NETL-RUA
Regional University Alliance

U.S. DEPARTMENT OF ENERGY

Turbine Thermal Management

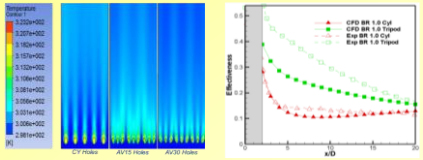
Mary Anne Alvin
Division Director, Project Technical Coordinator

NETL Carnegie Mellon PENNSTATE University of Pittsburgh VirginiaTech WestVirginiaUniversity URS

Advanced Film Cooling

VT, NETL

- *Tripod Hole Experimental Testing and CDF Modeling*



Materials Development

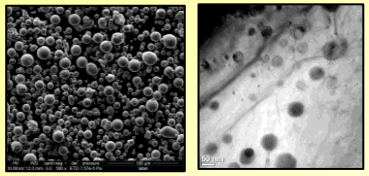
NETL, CFI, WPC, UPitt

- *Low Cost Bond Coat Systems*
- *Diffusion Barrier Coatings*
- *Extreme Temperature Overlayers*
- *High Temperature Testing with Steam*

Advanced Materials

NETL, NASA GRC, Ames Lab

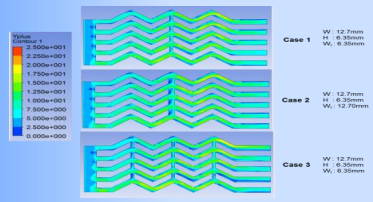
- *Ceramic Matrix Composites (CMCs)*
- *Oxide Dispersion Strengthened (ODS) Matrices*



Trailing Edge Cooling

UPitt, NETL

- *Experimental Testing and CDF Modeling of Zig-Zag Designs w/w-o Turbulators & w/w-oTrench*



Concept Manufacturing

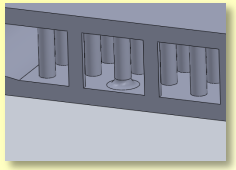
NETL, Mikro Systems Inc.

- *Internal Cooling Pin Fin Arrays*
- *Trailing Edge Configurations*
- *Film Cooling Tripod Holes*
- *Near Surface Embedded Micro-Channels*

Advanced Internal & Transpiration Cooling

UPitt, NETL

- *Advanced Fully Bridged and Detached Pin Fin Internal Cooling Concepts*
- *Near Surface Embedded Micro-Channel Concept*



Secondary Flow Rotating Rig

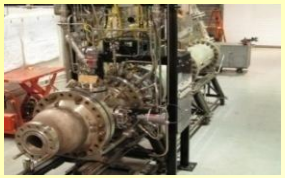
PSU, NETL

- *World Class Test Facility to Reduce Fuel Burn*

Aerothermal Testing

NETL

- *High Temperature, Pressurized Testing of Advanced Cooling Concepts under Combustion Gas Conditions*



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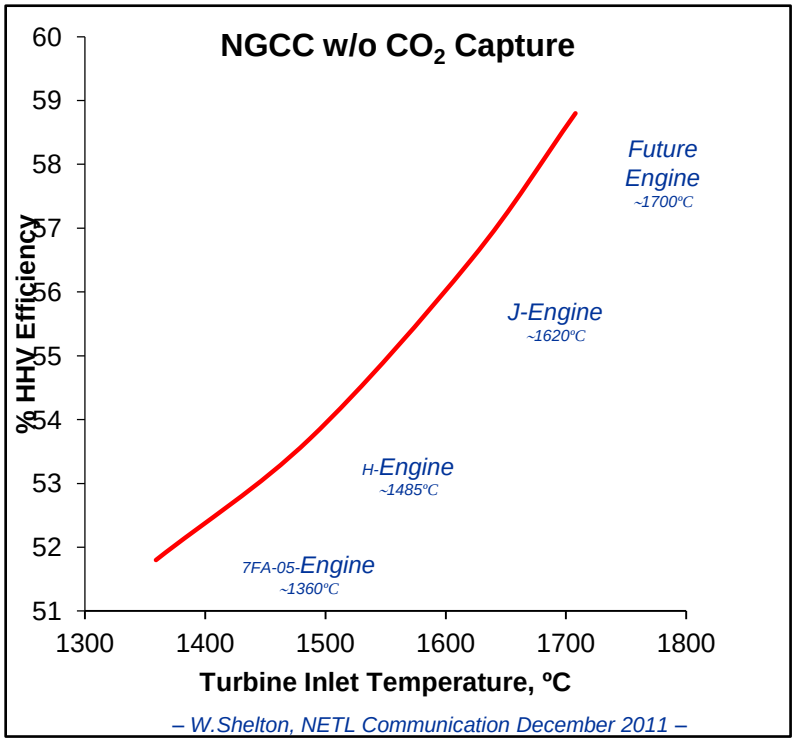
Turbine Thermal Management

NETL-RUA Turbine Thermal Management project is being conducted to support DOE FE's goals of achieving 3-5 percentage point plant efficiency gain by permitting a higher turbine firing temperature as a result of realizing more effective cooling, development and utilization of extreme temperature thermal barrier coating protection systems, and leakage flow reduction.



– W.Shelton, NETL Communication December 2011 –

Technology Development Areas

- *Detached and Fully Bridged Pin-Fin Internal Cooling*
- *Trailing Edge Cooling*
- *Near Surface Embedded Micro-Channel (NSEMC) Cooling*
- *Tripod Hole Film Cooling*
- *Coupon Manufacturing*

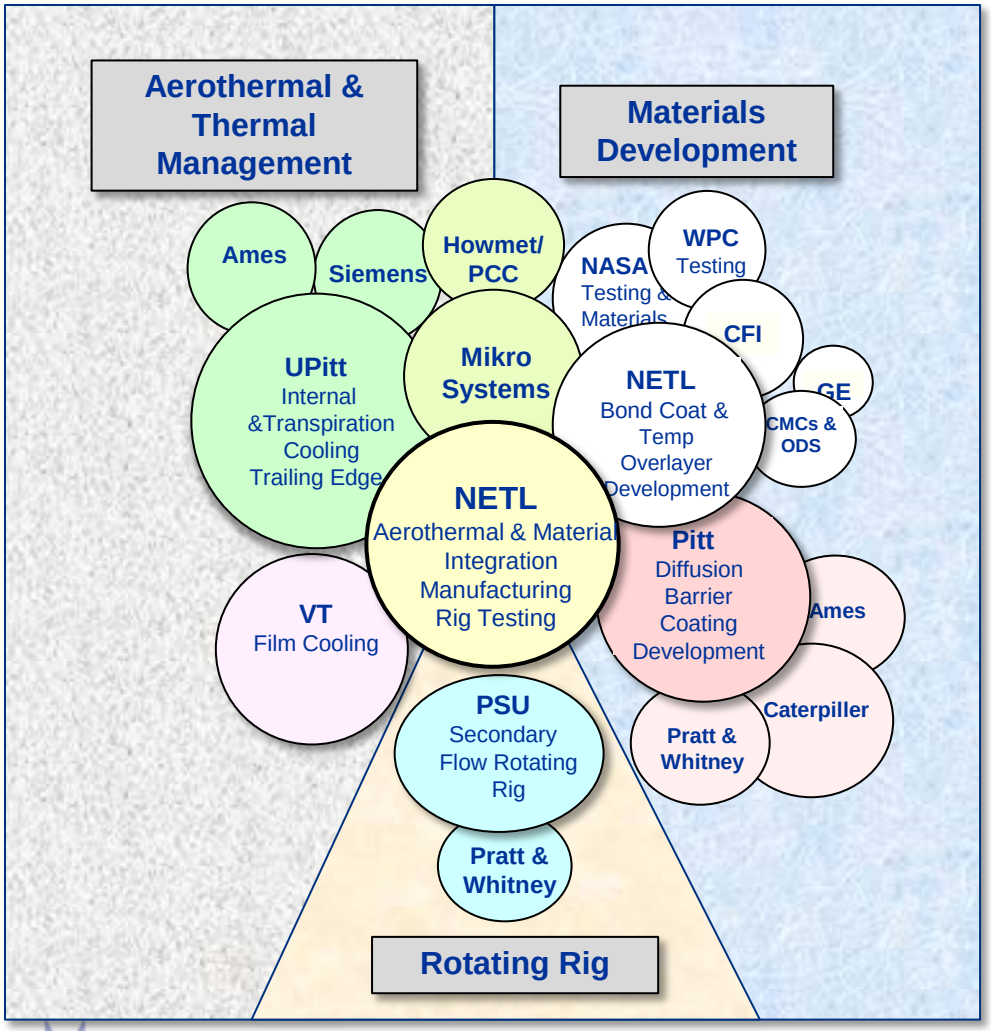
- *Diffusion Bond Coat Enhancement*
- *Diffusion Barrier Coating (DBC) Integration*
- *Enhanced Surface Feature Assessment*
- *ODS Development & NSEMC Integration*
- *CMC Assessment*

- *NETL High Temperature, Pressurized Testing*
- *Secondary Flow Rotating Rig*

Concept → Lab Bench-Scale Testing & CFD Modeling → Casting → Coupon Testing → Bench-Scale/Pilot Testing → Demonstration Plant → Commercial-Scale Testing → Commercial Implementation

Turbine Thermal Management

– Overall Approach –



*The **Turbine Thermal Management** project leverages government, academic, and industrial collaborations working synergistically in different aspects of aerothermal and materials issues to achieve the set overall goal through state-of-the-art analysis, modeling and testing.*

The program is uniquely structured to address:

(1) Development and Design of Aerothermal and Materials Concepts

(2) Design and Manufacturing of these advanced concepts

(3) Bench-Scale/Proof-of-Concept Testing of these concepts

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Turbine Thermal Management
– Materials Development –

***Objectives**: Development of a Thermal Barrier Composite Architecture for Use in Advanced Hydrogen-Fired and Oxy-Fuel Turbine Applications (TITs >1300ºC (~1370ºF)).*

Component Integration with Advanced Internal/Film Cooling Concepts.

***Major Accomplishments**:*

- *Patent Applications*
- *Bench-Scale Laboratory Furnaces (1100 ºC); Static Air, Isothermal /Cyclic Testing (René N5); A1D Exceeded SOTA Pt(Ni,Al) Diffusion Bond Coat Oxidation Performance*
- *Extreme Temperature Thermal Flux Testing at NASA GRC and Westinghouse Plasma Corporation*
  - *René N5/A1D/P&W EB-PVD YSZ/HfO_2-14mol%Y_2O_3-3mol%Gd_2O_3-3mol%Yb_2O_3*
  - *Steam: 50 hrs at 1500-1520 C; Minor Spallation after $T_{surface}$ >1575 C with $T_{interface}$ ~1150 C*

***Concept:** Multi-Layer Structure for Application on Nickel-Based Superalloys and Single Crystal Matrices*

Overlay Coating *NASA ZrO312* & HfO312** *Single/Bi-Layer*
YSZ Top Coat *7-8 YSZ Commercial* *High Purity, Low Conductivity*
Bond Coat *NETL-CFI A1D* *Commercial MCrAlY*
Diffusion Barrier *Cr + Ni + Re-rich σ-layer*
Metal Substrate *René N5, CMSX-4, PWA 1484* *Haynes 230, Haynes 214, IN939* *IN718, Haynes 188, MarM509*

Composite Architecture

***Current/Future Efforts**:*

- *Development of Further Enhanced Diffusion Bond Coat Systems*
  - *Co-Doping & Materials Performance and Characterization*
- *Application of A1D on Alternate Metal Substrates*
  - *Materials Performance and Characterization*
    - *CM247 (Siemens Energy)*
    - *IN939 (Siemens Energy)*
    - *PM2000 (Siemens Energy*
    - *MarM247 (Mikro Systems Airfoil Sections)*
    - *ODS (Ames Lab)*
- *Additional Patent Disclosures*

Turbine Thermal Management

– Advanced Materials –

Integration with Aerothermal

***Objectives**: Expand the NETL-RUA Portfolio to Include Ceramic Matrix Composite (CMC) Research Efforts for Use in Advanced Hydrogen-Fired and Oxy-Fuel Turbine Applications (TITs >1300ºC (~1370ºF)). Focus: Film Cooling*

Initiate Oxide Dispersion Strengthened (ODS) Systems Development for NETL-RUA's Micro-Channel Initiative

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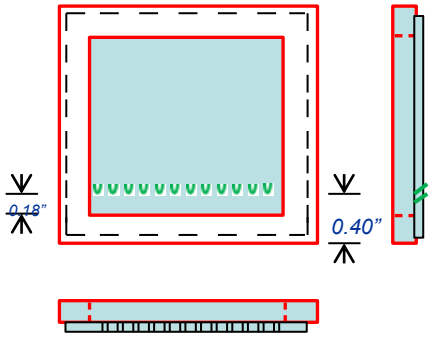
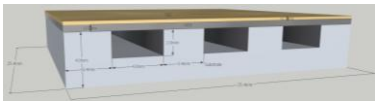
***Major Accomplishments**:*

- *Collaborative CMC Efforts Established with NASA GRC*
- *Collaborative ODS Efforts Established with Ames Laboratory*

Concept:



CMC Film Cooling Coupons w/w-o EBCs



Near Surface Embedded Micro-Channel Concept (NSEMC) with External ODS Layer

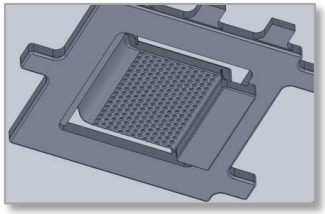
***Current/Future Efforts**:*

- *High Temperature, Pressurized Testing of CMCs with Film Cooling Holes w/w-o Environmental Barrier Coatings (EBCs) in NETL's Aerothrmal Test Facility*
- *Thermal Spray of Nickel-Based ODS on CM247 Channeled Coupons*
- *Thermal Spray of Nickel-Based ODS on Cast CM247 NSEMC Coupons for Hugh Temperature, Pressurizred Testing in NETL's Aerothermal Test Facility*
- *Patent Disclosures*

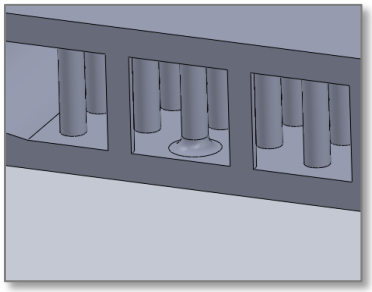
Turbine Thermal Management
– Advanced Internal & Transpiration Cooling –

Objectives: *Development of Novel/Advanced, Commercially Manufacturable, Internal Airfoil Cooling Concepts That Provide Reduced Cooling Flow and Improved Heat Management. These Concepts Include NETL-RUA's Near-Surface Embedded Micro-Channel (NSEMC) Concept and/or Porous Media Thermal Barrier Coatings.*

Major Accomplishments:
- *Collaborative Effort between UPitt and NETL*
- *Demonstrated Achievement of Nearly 5 Times Cooling Enhancement over Baseline Smooth Airfoil Channels*
- *Currently Mikro Systems Inc., Is Manufacturing Cast Coupons for NETL*



Concept:
- *Detached and Fully Bridged Pin Fins*
- *Architectures: Circular; Semi-Circular; Triangular; Diamond; etc.*



- *Conducted Experimental Testing and CDF Modeling*

Current/Future Efforts:
- *Demonstrate Concept Bench-Scale Performance during Exposure of Commercially Manufactured Coupons in NETL's High Temperature, Pressurized Aerothermal Test Facility*
- *Addressing Inclusion in Airfoil Design for Test Campaign 4-6 in PSU's Secondary Flow Rotating Rig*
- *Addressing Integration with Film Cooling Tripod Hole Configurations*
- *Transpiration Cooling Patent Disclosure(s)*

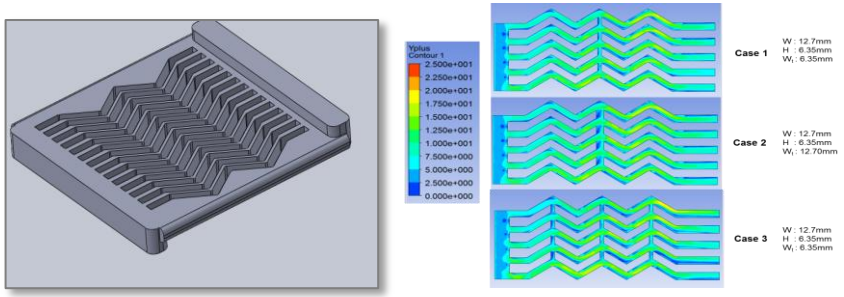
Turbine Thermal Management
–Trailing Edge Cooling –

Objectives: *Evaluation of Novel Airfoil Trailing Edge Channel Designs*

Task Efforts Support Development and Assessment of Trailing Edge Designs in Conjunction with OEMs as Siemens Energy, MikroSystems Inc., and Ames University.

Major Accomplishments:

- *Collaborative Effort between UPitt and NETL*
- *Optimizing Heat Transfer within Zig-ZagTrailing Edge Design*



Concept:

- *Zig-Zag Designs w/w-o Turbulators & w/w-oTrench*
  - *Conducted Experimental Testing and CDF Modeling*
- *Assessed Heat Transfer Characteristics of 28 Airfoil Coupons Fabricated by Mikro Systems Inc. (Triple Impingement; Multi-Mesh; Zig-Zag Configurations)*

- *Conducted CT Imaging at NETL; Demonstrated that Internal Alignment Impacted Heat Transfer Characteristics*

Current/Future Efforts:

- *Coupons Are Currently Being Cast for NETL*
- *Demonstrate Concept Bench-Scale Performance during Exposure of Commercially Manufactured Coupons in NETL's High Temperature, Pressurized Aerothermal Test Facility*
- *Addressing Inclusion in Airfoil Design for Test Campaign 4-6 in PSU's Secondary Flow Rotating Rig*

Turbine Thermal Management
– Film Cooling –

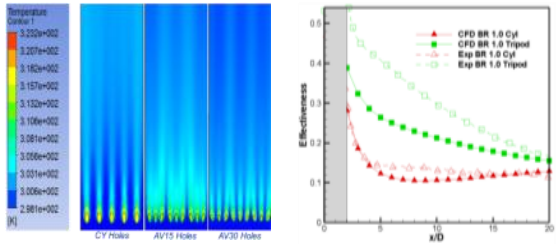
Objectives: *Evaluation of the Performance of the Tripod Hole Film Cooling Concept with Comparison to Current/Baseline Film Cooling Hole Configurations*

Assessment Includes Bench-Scale Testing Using Flat Surfaces, Low Speed Cascades, and Testing in NETL's Aerothermal Test Facility

Commercial Manufacturability of the Tripod Hole Design Is being Addressed, as well as Associated Local Thermal Stress, Creep and Fatigue Issues on Structural Material Stability during Extended Operation in Advanced Engine Gas Passages

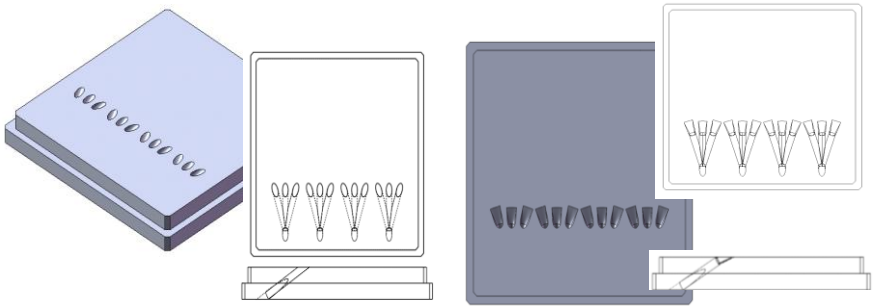
Major Accomplishments:

- *Collaborative Effort between VT and NETL*
- *Demonstrated a 50% Reduction in Film Cooling Flow Usage with the Tripod Hole Configuration*



(a) Temperature Contours (b) Laterally Averaged Effectiveness

Concept:



1st Design - Tripod 15 *2nd Design - Shaped(5) Tripod(15)*

- *Conducted Experimental Testing and CDF Modeling*

Current/Future Efforts:

- *Coupon Designs Are Currently Being Cast for NETL*
- *Demonstrate Concept Bench-Scale Performance during Exposure of Commercially Manufactured Coupons in NETL's High Temperature, Pressurized Aerothermal Test Facility*
- *Addressing Integration of Tripod Film Cooling Holes with Internal and NSEMC Cooling Configurations*
- *Addressing Inclusion in Airfoil Design for Test Campaign 4-6 in PSU's Secondary Flow Rotating Rig*

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Turbine Thermal Management
– Concept Manufacturing –

The Need Is Perceived by Industry that Each Cooling Concept or Design Must Be Commercially Manufacturable in Order to Warrant Continued Research, Development and Demonstration Efforts

***Objectives**: Establish Capabilities for Commercial Manufacturing of Test Coupons with Advanced NETL-RUA Aerothermal Designs and Material Systems*

***Major Accomplishments**:*

- *Collaborative Effort between NETL and Mikro Systems Inc.*
- *No Issues Were Identified by Mikro Systems Inc., for Casting of Parts*
- *Chamfering of Edges Identified as Part of the Casting Production Process*
- *Coupons Will Be First-of-a-Kind Produced Via Casting with Intricate Internal Cooling Features*

Concept:

- *Based on Experimental Testing and CDF Modeling Initial Designs Were Identified for Casting Using Mikro Systems Inc., TOMO Process*

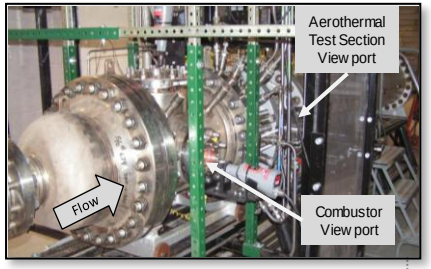
***Current/Future Efforts**:*

- *CM247 Fully Bridged Pin-Fin and Detached Pin-Fin Coupons Being Cast*
- *CM247 Tripod Hole Coupons Being Cast*
- *Additional Effort Is Being Directed to the NSEMC Design Prior to Casting Consideration*
- *Casting of 1.2-inch Blades Being Assessed with Incorporation of Advanced Cooling Configurations*

Turbine Thermal Management

– NETL Aerothermal Test Facility –

The NETL Aerothermal Test Facility Is a High Temperature, Pressurized Test Facility That Is Capable of Providing Realistic Gas Turbine Flow Conditions for Bench-Scale Assessment of Advanced Airfoil Cooling Concepts for Use in Next Generation Land-Based Gas Turbines



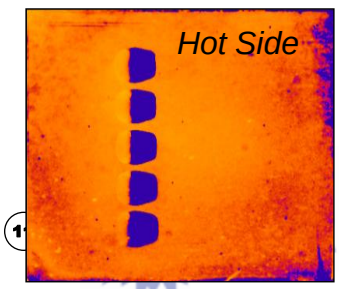
***Objectives**: Conduct Bench-Scale Testing of Manufacturable Aerothermal Cooling Architectures under Realistic Gas Turbine Conditions to Quantify the Benefit of Advanced Cooling Configurations*

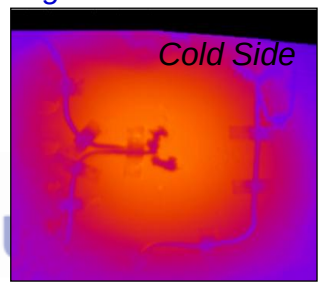
***Major Accomplishments**:*

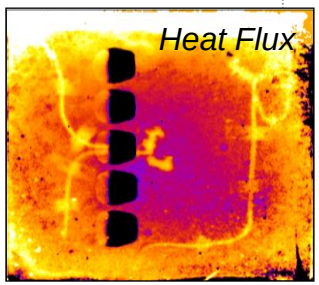
- *Rig Validation and Improvement*
  - *A Method to Quantify Necessary Improvements in Cooling Effectiveness Was Developed*
  - *Overall Effectiveness Increased with a Decrease in Pressure and an Increase in Blowing Ratio*
  - *Heat Flux Appeared to Decrease with a Decrease in Pressure and an Increase in Blowing Ratio*
  - *Comparisons with CFD Showed That Radiation Had a Significant Effect on Experimental Results*

Concept:

- *Optical Measurements Were Made on the Hot and Cold Sides of the Test Article for Each Condition*
- *Each Camera Was Calibrated with a Blackbody Source to Determine Temperature from Calculated Emitted Intensity*
- *Heat Flux Measurements Were Made Assuming 1-D Conduction through the Test Article*







***Current/Future Efforts**:*

- *High Temperature, Pressurized Testing of*
  - *CMC (Ceramic Matrix Composite) Coupons (NASA GRC)*
  - *Trailing Edge Coupons: Zig-Zag; Triple Impingement; Multi-Mesh*
  - *CM247 Coupons (Mikro, NETL, UPitt, VT)*
  - *Detached and Fully Bridged Pin-Fin Internal Cooling*
  - *Trailing Edge Cooling*
  - *Near Surface Embedded Micro-Channel Cooling*
  - *Tripod Hole Film Cooling*
    - *Haynes 230: Shaped Hole Configuration*

Turbine Thermal Management
– Secondary Flow Rotating Rig –

***Objectives**: Design, Development, Construction and Operation of a World-Class Secondary Flow Turbine Rotating Rig Test Facility to Reduce Fuel Usage by an Order of Magnitude or More*

Development of Disruptive New Designs in Sealing the Interfaces between Stationary and Rotating Airfoil Components to Increase Turbine Efficiencies

The Facility Will Consist of a Section of a Turbine Including a Vane/Blade/Vane, which Is Referred to as a 1.5-Stage Turbine that Will Operate at Conditions Replicating a Modern Gas Turbine Engine

Concept:

Task 5.1 – Facility Development

- *Task 5.1.2 – Large Item Procurement*
- *Task 5.1.3 – Rig Design*
- *Task 5.1.4 – 1.5-Stage Test Section Design*
- *Task 5.1.5 – Test Section Component Procurement*
- *Task 5.1.6 – Building Modifications*
- *Task 5.1.7 – Rig Construction*
- *Task 5.1.8 – Bench-Top Section Assembly*
- *Task 5.1.9 – Control Room Infrastructure*
- *Task 5.1.10 – Test Section Shakedown*
- *Task 5.1.11 – Rig Shakedown*

***Current/Future Efforts**:*

- *M1Peer Review Response Submitted 12/14/12*
- *Design of the Rotating Rig Facility Completed*
- *New Offices for the Penn State Project Team: November 2012*
- *Facility Cooling System Anticipated Delivery Date: February-March 2013 Timeframe*
- *Magnetic Bearing System Purchase Order Anticipated End of January 2013 Submittal*
- *Procurement of New Kahn Dynamometer System. Purchase Oder Submitted to PSU Mid December 2012*
- *Purchase Order for Telemetry System to be Submitted to PSU Procurement Services*
- *Solid Modeling of Facility and Rig Ductwork Updates to Include Primary and Secondary Flow Ducts, Settling Chamber Designs, By-Pass Duct Systems, and Support Structures*
- *Detailed Instrumentation Plan On-Going*
- *Renovation of the Facility Building Complete. Completion Time Estimate for Entire Electrical Installation Is February 2013*
- *CO_2 Gas Concentration Analyzer Purchased. Methodology to Benchmark Accurate gas Sampling On-Going*
- *Conduct of Test Plan: Inclusion of Advanced Aerothermal Cooling Concepts*

Turbine Thermal Management
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Dr. Geo Richards, ORD Focus Area Lead
Mr. Ed Robey, RES Activity Manager

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Dr. Joe Grady, Dr. Ram Bhatt, Dr. Virram Shyam, NASA GRC

Stakeholder's Review Panel
Aerothermal and Heat Transfer:
- *Dr. Ron Bunker, GE*
- *Dr. John Marra, Siemens Energy*
- *Dr. Klaus Braun, SwRI*
- *Dr. Jim Heidmann, NASA GRC*
- *Dr. Atul Kohli, PW*
- *Dr. Dick River, WPAFB*
- *Dr. Jim Downs, FTT*
- *Dr. Eli Razinsky, Solar Turbines*
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Turbine Thermal Management
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