 2003 ASME Turbo Conference in Atlanta, June 2003
- Thermal Performance of Angled, V-Shaped, and W-Shaped Rib Turbulators in Rotating, Rectangular (AR=4:1) Cooling Channels - Submitted for Approval for Presentation at the ASME Turbo Expo Conference, June 14-17, 2004, Vienna
- Computation of Flow and Heat Transfer in Two-Pass Rotating Rectangular Channels (AR=1:1), (AR=1:2), (AR=1:4) With 45-Degree Angled Ribs by Reynolds Stress Turbulence Model - Submitted for approval for presentation at the ASME Turbo Expo Conference, June 14-17, 2004, Vienna
- Heat Transfer in Two-Pass Rotating Rectangular Channels (AR=1:2 and AR= 1:4) With 45 Degree Angled Rib Turbulators - Submitted for Approval for Presentation at the ASME Turbo Expo Conference, June 14-17, 2004 , Vienna

SR095

Georgia Institute of Technology

Principal Investigator: Ben Zinn

Project Title: *Understanding and Control of Combustion Dynamics in Gas Turbine Combustors*

- Modeling Response of Premixed Flames to Mixture Ratio Perturbations - Submitted for Presentation at the 2003 ASME Turbo Conference Atlanta, June 2003

SR096

University of Minnesota

Principal Investigator: Terrence Simon

Project Title: *Aerothermal Effects of Interfacial Leakage and Film Cooling Schemes with Endwall and Leading Edge Contouring*

- Turbine Endwall Aerodynamics and Heat Transfer - Journal Article
- Flow Measurements in a First Stage Nozzle Cascade Having Endwall Contouring, Leakage and Assembly Features - Proceedings of 2005 ASME Turbo Expo, Power for

Land, Sea & Air, June 6-9, 2005, Reno/Taho, Nevada, USA

- Heat Transfer Measurements in a First Stage Nozzle Cascade Having Endwall Contouring, Leakage and Assembly Features - Proceedings of HT2005, 2005 ASME Summer Heat Transfer Conference, July 17-22, 2005, San Francisco, California, USA
- Flow Measurements in a First Stage Nozzle Cascade having Leakage and Assembly Features: Effects of Endwall Steps and Leakage on Aerodynamic Losses - Conference Presentation at the 2005 ASME International Mechanical Engineering Congress and Exposition, November 5-11, 2005, Orlando, Florida
- Heat Transfer Measurements in a First Stage Nozzle Cascade Having Endwall Contouring: Misalignment and Leakage Studies - Proceedings of GT2006 ASME Turbo Expo 2006: Power for Land, Sea and Air, May 8-11, 2006, Barcelona, Spain
- Adiabatic Effectiveness Measurements in a First Stage Nozzle Cascade Having Endwall Contouring, Leakage and Assembly Features - Proceedings of GT2006 ASME Turbo Expo 2006: Power for Land, Sea and Air, May 8-11, 2006, Barcelona, Spain

SR097

University of Connecticut

Principal Investigator: Eric Jordan

Project Title: *Measurement of Three Critical Parameters as a Basis for a Simple Life Prediction Method*

- Thermally Grown Oxide Stress Evolution as a Function of Thermal Cycling in an Electron Beam Physical Vapor Deposit TBC - Journal Article
- Failure Mechanisms of Dense Vertically Cracked Thermal Barrier Coatings - Journal Publication
- Damaged Evolution in an Electron Beam Physical Vapor Deposited Thermal Barrier Coatings as a Function of Cycle Temperature and Time - Journal Publication
- Photoluminescence Piezospectroscopy: A Multi-Purpose Quality Control And NDI Technique For Thermal Barrier Coatings - Journal Publication
- Evolution of Photo-Simulated Luminescence of EB-PVD/Pt-Al Thermal Barrier Coating - Submitted for Approval for Journal Publication
- Remaining Life Prediction of Thermal Barrier Coatings Based on Photoluminescence Piezo-Spectroscopy Measurement - Submitted for Approval for Journal Publication
- Analysis of Localized Damage of EB-PVD/Pt-Al Thermal Barrier Coatings - Being Submitted for Journal Publication
- Effect of Temperature on Rumpling and Thermally Grown Oxide Stress in an EB-PVD Thermal Barrier Coating - Submitted for Approval for journal publication - "Surface and Coatings Technology"

SR098

Louisiana State University

Principal Investigator: Sumanta Acharya

Project Title: *Experiments and Computations on Film Cooled End Wall with Contouring*

- Experimental Investigation of Flow Structure and Nusselt Number in a Low Speed Linear Blade Passage With and Without Leading Edge Fillets - Journal Publication
- Unsteady RANS Simulation of Turbulent Flow and Heat Transfer in Ribbed Coolant Passages of Different Aspect Ratios - Journal Publication
- Large Eddy Simulations of Flow and Heat Transfer in Rotating Ribbed Duct Flows - Journal Publication
- Flow and Heat Transfer in an Internally Ribbed Duct With Rotation: An Assessment of LES and URANS - Journal Publication
- Turbulent Heat Transfer in Ribbed Coolant Passages of Different Aspect Ratios: Parametric Effects - Journal Publication
- Experimental Investigation of Secondary Flow Structure in a Blade Passage with and Without Leading Edge Fillets - Journal Publication
- The Role of Leading-Edge Contouring on End-Wall Flow and Heat Transfer: Computations and Experiments - Proceedings of GT2006 ASME Turbo Expo 2006: Power for Land, Sea and Air, May 8-11, 2006, Barcelona, Spain
- Heat Transfer at High Rotation Numbers in a Two-Pass 4:1 AR Rectangular Channel With 45-Degree Skewed Ribs - Proceedings of GT2006 ASME Turbo Expo 2006: Power for Land, Sea and Air, May 8-11, 2006, Barcelona, Spain

SR099

Virginia Polytechnic Institute and State University

Principal Investigator: Uri Vandsburger

Project Title: *Modeling and Control of Ultra-Lean Premixed Combustion Dynamics for Gas Turbines*

- Thesis: Paul Black, M.S.
Title: "Acoustic Transfer Functions Derived from Finite Element Modeling for Thermoacoustic Stability Predictions of Gas Turbine Engines"
- Thesis: Christopher Reed Martin: MS.
Title: "Systematic Prediction and Parametric Characterization of Thermo-Acoustic Instabilities in Premixed Gas Turbine Combustors"
- Thesis: David, James Losh: MS.
Title: "Linear Stability Analysis of a Rijke Tube and Modeling of Turbulent Combustion using Dynamic Well-Stirred Reactors (Electronic Resource)"
- Thesis: Alok Dhagat, MS.
Title: "Three-Dimensional Acoustic Finite element Models for Thermoacoustic Stability Predictions for Gas Turbine Engines"
- Thesis: Joseph Ranalli, PhD.

Title: "Dynamic Characterization of LP, Hydrocarbon, Hydrogen, and Syngas Combustors"

SR100

Virginia Polytechnic Institute and State University

Principal Investigator: Danesh Tafti

Project Title: *Enhanced Prediction Techniques Based on Time Accurate Simulations for Turbine Blade Internal Cooling*

- Investigation of Detached Eddy Simulations in Capturing the Effects of Coriolis Forces and Centrifugal Buoyancy in Ribbed Ducts - Submitted ASME J. Heat Transfer , September 2006, accepted
- Capturing the Effects of Rotation in Sudden Expansion Ducts Using Detached Eddy Simulations - Submitted AIAA J., September 2006
- Simulation of Flow and Heat Transfer in the Developing Flow Region of a Rotating Gas Turbine Blade Internal Cooling Duct with Coriolis and Buoyancy Forces - ASME J. Turbomachinery 129, pp. 1-7, 2007
- A Comparative Study of DES and URANS for Flow Prediction in a Two-Pass Internal Cooling Duct - ASME J. Fluids Engineering , 128(6), pp. 1336-1345, November 2006
- Detached Eddy Simulation of Flow and Heat Transfer in Fully-Developed Rotating Internal Cooling Channel With Normal Ribs - Int. J. Heat and Fluid Flow 27(3), pp. 351-370, 2006
- Large Eddy Simulation of Flow and Heat Transfer in the 180° Bend Region of a Stationary Ribbed Gas Turbine Blade Internal Cooling Duct - ASME J. Turbomachinery (128), pp.763-771, 2006
- Detached Eddy Simulation of Turbulent Flow and Heat Transfer in a Two-Pass Internal Cooling Duct - Int. J. Heat and Fluid Flow 27(1), pp. 1-20, 2006
- Experimental Validation of Large Eddy Simulations of Flow and Heat Transfer in a Stationary Ribbed Duct - Int. J. Heat and Fluid Flow 27 (2), pp. 243-258, 2006
- Detached Eddy Simulation of Turbulent Flow and Heat Transfer in a Ribbed Duct - ASME J. Fluids Engineering 127(5), pp. 888-896, 2005
- Evaluating the Role of Subgrid Stress Modeling in a Ribbed Duct for the Internal Cooling of Turbine Blades - Int. J Heat and Fluid Flow 26(1), pp. 92-104, 2005
- Large Eddy Simulations of Flow and Heat Transfer in a 90° Ribbed Duct With Rotation - Effect of Coriolis and Centrifugal Buoyancy Forces - J. Turbomachinery 126(4), pp. 627-636, 2004
- Large Eddy Simulation of the Fully Developed Flow and Heat Transfer in a Rotating Duct With 45° Ribs - GT 2006-90229, ASME Turbo Expo 2006, 8- 11 May 2006, Barcelona, Spain
- A Comparative Study of DES and URANS in a Two-pass Internal Cooling Duct With Normal Ribs - IMECE2005-79288, 2005 ASME International Mechanical Engineering

Congress and Exposition, November 5-11, 2005 , Orlando , Florida

- Large Eddy Simulation of Flow and Heat Transfer in an Internal Cooling Duct with High Blockage Ratio 45 o staggered Ribs - GT 2005-68086, Proceedings of ASME Turbo Expo 2005, June 6-9, Reno-Tahoe , USA
- Large Eddy Simulation of Flow and Heat Transfer in a Ribbed Duct With Skewed Ribs of Rounded Cross-section - GT 2005-68117, Proceedings of ASME Turbo Expo 2005, June 6-9, Reno-Tahoe, USA
- Detached Eddy Simulation of Flow and Heat Transfer in a Stationary Internal Cooling Duct with Skewed Ribs - GT 2005-68118, Proceedings of ASME Turbo Expo 2005, June 6-9, Reno-Tahoe , USA
- Large Eddy Simulation of Flow and Heat Transfer in the 180° Bend Region of a Stationary Ribbed Gas Turbine Blade Internal Cooling Duct - Proceedings of the ASME Turbo Expo 2005, Reno-Tahoe, Nevada, ASME Paper No. GT2005-68518
- Large Eddy Simulation of Flow and Heat Transfer in the Developing Flow Region of a Rotating Gas Turbine Blade Internal Cooling Duct With Coriolis and Buoyancy Forces - Proceedings of the ASME Turbo Expo 2005, Reno-Tahoe, Nevada, ASME Paper No. GT2005-68519
- Flowfield Measurements in a Ribbed Channel Relevant to Internal Turbine Blade Cooling - GT2004-53361, ASME Turbo Expo 2004, Vienna, Austria
- Detached Eddy Simulation of Turbulent Flow and Heat Transfer in a Duct - HT- FED 2004-56152, 2004 ASME Heat Transfer/Fluids Engineering Summer Conference, July 11-15, Charlotte
- Large Eddy Simulation of Flow and Heat Transfer in a Staggered 45° Ribbed Duct - GT2004-53800, ASME Turbo Expo: 2004, Vienna , Austria
- Large Eddy Simulations of Flow and Heat Transfer in a 90° Ribbed Duct with Rotation – Effect of Coriolis Forces - GT2004-53796, ASME Turbo Expo 2004, Vienna , Austria
- Large Eddy Simulations of Flow and Heat Transfer in a 90° Ribbed Duct with Rotation - Effect of Coriolis and Centrifugal Buoyancy Forces - GT2004-53799, ASME Turbo Expo 2004, Vienna , Austria
- Large Eddy Simulation of the Developing Region of a Stationary Ribbed Internal Turbine Blade Cooling Channel - GT2004-53832, ASME Turbo Expo 2004, Vienna, Austria
- Large Eddy Simulation of the Developing Region of a Rotating Ribbed Internal Turbine Blade Cooling Channel - GT2004-53833, ASME Turbo Expo 2004, Vienna, Austria
- Large Eddy Simulations of Heat Transfer in A Ribbed Channel for Internal Cooling of Turbine Blades - Paper No. GT2003-38122, Proceedings of ASME/IGTI Turbo Expo, Atlanta, Georgia , June 16-19, 2003
- Large Eddy Simulation of Flow and Heat Transfer in an Internal Cooling Duct with

High Blockage Ratio 45° Staggered Ribs GT 2005-68086 - Proceedings of ASME Turbo Expo 2005, June 6-9, 2005, Reno, Nevada

SR101

University of Pittsburgh

Principal Investigator: Fred Pettit

Project Title: *Mechanism-Based Testing Methodology for Improving the Oxidation, Hot Corrosion and Impact Resistance of High Temperature Coatings for Advanced Gas Turbines*

- Accelerated Cyclic Oxidation Testing Protocols for Thermal Barrier Coatings and Alumina-Forming Alloys and Coatings - Materials and Corrosion
- Use of Indentation Fracture Tests to Investigate Toughness Loss Mechanisms in Thermal Barrier Coating Systems - submitted to Materials Science & Technology 2005 Conference

SR102

Georgia Institute of Technology

Principal Investigator: Jerry Seitzman

Project Title: *Advanced Sensor Approaches for Monitoring and Control of Gas Turbine Combustors*

- Acoustic Characterization of Piloted, Premixed Flames Under Near Blowout Conditions - Submitted for Journal Publication
- Acoustic Detection of Imminent Blowout in Pilot and Swirl Stabilized Combustors - Submitted for Presentation at the 2003 ASME/IGTI Turbo Expo in Atlanta, June 2003

SR103

University of Central Florida

Principal Investigator: Y. H. Sohn

Project Title: *Assessments of Failure Mechanisms for Thermal Barrier Coatings by Photoluminescence, Electrochemical Impedance and Focused Ion Beam*

- Effects of Phase Constituents and Microstructure in Thermally Grown Oxide on The Thermal Cycling Lifetime and Failure of Thermal Barrier Coatings - Surface and Coatings Technology, Accepted for Publication, in Press, 2005
- Non-Destructive Evaluation of Degradation in Multi-Layered Thermal Barrier Coatings by Electrochemical Impedance Spectroscopy - Materials Science and Engineering A, Accepted for Publication, in Press, 2005
- Non-Destructive and Microstructural Characterization of Thermal Barrier Coatings - Journal of Metals, Vol. 56 (2004) 53-56
- An Observation of Nearly Failed Electron Beam Physical Vapor Deposited Thermal Barrier Coating with Grit Blasted (Ni,Pt)Al Bond Coat: Photostimulated Luminescence and Transmission Electron Microscopy - Thin Solid Films, Vol. 466 (2004) pp. 128-136
- Electrochemical Impedance Spectroscopy of Porous ZrO₂ – 8 wt.% Y₂O₃ and

Thermally Grown Oxide on Nickel Aluminide - Materials Science and Engineering A, Vol. A372 (2004) pp. 278-286

- Electrochemical Impedance Spectroscopy of Thermal Barrier Coatings as a Function of Isothermal and Cyclic Thermal Exposure - Surface and Coatings Technology, Vol. 177-178 (2004) pp. 140-151
- Microstructure of As-Coated Thermal Barrier Coatings with Varying Lifetimes - Surface and Coatings Technology, Vol. 177-178 (2004) pp. 89-96
- Phase Transformation of Thermally Grown Oxide on (Ni,Pt)Al Bond Coat During Electron Beam Physical Vapor Deposition and Subsequent Oxidation - Surface and Coatings Technology, Vol. 177-178 (2004) pp. 121-130

SR104

Brigham Young University

Principal Investigator: Jeffrey Bons

Project Title: *Turbine Surface Degradation With Services and Its Effects on Performance*

- Simulated Land-Based Turbine Deposits Generated in an Accelerated Deposition Facility - Submitted for Approval for Conference Presentation at the ASME Turbo Expo June 14-17, 2004, Vienna, Austria
- Direct Simulation of Surface Roughness Effects With RANS and DES on Viscous Adaptive Cartesian Grids - Presented at the AIAA Fluid Dynamics Conference, June 28- July 1, 2004, Portland, Oregon
- High Pressure Turbine Deposition in Land Based Gas Turbines from Various Synfuels - Presented at the 2005 IGTI Turbo Expo, Reno, NV (Paper # GT2005-68479) and also accepted for archival journal publication in the ASME Journal of Turbomachinery
- Turbine Blade Surface Deterioration by Erosion - Presented at the 2004 IGTI in Vienna, Austria (Paper # GT 2004-54328 “”) in June, 2004, also published in the ASME Journal of Gas Turbines for Power and Propulsion and was awarded the 2005 Aircraft Engine Committee award for best paper
- Effects of Strong Irregular Roughness on the Turbulent Boundary Layer - accepted for publication in Flow, Turbulence and Combustion Journal
- Flow and Heat Transfer over Rough Surfaces: Usefulness of 2- D Roughness-Resolved Simulations - Presented at the AIAA 44th Aerospace Sciences Meeting and Exhibit in Reno, NV, 9-12 Jan 2006 (paper #AIAA 2006-0025)
- A Comparison of Approximate vs. Exact Geometrical Representations of Roughness for CFD Calculations of cf and St - Presented at IMECE 2005 in Orlando, FL, Nov. 2005. Submitted for publication in ASME Journal of Turbomachinery June 2005. Accepted for publication – January 2006
- Evolution of Surface Deposits on a High Pressure Turbine Blade, Part : Physical Characteristics - Presented at the 2006 IGTI, Barcelona, Spain and published in the ASME Journal of Turbomachinery
- Evolution of Surface Deposits on a High Pressure Turbine Blade, Part 2: Convective

Heat Transfer - Presented at the 2006 IGTI, Barcelona, Spain and published in the ASME Journal of Turbomachinery

SR105

University of Wisconsin, Madison

Principal Investigator: Scott Sanders

Project Title: *Advanced Optical Sensor for Monitoring and Control of Multiple Gas and Turbine-Blade Properties*

- no publications reported

SR106

Cleveland State University

Principal Investigator: Surendra N. Tewari

Project Title: *Spectroscopic In-Situ Non-Destructive Evaluation to Monitor the Health of Thermal Barrier Coatings*

- no publications reported

SR107

University of Connecticut

Principal Investigator: Eric Jordan

Project Title: *Superior Thermal Barrier Coatings for Industrial Gas Turbine Engines Using a Novel Solution Plasma Spray Process*

- no publications reported

SR108

Clemson University

Principal Investigator: John Wagner

Project Title: *An Advanced Diagnostic and Prognostic System for Gas Turbine Generator Sets With Experimental Validation*

- no publications reported

SR109

Pennsylvania State University

Principal Investigator: Domenic Santavicca

Project Title: *The Effects of Fuel Distribution, Velocity Distribution, and Fuel Composition on Static and Dynamic Instabilities and NO_x Emissions in Lean Premixed Combustors*

- no publications reported

SR110

Virginia Polytechnic Institute and State University

Principal Investigator: Karen Thole

Project Title: *Improved Film Cooling Performance for Turbine Vanes and Endwalls with Realistic Surface Condition*

Virginia Tech - Publications

- Effects of Mid-Passage Gap, Endwall Misalignment, and Roughness on Endwall Film-Cooling - Journal of Turbomachinery , vol. 128, pp. 62-70, ASME Turbo Expo, Reno, (GT2005-68900) – Awarded the Heat Transfer Committee Best Paper Award for 2005
- The Effects of Varying the Combustor- Turbine Gap - Accepted to the Journal of Turbomachinery, ASME Turbo Expo, Barcelona , (GT2006-90089)
- Effects of Surface Deposition, Hole Blockage, and TBC Spallation on Vane Endwall Film Cooling - Accepted to the Journal of Turbomachinery, ASME Turbo Expo, Barcelona, (GT2006-90379)
- Effects of Deposits on Film Cooling of a Vane Endwall Along the Pressure Side - Recommended to the Journal of Turbomachinery- ASME Turbo, Montreal, (GT2007-27131)
- Bump and Trench Modifications to Film Cooling Holes at the Vane Endwall Junction - Recommended to the Journal of Turbomachinery, ASME Turbo Expo, Montreal, (GT2007-27132)
- Flowfield Measurements of the Endwall Leading Edge With Film-Cooling - ASME Turbo Expo 2008: Power for Land, Sea and Air, June 2008, Berlin, Germany

Virginia Tech - Theses

- Effects of Realistic First-Stage Turbine Endwall Features - M.S. Thesis, Cardwell, N. D., 2005, Virginia Tech
- Effects of Surface Conditions on Endwall Film-Cooling - Ph.D. Dissertation, Sundaram, N., 2007, Virginia Tech (to be published)

University of Texas at Austin - Publications

- Degradation of Film Cooling Performance on a Turbine Vane Suction Side Due to Surface Roughness - ASME Gas Turbine Expo, Reno, Nevada, ASME Paper GT2005-69045
- The Effects of Obstructions on Film Cooling Effectiveness on the Suction side of a Gas Turbine Vane - ASME Turbo Expo, Barcelona, Spain, ASME Paper GT-2006-90577
- High Resolution Film Cooling Effectiveness Measurements of Axial Holes Embedded in a Transverse Trench with Various Trench Configurations - ASME Turbo Expo, Barcelona, Spain , ASME Paper GT-2006-90226
- High Resolution Film Cooling Effectiveness Comparison of Axial and Compound Angle Holes on the Suction Side of a Turbine Vane - ASME Turbo Expo, Barcelona, ASME Paper GT-2006-90225
- Degradation of Film Cooling Performance on a Turbine Vane Suction Side Due to Surface Roughness - ASME J. of Turbomachinery, vol. 128, 2006, pp. 547-554
- Effects of Regular and Random Roughness on the Heat Transfer and Skin friction Coefficient on the Suction Side of a Gas Turbine Vane - ASME Turbo Expo, Montreal, Canada , ASME Paper GT-2007-27285

- Effects of Obstructions and Surface Roughness on Film Cooling Effectiveness With and Without a Transverse Trench - ASME Gas Turbine Expo, Montreal, Canada, ASME Paper GT2007-28003
- Effects of Surface Roughness and Near Hole Obstructions on Film Cooling Effectiveness - ASME Gas Turbine Expo, Montreal , Canada , ASME Paper GT2007-28004
- High Resolution Film Cooling Effectiveness Comparison of Axial and Compound Angle Holes on the Suction Side of a Turbine Vane - ASME J. of Turbomachinery, 2007 (accepted)
- High Resolution Film Cooling Effectiveness Measurements of Axial Holes Embedded in a Transverse Trench With Various Trench Configurations - ASME J. of Turbomachinery, 2007. (accepted)

University of Texas at Austin - Theses

- Roughness Impact on Turbine Vane Suction Side Film Cooling Effectiveness - M.S. Thesis, Robertson, D.R., 2004, University of Texas at Austin
- Suction Side Roughness Effects on Film Cooling Heat Transfer on a First Stage Nozzle Guide Vane - M.S. Thesis, Rutledge, J.L., 2004, University of Texas at Austin
- The Effects of Obstructions on Film Cooling Effectiveness on the Suction Side of a Gas Turbine Vane - M.S. Thesis, Demling, T., 2005, University of Texas at Austin
- Effects of Roughness on Film Effectiveness on the Pressure Side of a Turbine Vane - M.S. Thesis, Warren, D. J., 2005, University of Texas at Austin
- Film Cooling Effectiveness of Suction Side Axial Holes, Compound Angle Holes, and Axial Holes Embedded within an Overlying Transverse Trench - M.S. Thesis, Waye, S.K., 2005, University of Texas at Austin
- Effects of Regular and Random Roughness on the Heat Transfer and Skin Friction Coefficient on the Suction Side of a Gas Turbine Vane - M.S. Thesis, Dees, J.E., 2006, University of Texas at Austin
- Rough Wall and Near-Hole Obstruction Effects on Film Cooling with and without a Transverse Trench - M.S. Thesis, Somawardhana, R.P., 2006, University of Texas at Austin

SR111

Georgia Institute of Technology

Principal Investigator: Tim Lieuwen

Project Title: *Combustion Instability and Blowout Characteristics of Fuel Flexible Combustors*

- Online Combustor Stability Margin Assessment Using Dynamic Pressure Data - Submitted for Approval for Journal Publication and Conference Presentation at IGTI 2004, Vienna
- Impacts of Hydrogen Addition on Near-Lean Blowout Dynamics in a Swirling Combustor - Proceedings of the GT2007 ASME Turbo Expo 2007: Power for Land,

Sea and Air, May 14-17, 2007, Montreal, Canada

SR112

University of California, Irvine

Principal Investigator: Scott Samuelsen

Project Title: *Correlation of Ignition Delay With IGCC Type Fuels*

- no publications reported

SR113

Texas A&M University

Principal Investigator: J.C. Han

Project Title: *Heat Transfer from Rotating Blade Platforms With and Without Film Cooling*

- Film Cooling Effectiveness on a Rotating Turbine Platform Using Pressure Sensitive Paint Technique - Journal Publication
- Prediction of Film Cooling and Heat Transfer on a Rotating Blade Platform with Stator-Rotor Purge and Discrete Film-Hole Flows in a 1-1/2 Turbine Stage - Journal Publication
- Effect of Upstream Wake with Vortex on Turbine Blade Platform Film Cooling and Simulated Stator-Rotor Purge Flow - Journal Publication

SR114

University of Central Florida

Principal Investigator: Eric Petersen

Project Title: *Combustion Characterization and Modeling of Fuel Blends for Power Generation Gas Turbines*

- Acceleration of Shock-Induced Ignition in CH₄/Air and CO/Air Mixtures Using Hydrogen Addition - Journal Paper, Combustion Science and Technology
- Test-Time Extension Behind Reflected Shock Waves Using CO₂-He and C₃H₈-He Driver Mixtures - Journal Paper, Shock Waves
- Design and Validation of a Reduced Test Matrix for the Autoignition of Gas Turbine Fuel Blends - Presentation for Proceedings of IMECE2005 2005 ASME International Mechanical Engineering Congress and Exposition, November 5-11, 2005, Orlando, Florida
- A Shock-Tube Study of The Ignition and Oxidation Characteristics of Syngas at Elevated Pressures - Abstract for the 2005 Fall Meeting of the Eastern States Section of the Combustion Institute
- Effect of Higher-Order Hydrocarbons on the Ignition of Lean Methane-Air Mixtures at Elevated Pressures - Abstract for the 2005 Fall Meeting of the Eastern States Section of the Combustion Institute
- Experimental Study on the Low-Temperature Ignition Behavior of Gas Turbine Fuel Blends - Abstract for the 2005 Fall Meeting of the Eastern States Section of the Combustion Institute

SR115

University of Pittsburgh

Principal Investigator: MinkingChyu

Project Title: *Effects of Coating Blockage and Deposits on Film Cooling Effectiveness and Heat Transfer*

- no publications reported

SR116

University of Pittsburgh

Principal Investigator: Fred Pettit

Project Title: *Investigation of Materials Performances in High Moisture Environments Including Corrosive Contaminants Typical of Those Arising by Using Alternate Fuels in Gas Turbines*

- The Effect of Ca-rich Deposits on the High Temperature Degradation of Coated and Uncoated Superalloys - Publication: Materials Science Forum and Conference Presentation at the Les Embiez 2007 Conference

SR117

Pennsylvania State University

Principal Investigator: Robert J. Santoro

Project Title: *Autoignition Studies of Syngas and Hydrogen (SGH) Fuels*

- no publications reported

SR118

University of Central Florida

Principal Investigator: Yong-Ho Sohn

Project Title: *Degradation of Thermal Barrier Coatings with Syngas Combustion: Testing by Hyperbaric Advanced Development Environmental Simulator (HADES) and Characterization by Advanced Electron Microscopy*

- no publications reported

SR119

University of North Dakota

Principal Investigator: Forrest Ames

Project Title: *Aero Losses, Heat Transfer, Discharge Coefficients for Different Vane Trailing Edge Configurations for Syngas Fired Turbines*

- Gill Slot Trailing Edge Aerodynamics-Effects of Blowing Rate, Reynolds Number, and External Turbulence on Aerodynamics Losses and Pressure Distribution - Journal Publication
- Gill Slot Trailing Edge Heat Transfer - Effects of Blowing Rate, Reynold Number, and External Turbulence on Heat Transfer and Film Cooling Effectiveness - Journal Publications
- Aerodynamics of a Letterbox Trailing Edge - Effects of Blowing Rate, Reynolds Number, and External Turbulence on Aerodynamics Losses and Pressure Distribution -

ASME Turbo Expo 2008: Power for Land, Sea and Air, June 2008, Berlin, Germany

- Heat Transfer and Pressure Drop Measurements in Constant and Covering Section Pin and Diamond Pdedstal Arrays - ASME Turbo Expo, June 2009, Orlando, FL
- Aerodynamics of a Covered Trailing Edge Vane - Effects of Blowing Rate, Reynolds Number, and External Turbulence - ASME Turbo Expo, June 2009, Orlando, FL
- Letterbox Trailing Edge Heat Transfer Effects of Blowing Rate, Reynolds Number, and External Turbulence on Heat Transfer and Film Cooling Effectiveness - ASME Turbo Expo 2008: Power for Land, Sea and Air, June 2008, Berlin, Germany
- Effects of a Realistically Rough Surface on Vane Heat Transfer Including the Influence of Turbulence Condition and Reynolds Number - ASME Turbo Expo, June 2010, Glasgow, UK
- Effects of a Realistically Rough Surface on Vane Aerodynamic Losses Including the Influence of Turbulence Condition and Reynolds Number - ASME Turbo Expo, June 2010, Glasgow, UK

SR120

Brigham Young University

Principal Investigator: Jeffrey Bons

Project Title: *Deposition of Alternative (Syngas) Fuels on Turbine Blades with Film Cooling*

- Effects of Particle Size, Gas Temperature, and Metal Temperature on High Pressure Turbine Disposition in Land Based Gas Turbines from Various Synfuels - ASME Turbo Expo, Power for Land, Sea and Air, May 2007, Montreal, Canada
- Deposition Near Film Cooling Holes on a High Pressure Turbine Vane - ASME Turbo Expo 2008: Power for Land, Sea and Air, June 2008, Berlin, Germany
- Effect of Hole Spacing on Deposition of Fine Coal Flyash Near Film Cooling Holes - ASME Turbo Expo, Power for Land, Sea and Air, June 2009, Orlando, Florida
- Film Cooling Effectiveness and Heat Transfer Near Deposit-Laden Film Holes - ASME Turbo Expo, Power for Land, Sea and Air, June 2009, Orlando, Florida

SR121

Massachusetts Institute of Technology

Principal Investigator: Ahmed Ghoniem

Project Title: *Fundamental Studies in Syngas Premixed Combustion Dynamics*

- no publications reported

SR122

Georgia Institute of Technology

Principal Investigator: Jerry Seitzman

Project Title: *Turbulent Flame Speed Measurements and Modeling of Syngas Fuels*

- Global Turbulent Consumption Speeds (S_{T,GC}) of H₂/CO Blends- ASME Turbo Expo, June 2009, Orlando, FL

- Disturbance Field Characteristics of a Transversely Excited Swirl Flame - ASME Turbo Expo, June 2010, Glasgow, UK
- Response of Swirl-Stabilized Flames to Transverse Acoustic Excitation - Submission to the AIAA Aerospace Sciences Meeting

SR123

Virginia Polytechnic Institute and State University

Principal Investigator: Danesh Tafti

Project Title: *Syngas Particulate Deposition and Erosion at the Leading Edge of a Turbine Blade with Film Cooling*

- Large Eddy Simulations of a Three Row Leading Edge Film Cooling Geometry - 2008 ASME International Mechanical Engineering Congress and Exposition, November 2008, Boston, MA
- Effect of Blowing Ratio in the Near Stagnation Region of a Three-Row Leading Edge Film Cooling Geometry Using Large Eddy Simulations - ASME Turbo Expo, June 2009, Orlando, FL
- Effect of Blowing Ratio on Syngas Flyash Particle Deposition on a Three-Row Leading Edge Film Cooling Geometry Using Large Eddy Simulations- ASME Turbo Expo, June 2009, Orlando, FL
- Composition Dependent Model for the Prediction of Syngas Ash Deposition With Application to a Leading Edge Turbine Vane - ASME Turbo Expo, June 2010, Glasgow, UK
- Syngas Ash Deposition Simulation Method for Experimentation - ASME Turbo Expo, June 2010, Glasgow, UK
- Effects of Blowing Ratio on Early Stage Deposition on Syngas Ash on a Film-Cooled Vane Leading Edge Using Large Eddy Simulations - Journal Publication

SR124

University of Pittsburgh

Principal Investigator: Gerald Meier

Project Title: *Materials for Oxy-Fuel Turbomachine Conditions*

- no publications reported

SR125

University of California, Santa Barbara

Principal Investigator: Ted Bennett

Project Title: *Evaluating Coatings for Current and Future Service with Thermal Property Measurements*

- Front Surface Thermal Property Measurements of Air Plasma Spray Coatings- Journal Publication
- Evolution of Thermal Properties of EB-PVD 7YSZ Thermal Barrier Coatings with Thermal Cycling - Journal Publication

SR126

University of Colorado

Principal Investigator: John Daily

Project Title: *High Pressure Kinetics of Syngas and Nearly Pure Hydrogen Fuels*

- no publications reported

SR127

University of Texas, Austin

Principal Investigator: David Bogard

Project Title: *Simulating Particle Deposition and Mitigating Deposition Degradation Effects in Film Cooled Turbine Sections*

- The Effects of Simulated Particle Deposition on Film Cooling - ASME Turbo Expo, June 2009, Orlando, FL
- Experimental Simulation of Contaminant Deposition on a Film Cooled Turbine Airfoil Leading Edge - Conference Presentation
- Simulations of Multi-Phase Particle Deposition on Endwall Film-Cooling - ASME Turbo Expo, June 2010, Glasgow, UK
- Simulations of Multi-Phase Particle Deposition on Endwall Film-Cooling Holes in Transverse Trenches - ASME Turbo Expo, June 2011, Vancouver, Canada
- Experimental Simulation of Contaminant Deposition on a Film Cooled Turbine Vane Pressure Side With A Trench - ASME Turbo Expo, June 2011, Vancouver, Canada
- Measurements of Adiabatic Film and Overall Cooling Effectiveness on a Turbine Vane Pressure Side With a Trench - ASME Turbo Expo, June 2011, Vancouver, Canada

Appendix A – Performing Member Universities

1. Air Force Institute of Technology, Ohio
2. University of Alabama, Birmingham, Alabama
3. University of Alabama, Huntsville, Alabama
4. University of Alabama, Tuscaloosa, Alabama
5. University of Alaska-Fairbanks, Alaska
6. Arizona State University, Arizona
7. Arkansas Tech University, Arkansas
8. University of Arkansas, Arkansas
9. Auburn University, Alabama
10. Boston University, MA
11. Brigham Young University, Utah
12. State University of NY @ Buffalo, New York
13. California Institute of Technology, California
14. University of California, Berkeley, California
15. University of California, Davis, California
16. University of California, Irvine, California
17. University of California, Los Angeles, California
18. University of California, San Diego, California
19. University of California, Santa Barbara
20. Carnegie Mellon University, Pennsylvania
21. University of Central Florida, Florida
22. University of Cincinnati, , Ohio
23. Clarkson University, New York
24. Clemson University, South Carolina
25. Cleveland State University, Ohio
26. University of Colorado, Boulder, Colorado
27. Colorado State University, Colorado
28. University of Connecticut, Connecticut
29. Cornell University, New York
30. University of Dayton, Ohio
31. University of Delaware, Delaware
32. University of Denver, Colorado
33. Drexel University, Pennsylvania
34. Duke University, North Carolina
35. Embry Riddle Aeronautical University, Florida
36. Florida Atlantic University, Florida
37. Florida Institute of Technology, Florida
38. University of Florida, Florida
39. Georgia Tech, Georgia
40. University of Hartford, Connecticut
41. University of Hawaii, Manoa, Hawaii
42. University of Houston, Texas
43. University of Idaho, Idaho
44. University of Illinois @ Chicago, Illinois
45. Iowa State University, Iowa
46. University of Iowa, Iowa
47. University of Kansas, Kansas
48. University of Kentucky, Kentucky
49. Lehigh University, Pennsylvania
50. Louisiana State University (LSU), Louisiana
51. University of Maryland, College Park, Maryland
52. University of Massachusetts, Amherst, Massachusetts
53. University of Massachusetts, Lowell, Massachusetts
54. Mercer University, Georgia
55. Michigan State University, Michigan
56. Michigan Technological University, Michigan
57. University of Michigan, Michigan
58. University of Minnesota, Minnesota
59. Mississippi State University, Mississippi
60. University of Missouri-Rolla, Missouri
61. Massachusetts Institute of Technology (MIT), Massachusetts
62. Montana State University, Montana
63. University of Nevada, Las Vegas, Nevada
64. University of New Orleans, Louisiana
65. State University of NY, Stony Brook (SUNY), New York
66. North Carolina State University, North Carolina
67. North Dakota, University of, North Dakota
68. Northeastern University, Massachusetts
69. Northwestern University, Illinois
70. University of Notre Dame, Indiana
71. Ohio State University, Ohio
72. University of Oklahoma, Oklahoma
73. Pennsylvania State University, Pennsylvania
74. University of Pittsburgh, Pennsylvania
75. Polytechnic University, NY
76. Princeton University, New Jersey
77. Purdue University, Indiana
78. Rensselaer Polytechnic Institute, NY
79. University of South Carolina, South Carolina
80. Southern University, Louisiana
81. University of Southern California, California
82. University of South Florida, Florida
83. Stanford University, California
84. Stevens Institute of Technology, New Jersey
85. Syracuse University, NY
86. Tennessee Technological University, Tennessee
87. University of Tennessee, Tennessee
88. University of Tennessee Space Institute (UTSI), Tennessee
89. Texas A&M University, Texas
90. University of Texas, Arlington, Texas
91. University of Texas, Austin, Texas
92. University of Tulsa, Oklahoma
93. University of Utah, Utah
94. Valparaiso University, Indiana
95. Vanderbilt University, Tennessee
96. University of Virginia, Virginia
97. Virginia Polytechnic Institute (VPI), Virginia
98. Virginia Commonwealth University, Virginia
99. Washington State University, Washington
100. Washington University, Missouri
101. University of Washington, Washington
102. Wayne State University, Michigan
103. Western Michigan University, Michigan
104. West Virginia University, West Virginia
105. University of Wisconsin, Madison, Wisconsin
106. University of Wisconsin, Milwaukee, Wisconsin
107. Wichita State University, Kansas
108. Worcester Polytechnic Institute, Massachusetts
109. Wright State University, Ohio
110. University of Wyoming, Wyoming
111. Yale University, Connecticut

Appendix B – Industrial Review Board Members

Voting Members

General Electric*
Pratt & Whitney*
Rolls Royce Corporation
Siemens Power Generation, Inc. (formerly Westinghouse)*
Solar Turbines*

Associate Members

British Petroleum*
Capstone Turbine Corporation
Clean Energy Systems, Inc.*
Duke Energy (formerly Cinergy)*
Electric Power Research Institute*
ExxonMobil*
Ingersoll Rand Energy Systems*
Parker Hannifin*
Precision Combustion, Inc.*
Ramgen
Southern Company*
Woodward Governor Company*

Those organizations denoted by an asterisk were Industrial Review Board members at the conclusion of the UTSR Cooperative Agreement.

Appendix C – Final Reports from UTSR Projects

Due to file size limitations, the University final reports have been removed from this uploaded version of the final report. Copies of this final report delivered to NETL and the Industrial Review Board on CD include all of the University final reports.