Materials and Component Development for Advanced Turbine Systems

22nd Annual Conference on Fossil Energy Materials

M. A. Alvin
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Omni William Penn Hotel
Pittsburgh, PA

National Energy Technology Laboratory

University of Pittsburgh, West Virginia University
Coatings for Industry, Howmet International
Westinghouse Plasma Corporation, Praxair Surface Technologies

DOE FE Coal Program
— Goals —

Advanced Power Systems

By 2010 Develop Advanced Coal-Based Power Systems Capable Of 45-50% Efficiency at <$1000/kw

Near Zero Emissions Energy From Coal

By 2015 Demonstrate Future Coal-Based Energy Plants That Offer Zero Emissions (Including CO_2 with Multi-Product Production (Electricity & H_2)

	Syngas Turbine 2010	Hydrogen Turbine 2015	Oxy-Fuel Turbine 2010	Oxy-Fuel Turbine 2015
Combustor Exhaust Temp, °C (°F)	~1480+ (~2700+)	~1480+ (~2700+)		
Turbine Inlet Temp, °C (°F)	~1370 (~2500)	~1425 (~2600)	~620 (~1150)	~760 (~1400) (HP) ~1760 (~3200) (IP)
Turbine Exhaust Temp, °C (°F)	~595 (~1100)	~595 (~1100)		
Turbine Inlet Pressure, psig	~265	~300	~450	~1500 (HP) ~625 (IP)
Combustor Exhaust Composition, % Component Life: 30,000 hrs	CO_2 (9.27) H_2O (8.5) N_2 (72.8) Ar (0.8) O_2 (8.6)	CO_2 (1.4) H_2O (17.3) N_2 (72.2) Ar (0.9) O_2 (8.2)	H_2O (82) CO_2 (17) O_2 (0.1) N_2 (1.1) Ar (1)	H_2O (75-90) CO_2 (25-10) O_2, N_2, Ar (1.7)

NETL

R.A.Dennis, "FE Research Direction – Thermal Barrier Coatings and Health Monitoring Techniques," Workshop on Advanced Coating Materials and Technology for Extreme Environments, Pennsylvania State University, State College, PA, September 12 - 13, 2006

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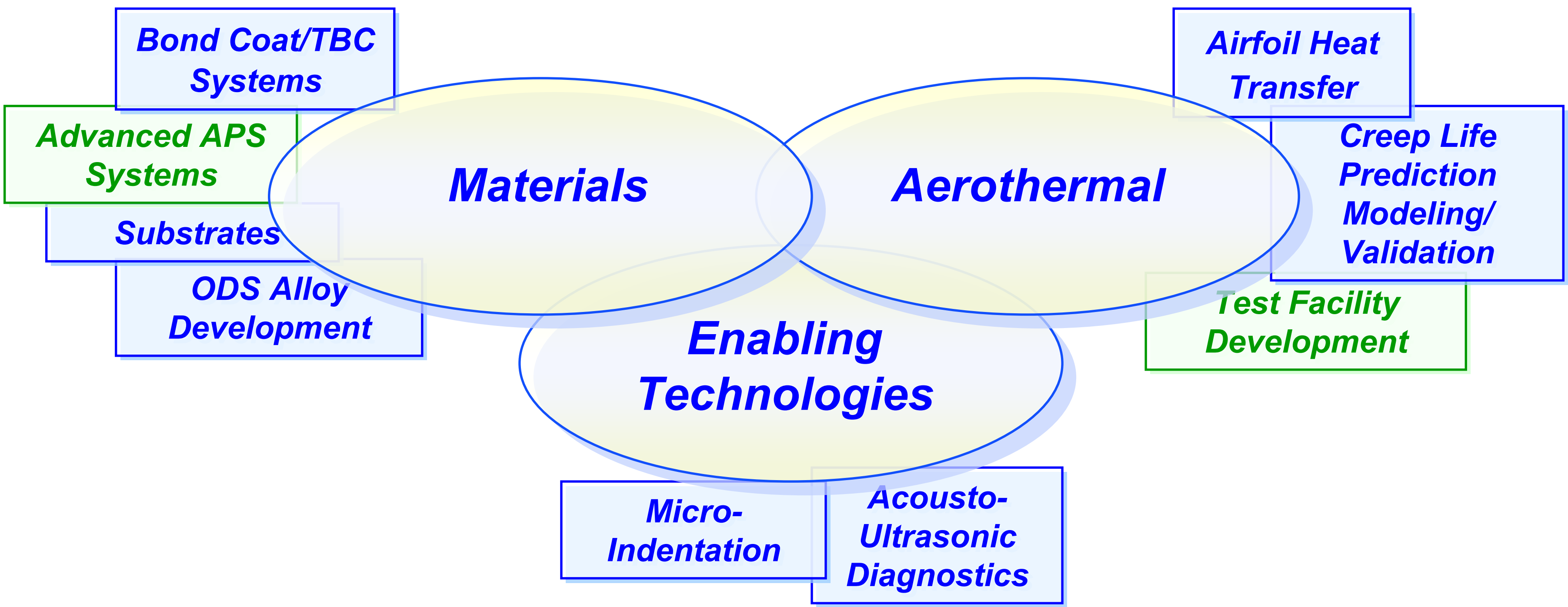


Development of Spray Coated Bond Coat Systems

Objectives

- Development of Advanced Bond Coat/TBC System
  - Integration of BC/TBC YSZ into a Gradient Architecture
  - Modification of a Commercial Spray Coating Technology
  - Achieve Performance and Durability of SOTA Systems
  - Achieve Performance at >1100°C
- Establish Broad-Based Expert Collaboration Effort
- Achieve FE Goals via Integration of Enabling Technology Areas

Accomplishments

- NETL-A Achieved ~50-63% of Thermal Cycle Life to Failure in Comparison to Pt-Al Bond Coat System
  - Relatively Smooth External BC Surface Resulted; BC Strengthening Considered Via Refractory Elements
- NETL-A1/EBPVD YSZ Exceeded MCrAlY/EBPVD YSZ 1100°C Cycle Life to Failure (560 vs 140 Cycles)
- NETL-A1/EBPVD YSZ Achieved ~61% of the 1100°C Cycle Life to Failure in Comparison to Pt-Al/EBPVD YSZ System on René N5 (560 vs 910 Cycles)
- Completed 3 Test Campaigns at WPC Totaling 406 hrs of Unattended Operation at 1100°C
  - HTTF Confirms Enhanced Performance of Pt-Al/EBPVD Systems
  - HTTF Confirms Early Failure of MCrAlY/EBPVD Systems (97 hrs)

Current Focus

- Materials Development: CFI, Howmet
- René N5; Haynes 230
- Bottom Loading Furnace Testing at UPitt (900, 1100°C)
- High Temperature Thermal Flux Testing (HTTF) at Westinghouse Plasma Corp
  - 1100°C
  - 500 rpm

Forward Efforts

- Integration of BC/TBC: Assessment of Surface Specifications for APS Application
- HT Thermal Flux Testing of BC/APS Systems
- Optimization of NETL-A Relative to SOTA Systems
  - Reactive Element Additions, Concentrations
- Assessment of Oxidation Stability of NETL-A Relative to SOTA MCrAlY BCs
- Inclusion of OEM (Pratt & Whitney) Materials

NETL

M.A.Alvin, J.Klotz, K.Klotz, F.Pettit, M.Yanar, G.Meier, R.Honick, K.Murphy, T.Hansen, R.Grunstra, I.Martorell, S.Dighe

Development of Advanced APS TBCs

Objectives

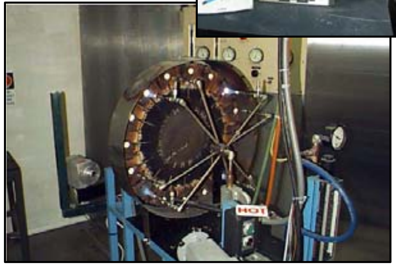
- ***Improve Adherence, Performance, Viability of Thick APS-YSZ TBCs on Ni-Based Superalloys for Turbine Blades, Vanes, and Combustor Components***
- ***Establish Processing/Microstructure/Property Interrelationships***
- ***Control 7YSZ-APS Thickness, Density, Pore and Crack Morphology***
- ***Utilize Conventional and High Purity YSZ***
- ***Optimize NiCoCrAlY Bond Coat (Variation in Y Content & Surface Roughness)***
- ***Conduct Cyclic Oxidation & JETS Testing***
- ***Define Plasma Sprayed TBC Degradation Mechanisms***

Accomplishments

- ***For IN 718 JETS Testing, Demonstrated Viability of 375μm APS after 2000 Cycles − TBC Surface Temp: 1300°C-450°C; Through Wall Gradient: 1300°C-1000°C***
- ***Demonstrated TBC Through Wall Gradient (Δ°C): 350°C/375 μm; 395°C/750 μm; 550°C/1125 μm***
- ***For High Purity YSZ, Demonstrate Sintering Resistance***
- ***Demonstrated Failure in YSZ Is Primarily along Splat Boundaries***
- ***All TBC Exhibit Edge Cracking; Two Failure Modes***
  - ***For >1 mm APS, Cracks Develop in Lower 20% of TC (20 Cycles @ 1100°C)***
  - ***For < 1mm APS, Cracking Associated with BC Oxidation (140-220 Cycles @ 1100°C)***

Current Focus

- ***Materials Development: Praxair Surface Technologies***
- ***IN 718; René N5 (GE Aircraft Engines); HA 188***
- ***Bottom Loading Furnace Testing (1100°C)***
- ***JETS Test Rig (1400°C-450°C)***



Forward Efforts

- ***Continue Microstructural Characterization/Optimization***
- ***Establish Mechanical Properties: Modulus of Elasticity; Fracture Strength as F(T); Thermal Conductivity of As-Processed and Tested Matrices***
- ***Define Optimized BC/TC Processing Parameters***
- ***Compare Performance to SOTA EBPVD & Segmented Plasma Spray Coatings***
- ***Prepare Solution Spray Precursor TBCs (Univ.Conn)***

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G.Meier, F.Pettit, M.Helminiak, N.Yanar, T.A.Taylor, B.Nagaraj, M.A.Alvin

Substrate Development

Objectives

- *Evaluate Experimental Aero-Engine Refractory Metal-Based Alloys for Use in Advanced Land-Based Gas Turbine Applications (1300-1500ºC)*
- *Evaluate Corrosion/Oxidation Resistance in 1300-1450ºC Moist vs Dry Environments*

Accomplishments

- *Completed Literature Review*
- *Initial Nb-Based Superalloy Button Generated*

Current Focus

- *Northwestern Univ. Nb-Based Matrix: 58Nb-15Al-8Y-7Pt-6Ti-3Hf-3Cr at%*

Forward Efforts

- *Identify Potential Alloy Development Strategies to Improve Performance*
- *Produce Alloys at NETL*

Pittsburgh Materials Technologies (PMT)

O.Dogan, D.Alman, P.Jablonski

ODS Development

Objectives

- *Investigate Alloying Effects on Dispersion Stability and Oxidation Resistance of Nickel-Based ODS Alloys with ODS Powder Mixtures Prepared by an Innovative Mechano-Chemical Bonding Technology*

Accomplishments

- *Effort Recently Initiated*

Current Focus

- *Establish Suitable Processing Conditions to Achieve a Homogenized ODS Powder Mixture Comparable to That Achieved with Mechanical Alloying*
- *Conduct Computational Simulations to Facilitate the Design of High Strength and Excellent Oxidation Resistance ODS Alloys*
- *Assess ODS Alloy Mechanical Behavior Using Micro-indentation*

Forward Efforts

NETL

B.S.Kang

Micro-Indentation Testing

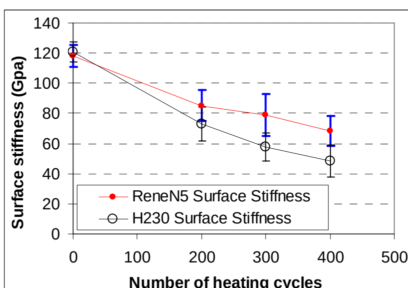
Objectives

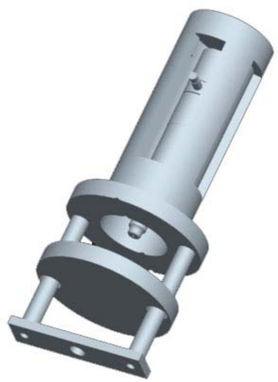
- *Develop Micro-Indentation Technique for Determining Mechanical Property Degradation and Debonding/Spallation of TBC Systems*
- *Develop Portable Test Unit*
- *Demonstrate Feasibility of Technique/Equipment on As-Manufactured and Bench-Scale Tested Commercial and NETL BC/TBC Systems*

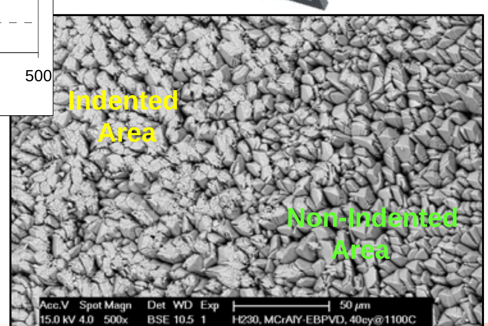
Accomplishments

- *Demonstrated Young's Modulus of ~200-210 GPa for Haynes 230, and ~130-150 GPa for René N5*
- *Loss of Surface Stiffness Demonstrated for Bench-Scale NETL-1 BC Systems. After 400 Thermal Cycles at 1100°C, Surface Stiffness Was Reduced By ~41.7% on René N5, and ~62.5% on Haynes 230. Data Strongly Correlated with Weight and Microstructural Changes.*
- *Complete Contour Profiles Developed for Full TBC Systems on René N5 and Haynes 230. Within the Initial 20 Thermal Cycles at 1100°C, Surface Stiffness Was Reduced By ~2.8% for APS/MCrAlY, and ~15.1% for EBPVD/MCrAlY Systems.*

Current Focus







Forward Efforts

- *Construct and Demonstrate Capability of a Prototype Hand-Held Portable Unit*
- *Demonstrate Technique Feasibility for Curved Surfaces*
- *Initiate Prototype High Temperature Unit Development (Initially at 600-800°C; Follow-On to ~1100°C)*
- *Assess Material Stiffness Property Changes on Thermally Aged Materials: Bench-Scale Flat Coupons and Tubes; Field-Tested Materials If Available*

NETL

B.S.Kang, C.Feng, J.M.Tannenbaum, M.A.Alvin

Non-Linear Acousto-Ultrasonic Diagnostics

Objectives

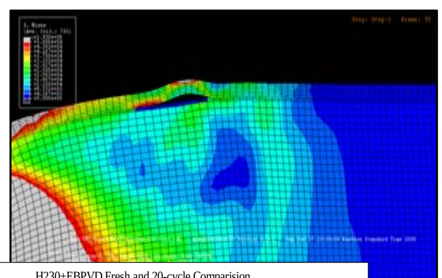
- *Develop Acousto-Ultrasonic Sensor to Detect Potential Interface Delamination and/or Changes within TBC Systems*
- *Demonstrate Sensor Feasibility as a Function of Extended 1100℃ Cyclic Oxidation:*
  - *NETL BC/René N5 and Haynes 230*
  - *SOTA YSZ-APS-EBPVD/MCrAlY/René N5 and Haynes 230*
- *Develop FEA Wave Propagation Simulations, and Correlate/Validate Experimental Data*

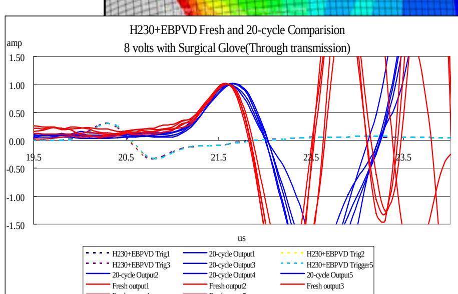
Accomplishments

- *Thermally Cycled NETL BC – Initial 400 Cycles at 1100℃*
  - *René N5: Slight Shift in Waveform Reflecting Minor Crack Formations and Spalled Areas*
  - *Haynes 230: Marked Differences in Waveform and Travel Time Indicative of Significant Crack Formations and Spallation of Chromia and BC*
- *Thermally Cycled SOTA TBC Systems − Initial 20 Cycles at 1100℃*
  - *Pitch & Catch Analysis: Waveforms Shifted While Arrival Times Coincide with As-Manufactured Matrix*
  - *Through Transmission Analysis: Waveforms Shifted and Displayed Distinctive Differences from As-Manufactured Matrix*
- *Nonlinear Acoustic Effect Computed Using FEA with Void and Delamination Simulation*

Current Focus

- *Configuration: Miniature Piezoelectric Sensors; Dry Contact; Laser Vibrometer and Spectrum Analyzer*
- *FEA Abaqus & Algor Wave Propagation Simulations*





Forward Efforts

- *Utilizing Current Equipment, Monitor Acousto-Ultrasonic Signals during Extended, 1100℃, Cyclic Oxidation of SOTA YSZ-APS(EBPVD)/MCrAlY/René N5(Haynes 230) Systems*
  - *Correlate with NETL 1100℃ Cycle-to-Failure Data (100-140 Cycles EBPVD/MCrAlY; 200-240 Cycles APS/MCrAlY)*
  - *Address Architecture Design and Material Property Variations*
- *Assess Use of Eddy Current Probes*
- *Develop Portable Device for In-Situ Application (2-Sensor; 3-Sensor Configuration)*

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R.Chen, B.Zhang, T.Fu, M.A.Alvin

Airfoil Heat Transfer Modeling

Objectives

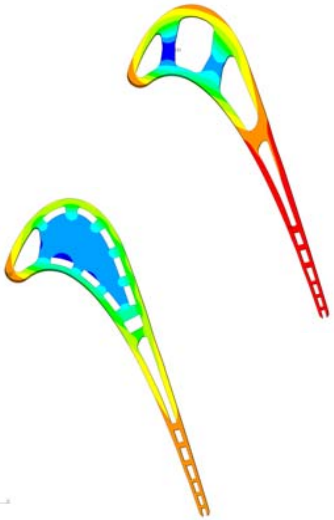
- *Develop 2D & 3D Computer Simulations Identifying Temperature and Heat Transfer Distributions over Generic Airfoil Configurations*
- *Assess the Impact Various Cooling Configurations on Temperature, Stress, Strain Characteristics under Varying Load Conditions*
- *Evaluate Aerothermal Effects of Various Working Fluid Compositions: Air (N_2), H_2O, H_2O/CO_2*
- *Identify Optimal Cooling Configurations and Guidelines to Lower Temperature Magnitude, and Minimize the Temperature Gradient and Associated Stress*

Accomplishments

- *P,T Distribution for Hydrogen-Fired and Oxy-Fuel Airfoil Exhibit Similar Trends to Those Under Convection Dominated Flow*
- *External Gas with Higher Steam Content Leads to Higher Heat Transfer Coefficient*
  - *Oxyfuel is ~40% Higher Than Hydrogen-Fired*
- *If Complete TBC Spallation Occurs, Surface Metal Temp Increase of ~200-250°C Is Projected*
- *Internal Cooling h_c Significantly Affects Substrate Metal Temperature*
  - *3-Fold Increase in Internal h_c Decreases Metal Surface Temp ~150-200°C for Hydrogen-Fired Airfoil*
- *Skin Cooling Reduces Metal Surface Temp ~50-100°C*
- *Internal Heat Transfer Coefficients Are Gradually Reduced from Leading Edge towards Trailing Edge*

Current Focus

- *Hydrogen-Fired and Oxy-Fuel Airfoils*
- *FEA Modeling Using FLUENT & ANSYS*
- *Serpentine (Reference NASA E³) & Skin (Super) Cooled Architectures*
- *Matrix Parameters:*
  - *Substrate: CMSX-4*
  - *250 μm Topcoat*
  - *10 μm TGO*
  - *100 μm Bond Coat*
- *Coolant: Steam &/or CO_2*
- *Film Cooling*



Forward Efforts

- *External Cooling*
  - *Shape-Hole Film Cooling*
  - *Pulse (Unsteady) Film Cooling*
- *Conjugate Heat Transfer Analysis*
  - *Combined Internal & External Thermal Modeling*
- *Structural & Coating Damage*
- *Complement/Integrate with Ames Aerothermal Effort*
- *Additional Consideration*
  - *Transpiration or Effusion Cooling*
  - *Internal Cooling*
    - *Surface Heat Transfer Enhancement*
    - *Advanced Internal Cooling Configurations*
    - *Skin Cooling, "Double Wall" Cooling*

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M.K.Chyu, S.Siw, V.Karaivanov, W.Slaughter, D.Mazzotta, M.A.Alvin

Airfoil Life Prediction Modeling

Objectives

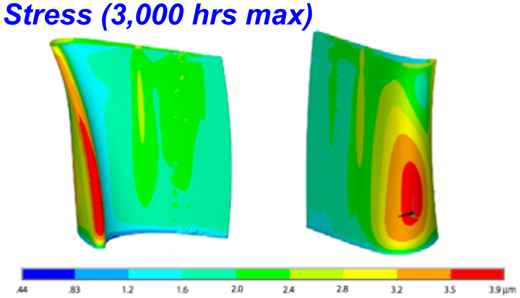
- *Develop 3D Finite Element Damage Mechanics Model*
  - *Define Local Creep Behavior over the Entire Airfoil for Hydrogen-Fired & Oxy-Fueled Applications*
  - *Assess Cumulative Creep Damage & Its Interactions with Corrosion-Assisted Fatigue Damage*
  - *Predict Airfoil Life*
- *Conduct Isothermal/Constant Load Thermal-Mechanical Testing to Validate Damage Mechanics Variables Pertaining to Both the Substrate Metal and TBC*
- *Assess Fatigue Crack Initiation & Growth, and Impact on Structural/Mechanical Integrity of the TBC*

Accomplishments

- *Creep Damage Model Integrated into FEA Package (ANSYS)*
  - *Includes Effect of Stress Relaxation*
  - *Centrifugal Load (Coating Mass): 3,600 rpm; Base Radius: 0.6 m*
  - *Internal T_c=527°C; h_c=1,000-3,000 W/m²K*
  - *250 µm YSZ; 2 µm TGO; 125 µm Bond Coat; 1,000 µm Substrate*
- *Incorporated Compact TGO Growth, Inward Growth & Phase Depletion into Model at Airfoil Outer Boundary*
- *Hydrogen-Fired: After 1,000 hrs, Limited Creep Damage Projected along Pressure Surface of Middle-Rib; Extensive Middle Rib Creep Damage after 4,000 hrs with Damage along Suction Surface Rib near Trailing Edge*
- *Oxy-Fuel: After 10 hrs, Extensive Creep Damage Projected along Suction Surface Near Leading Edge, Middle Rib Pressure Surface, & at Airfoil Base*

Current Focus

- *Hydrogen-Fired and Oxy-Fuel Airfoils*
- *ProEngineer, ANSYS, MatLab; Serpentine (Reference NASA E³) Architecture*
- *Model Validation: Bench-Scale Isothermal Testing Using René N5/MCrAlY/APS TBC at 900-1100°C with Applied Uniaxial Compressive Stress (3,000 hrs max)*



Forward Efforts

- *Apply Model to Assess Viability of Alternate Cooling Configurations (Skin (Super) Cooled)*
- *Account for Time & Temperature Dependence on YSZ Properties: YSZ Sintering & Thermal Conductivity*
- *Address Combinations of TBC Thermal Conductivity and Internal Convective Cooling Strategies That Are Most Effective at Mitigating Damage for Advanced Turbine Applications*
- *Incorporate Models for Substrate Fatigue Damage Mechanisms*
- *Incorporate Models for Additional Coating Layer Damage Mechanisms*
- *Experimentally Assess Substrate Deformation Dependence in Coating Layer Damage Models*

W.Slaughter, V.Karaivanov, S.Siw, M.K.Chyu, M.A.Alvin

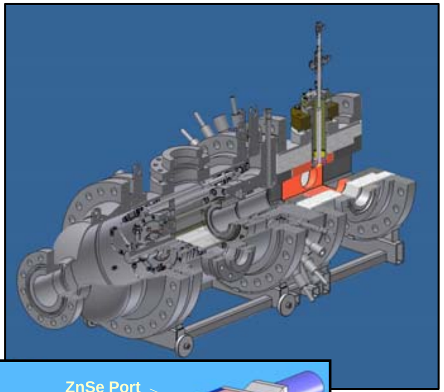
Aerothermal Test Facilities

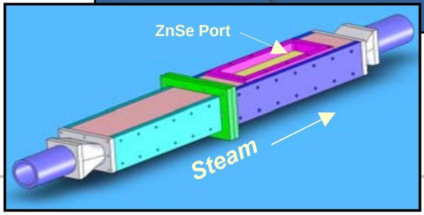
Objectives

- Experimentally Identify Aerothermal Cooling Improvements for Hydrogen-Fired and Oxy-Fueled Turbines Where Maximum Targeted Inlet Temperatures Are 1425°C and 1760°C, Respectively
- Optimize Film Hole/Slot Configurations
- Develop Optimal External Cooling Configurations
  - Assess Heat Transfer; Micro-Scale Cooling Hole Fabrication Including Stress Reduction & High Yield Manufacturability; Proper Coolant Selection & Flow Distribution
- Demonstrate Materials & Configuration Feasibility

Accomplishments

- Experimental Test Facility Designs Completed; Fabrication In Progress
  - External Film Cooling (NETL-Mgn)
  - Internal Steam Cooling (UPitt)





Current Focus

- Construction, Assembly, & Shakedown of Aerothermal Test Facilities
- Initiated Bench-Scale Testing in Q1/Q2-FY09
- External Cooling
  - Rectangular Haynes 230 Coupons
  - 1000°C; 5 atm
  - Gas Flow: $N_2/H_2O/O_2/CO_2$
  - Back-Side Air Cooled
- Internal Cooling
  - 20 psig Steam (& CO_2)

Forward Efforts

External Cooling

- Benchmark Convection Heat Transfer & Film Cooling Under Realistic Turbine Conditions
- Address Impact of Working Fluids on Turbine Performance
- Characterize Effects of Combustor Exhausts on Turbine Stage Heat Transfer
- Explore Innovative Cooling Concepts & Hole Shapes/Arrangements
- Develop Cooling Design Data & Correlations
- Conduct Prototype Testing for Technology Demonstration

Internal Cooling

- Conduct Heat Transfer Testing
- Develop Flow & Heat Transfer Correlation for Steam Cooling
- Assess Heat Transfer for High Aspect Ratio & Narrow Passages
- Evaluate Impact of Passage "Geometry" & Vortex Generators
- Address Materials Degradation near Flow-Solid Interface & Effect on Cooling Performance
- Explore Rotational Effects on Internal Cooling with Steam

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Publications

D. Mazzotta, M. K. Chyu, M. A. Alvin, "Aerothermal Characterization of Hydrogen Turbines," ASME Turbo Expo 2007, Land, Sea and Air, Montreal, Canada, May 14-17, 2007.

C. Feng, M. A. Alvin, B. S-J. Kang, "A Micro-Indentation Method for Assessment of TBC Bond Coat Systems," MS&T 2007 Conference, Detroit, MI, Sept. 2007.

M. A. Alvin, F. Pettit, G. Meier, N. Yanar, M. Chyu, D.Mazzotta, W. Slaughter, V. Karaivanov, B. Kang, C. Feng, R. Chen, T-C. Fu, "Materials and Component Development for Advanced Turbine Systems," EPRI 5th International Conference on Advances in Materials Technology for Fossil Power Plants, FL, Oct 3-5, 2007.

D. W. Mazzotta, S. Siw, V. Karaivanov, W. Slaughter, M. K. Chyu, and M. A. Alvin, "Gas-Side Heat Transfer in Syngas, Hydrogen-Fired and Oxy-Fuel Turbines," ASME Turbo Expo 2008, Gas Turbine Technical Congress and Exposition, Berlin, Germany, June 11, 2008.

V. Karaivanov, D. Mazzotta, W. Slaughter, M. Chyu, and M. A. Alvin, "Three-Dimensional Modeling of Creep Damage in Airfoils for Advanced Turbine Systems," ASME Turbo Expo 2008, Gas Turbine Technical Congress and Exposition, Berlin, Germany, June 12, 2008.

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