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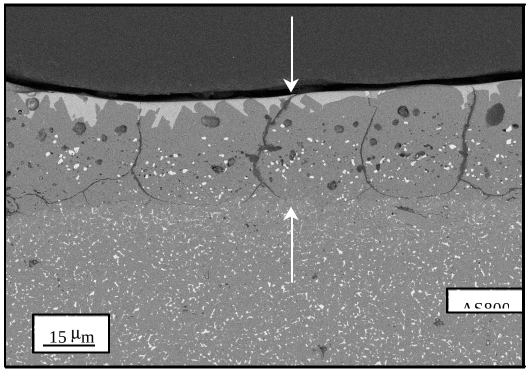
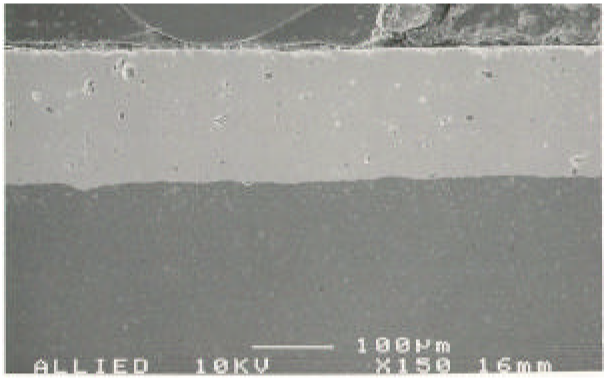
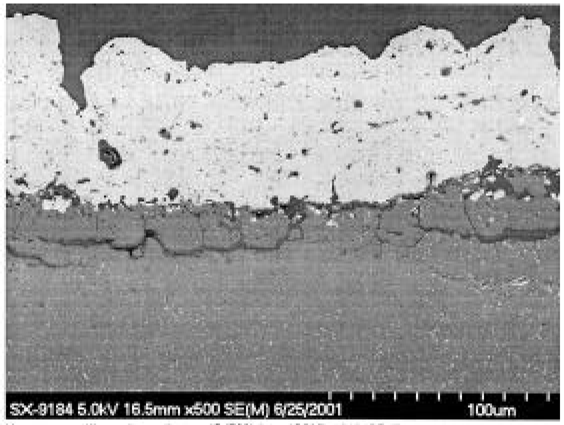
Environmental Barrier Coating Development Challenges





Honeywell Engines, Systems & Services
Dr. Bjoern Schenk
Manager, Strategic Technology



U.S. DOE EBC Workshop
November 6-7, 2002
Nashville, TN, USA

Advanced Technology

Core Team Members

- Honeywell Engines, Systems & Services
  - Dr. Bjoern Schenk, Strategic Technology, Phoenix
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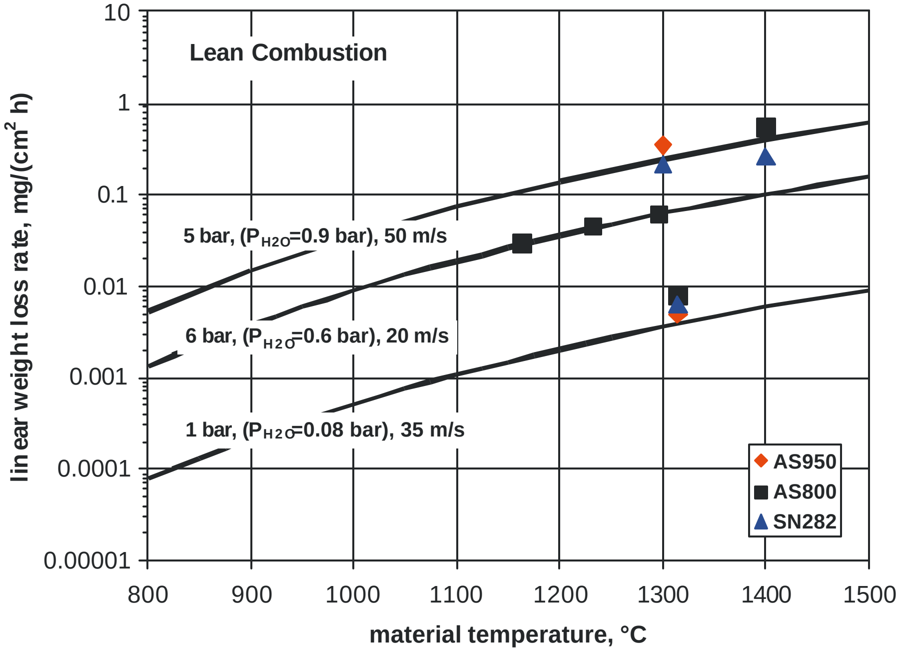
  - Dr. Jim Wimmer, Ceramic Components, Torrance
  - Dr. Chien-Wei Li, Advanced Materials R&D, Morristown
  - Dr. Derek Raybould, Advanced Materials R&D, Morristown
- Fraunhofer Institute for Ceramic Technologies and Sintered Materials (IKTS), Dresden, Germany
  - Dr. Hagen Klemm, Silicon Nitride Materials Development
- Universities
  - Dr. Kathy Faber, Northwestern
  - Dr. Martin Harmer and Dr. Helen Chan, Lehigh
  - Dr. Rishi Raj, UC Boulder
- Various Coating Suppliers
- Oak Ridge National Laboratory
  - Dr. Karren More and Dr. Matt Ferber

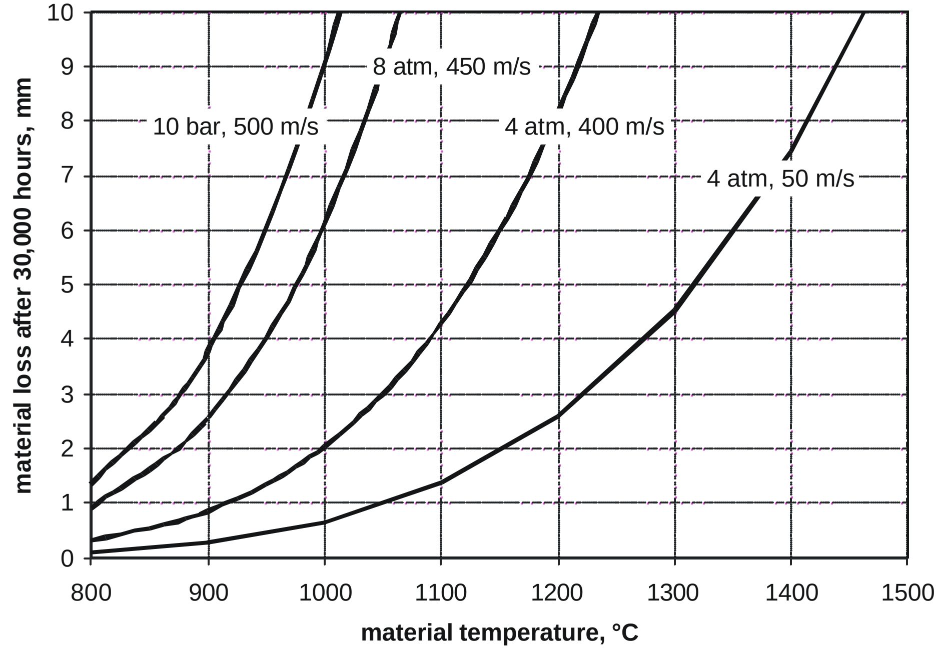
Agenda

- Introduction
- Initial Requirements
- First Generation EBC Development & Evaluation
- Lessons Learned and Future Challenges

Oxidation of Advanced Silicon Nitrides in Gas Turbine Environments

Comparison of Predicted Recession Rates with Experimental Data Obtained by Low Speed Burner Rig Testing

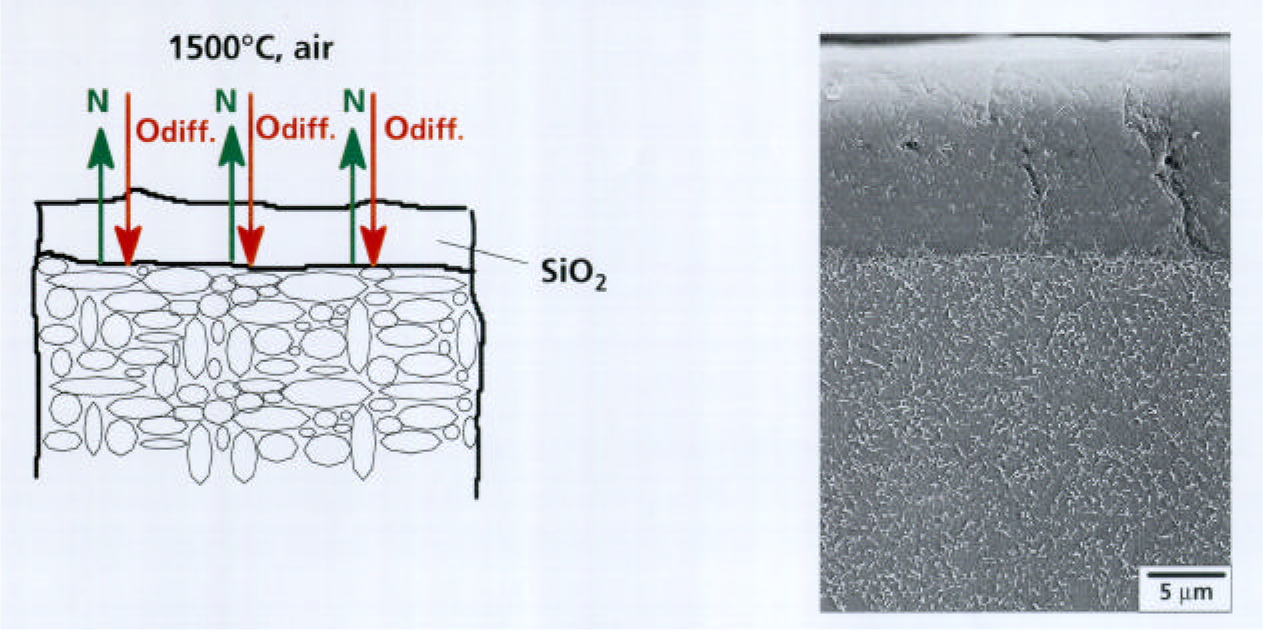




Ceramic hot section components in gas turbine engines are extremely limited by surface recession at typical operating conditions. Extensive coatings research and development needed for successful ceramic gas turbine applications.

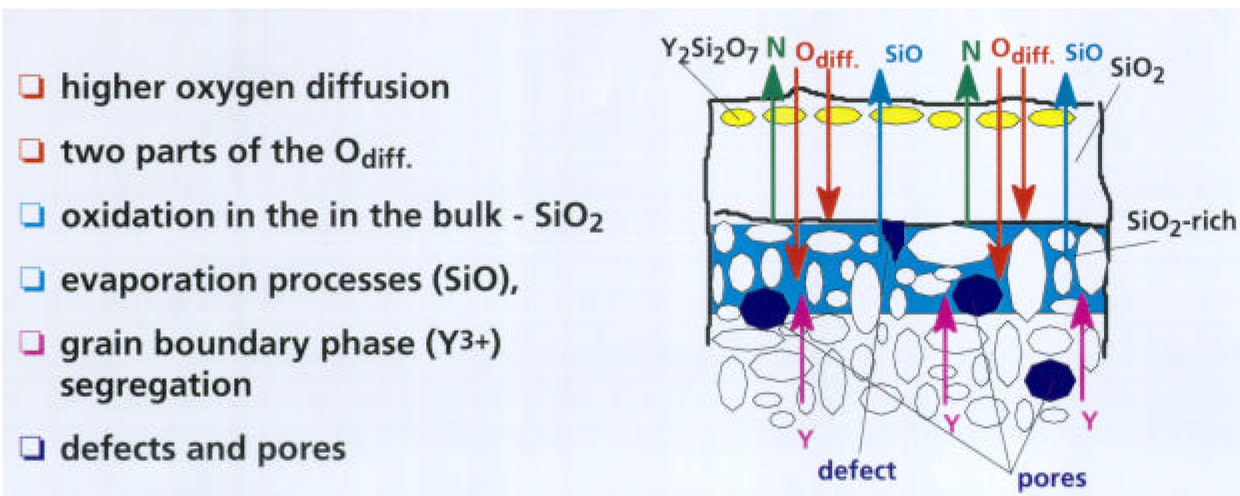
Oxidation of Pure Si_3N_4 in Stagnant Dry Air

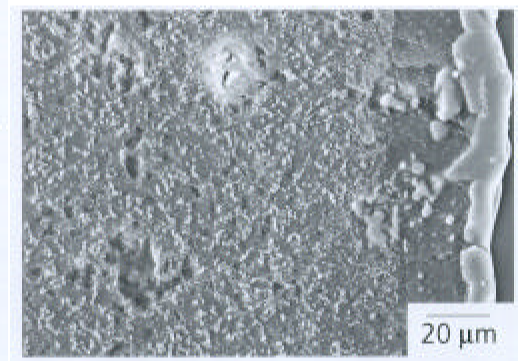
- formation of protective oxidation layer (SiO_2)
- oxygen diffusion as low as possible (pure SiO_2)
- reaction of the oxygen at the interface
- formation of cracks during crystallization
- application problematic (lack of toughness, high flaw sensitivity)



Oxidation of Additive-Containing Si_3N_4 in Stagnant Dry Air

- Additives result in materials with higher flaw tolerance
- additives typically result in degradation of high temperature properties
- additives have a strong influence on oxygen diffusion and reaction of oxygen in the bulk material





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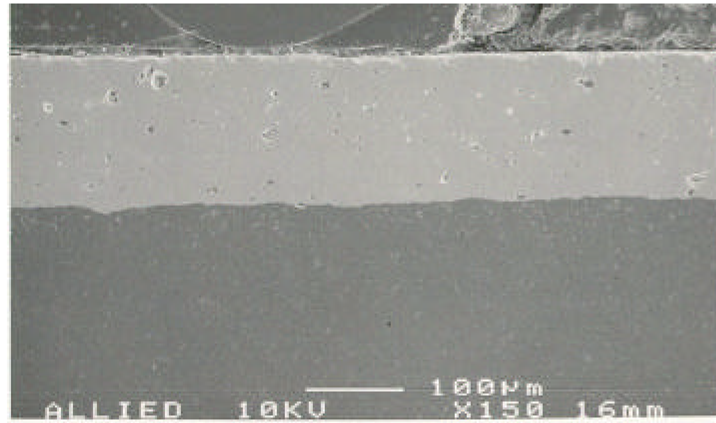
Initial EBC Requirements

- Thermodynamically stable in operating environment up to 1400°C
  - no significant grain growth & phase transformations
  - high stability against reactions with oxygen and water vaporlow vapor pressure at service conditions
- Thermal expansion similar to Si_3N_4 to minimize spallation
- Low modulus to minimize spallation potential
- Good adherence to as-processed silicon nitride component surfaces
- Chemical compatibility to substrate material
- Repeatable thickness, grain size distribution, and porosity
- Minimal impact on substrate strength

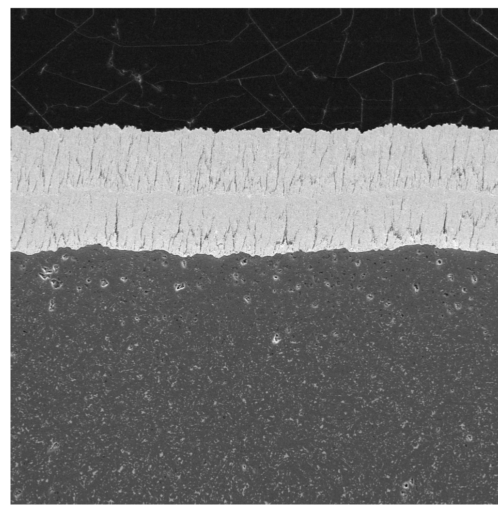
First Generation EBC Has Been Applied by Air Plasma Spray (APS) and EB-PVD

- **Plasma Spray**
  - **Coating is dense**
  - **"Low" temperature b-phase**
  - **Cyclic furnace testing demonstrated good adherence**
- **EB-PVD**
  - **Various trial runs for process optimization conducted**
- **Coatings were thermally treated to characterize grain growth**
- **Coating were thermally cycled to characterize adherence**



APS Ta_2O_5

AS800



EB-PVD Ta_2O_5

AS800

Supplementary IR&D Work on 1st Gen EBC

Motivation

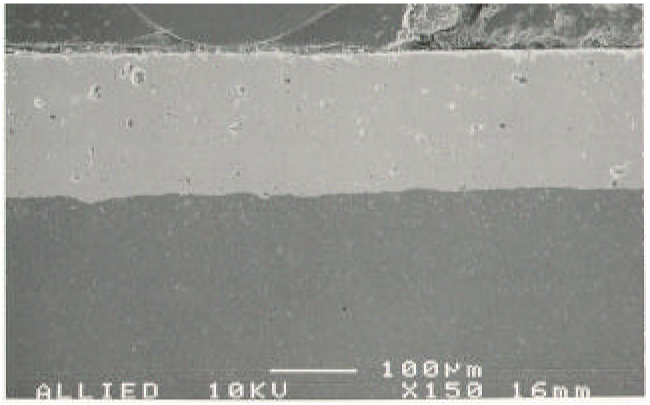
- Control of Phase Transformation
  - Phase Transformation at Elevated Temperatures (>2400°F) Can Induce Cracking
  - Non-Issue for Current Microturbine Applications, but Concern at Higher Temperatures
- Control of Grain Growth
  - Maintain Coating Strength
- Control of Thermal Expansion
  - Match CTE of Silicon Nitride

Accomplishments

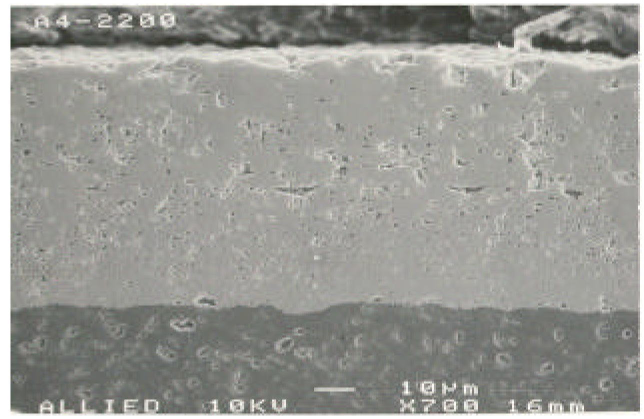
- Promising Grain Growth and Phase Transformation Inhibitors Identified
- Sprayable Powder With Tailored Compositions Demonstrated
  - Three batches were plasma sprayed and exposed to thermal cyclic test
- Tailored Compositions Improved Coating Cyclic Performance at 2400°F
- Keiser Rig Validation Subsequently Conducted

First Generation EBC Development

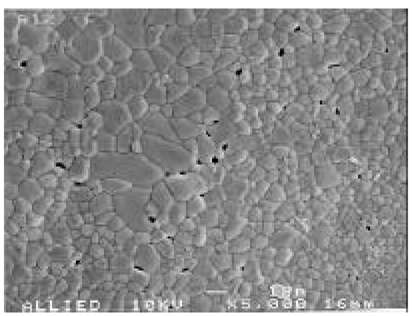
APS EBC after testing at 2200°F/500 h/1000 cycles



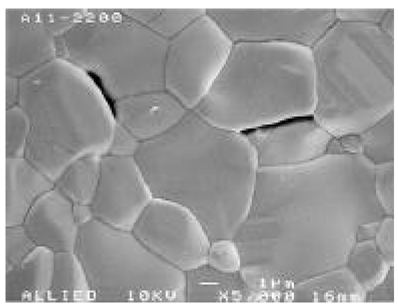
EB-PVD EBC after testing at 2200°F/500 h/1000 cycles



Grain growth of EBC at high temperature

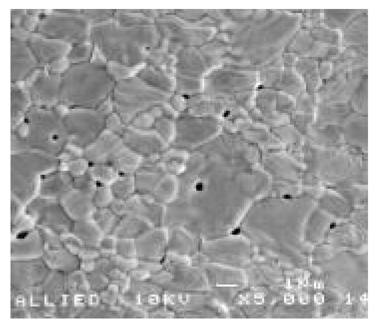


As-deposited (plasma)

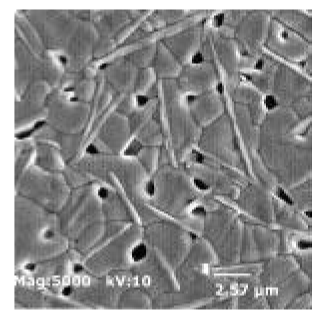


After 500 hours at 2200°F

Control grain growth of EBC by alloying



Composition A



Composition B
(from liquid precursor)

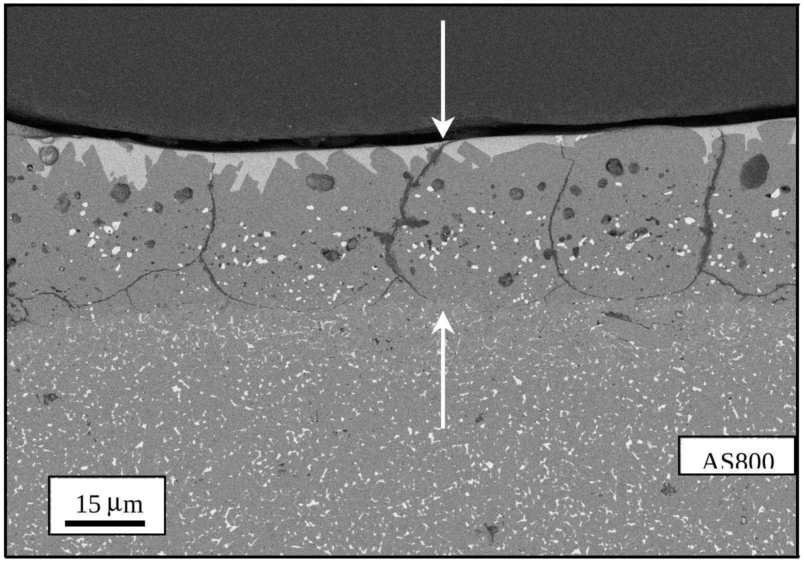
Separate DOE-Funded R&D Program Supports APS Ta_2O_5 Maturation

- **Identify Optimized Plasma Spray Processing Parameters**
- **Fundamental Understanding of Compositional Variations on Microstructure Development**
- **Establish Microstructure-Property Relationship**
- **Characterize and Understand Bonding Strength**

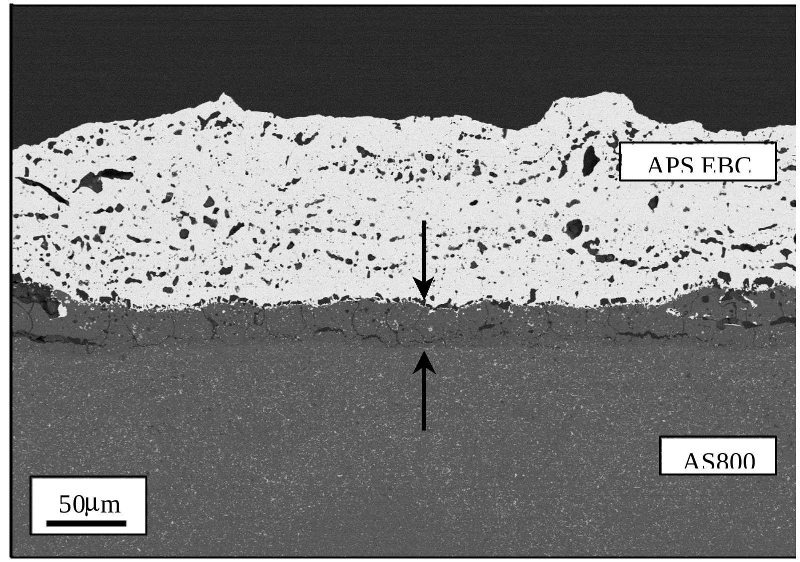
Test Results Suggested That Further EBC Development Is Required

Keiser Rig Testing: 500 h at 2400°F, 2 atm p_{H_2O}

uncoated



coated



- **Cracked cristobalite scale thickness similar on coated and uncoated specimen, but ...**
- **significant volatilization occurred on uncoated surface**
  - **2.5x higher disilicate concentration in silica scale**
- **Ta_2O_5-based EBCs were effective in inhibiting water vapor induced silica scale volatilization**

Lessons Learned
Additional EBC Requirements

- Effective oxygen and water vapor diffusion barrier
- Thermal expansion similar to Si_3N_4 and/or SiO_2 to minimize spallation
- Chemically compatible to SiO_2
- High stability against reactions with oxygen and water vapor, but also all other constituents of and impurities contained in gas turbine combustion gas flow
- Reasonable small particle impact and erosion resistance
- Applicable to complex-shaped components
- Affordable

Latest and future IR&D activities focus on

- better oxygen diffusion barrier capabilities & controlled oxygen reaction
- low cost coating application methods for complex shaped parts
- graded materials development

Detailed Requirements

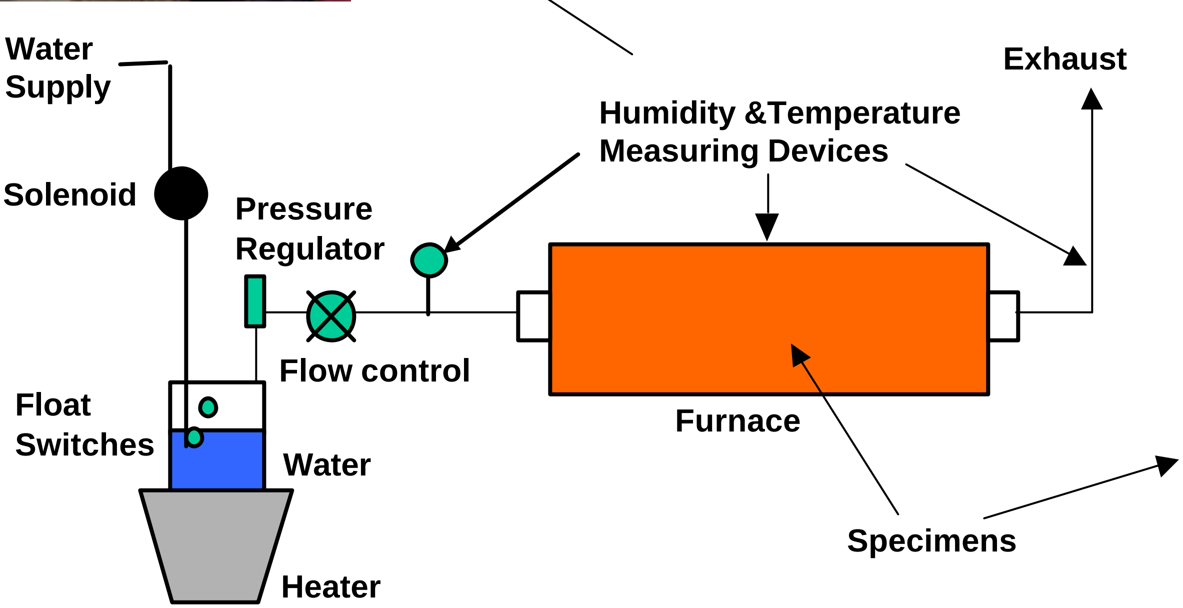
- Service Life of 14,000 hrs at 2400°F
- Corrosion (salt) and erosion resistance at 2400°F
- Keiser Rig life of 1,000 hrs at 2400°F
  - < 7-10µm uncracked thermally grown silica scale (TGO)
- High Speed Burner Rig life of 1,000 hrs at 2500°F, 1,500 ft/s gas velocity, and 1 atm water vapor partial pressure (20 spec./run, 250 hr batch time)
- Potentially various layers of different compositions
- Thickness 2-5 mil with total tolerance of 6 mil
- Non-line-of-sight coating technique
- Very low cost

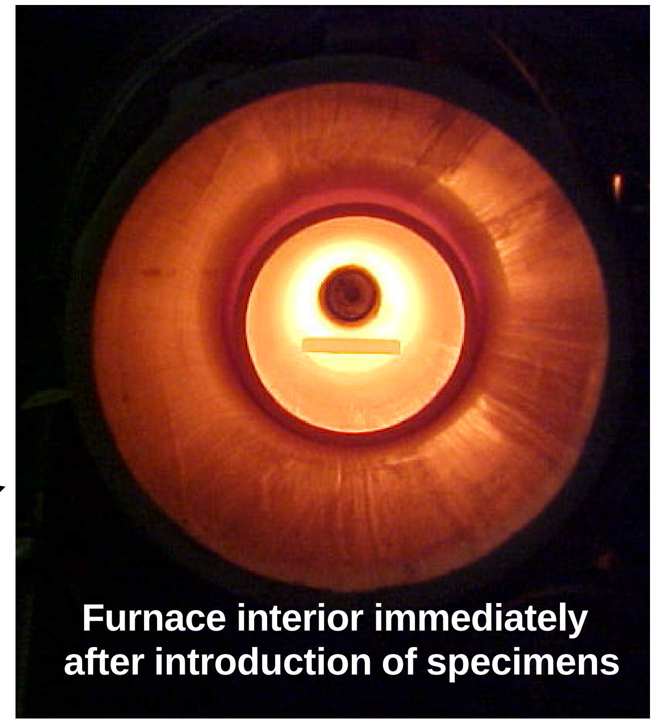
Typical Test Sequence

- Thermal expansion of compacted & sintered discs of each dense candidate layer
- Confirm basic chemical compatibility with Si_3N_4 & potential other layers (long-term testing might be required)
- X-ray check structure & composition of discs
- Deposit coatings on AS800 and AS950 by various methods and evaluate
  - Microstructure & porosity (excellent processing is key!)
  - Bonding to substrate
  - Impact on mechanical properties of substrate
- Static oxidation testing at 2400°F
- Cyclic oxidation testing at 2400°F
- Moist environment furnace testing at 2400°F and 1 atm p_{H2O}
- Burner rig testing

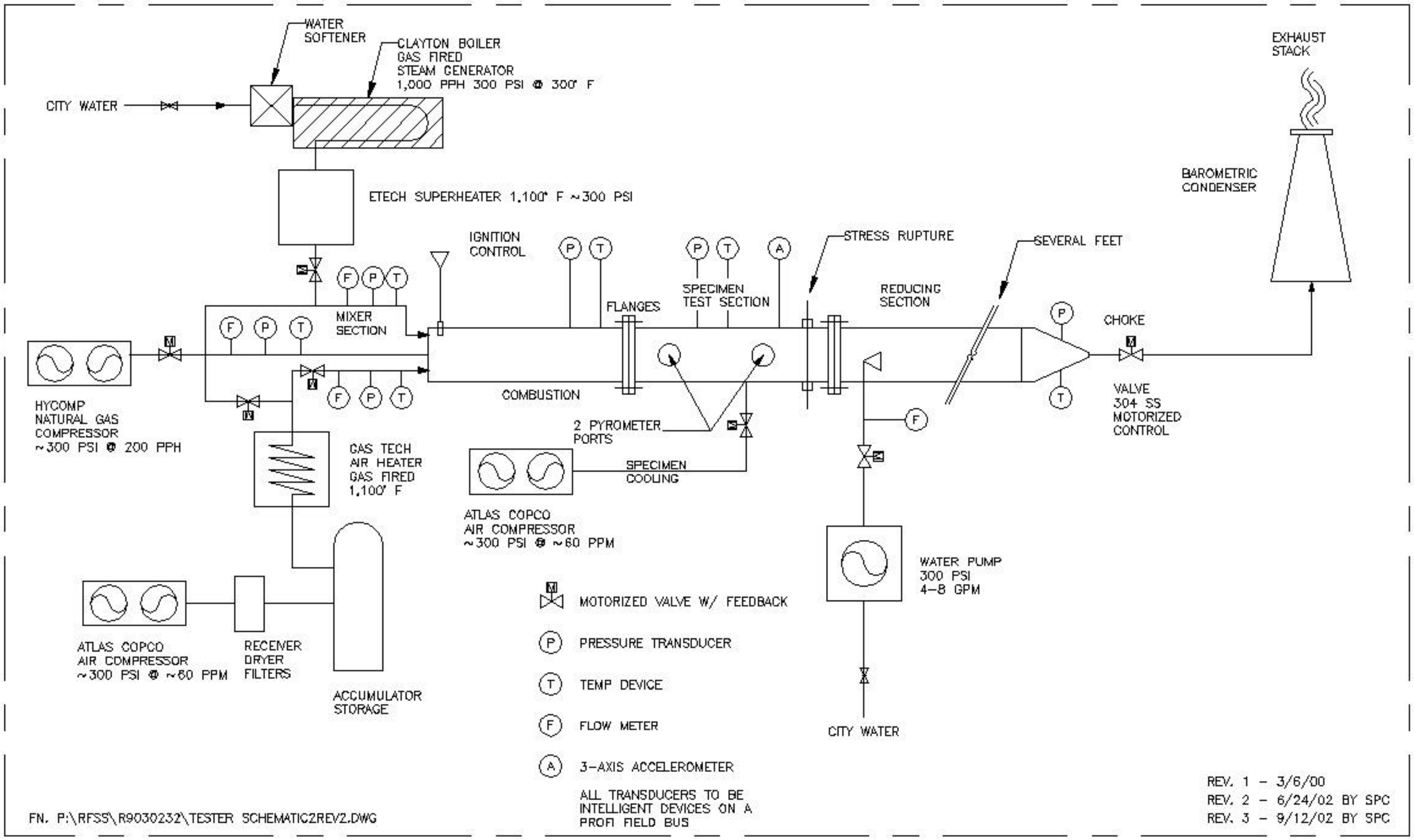
Quasi-Static Moist Environment Furnace Exposure Testing

Operating temperature range: 2000-2750°F
Average steam velocity: 1 m/min



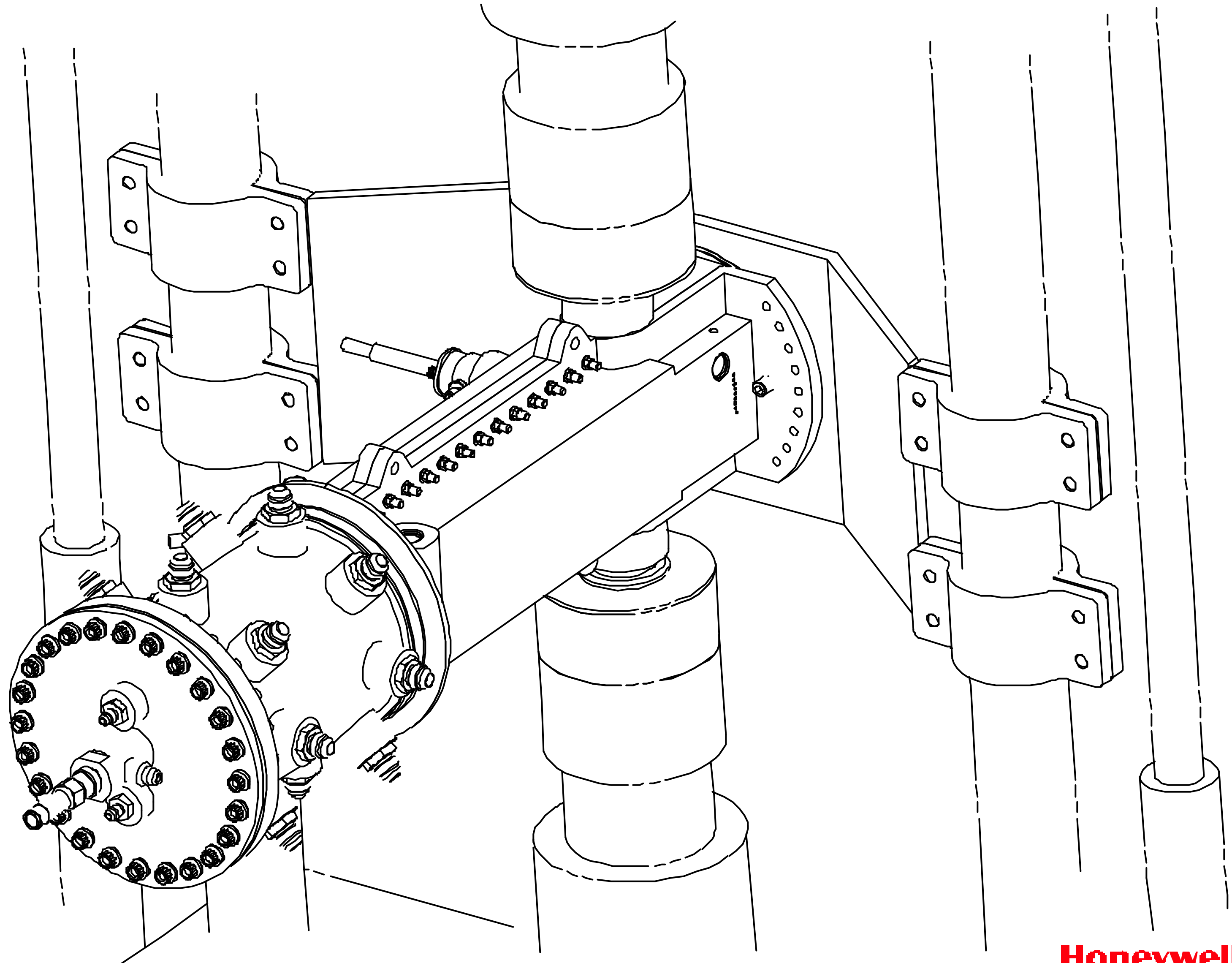


Facility Layout



Facility Customer Ready by 05/01/2003

Rig Layout



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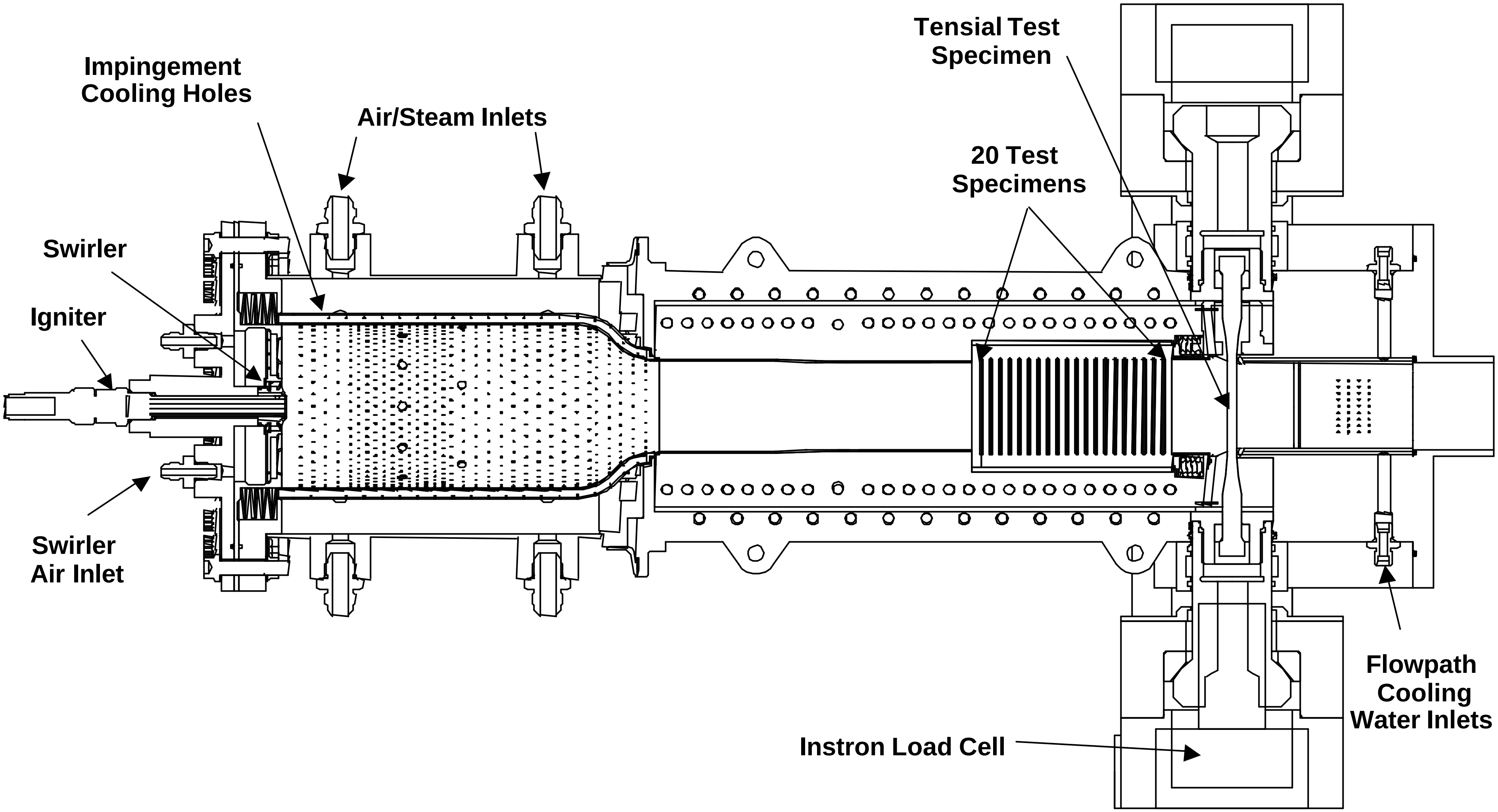
Rig Vertical Cross Section



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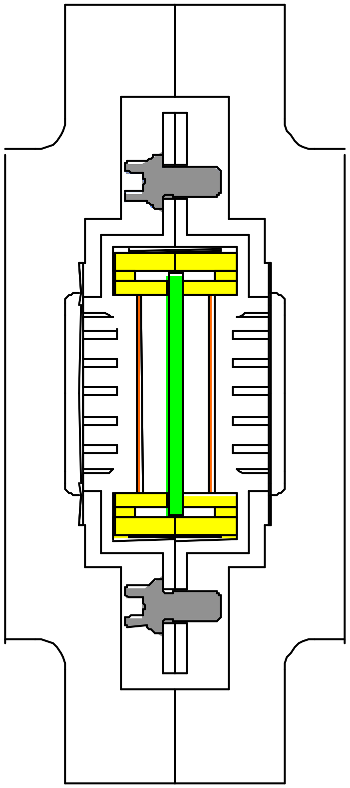
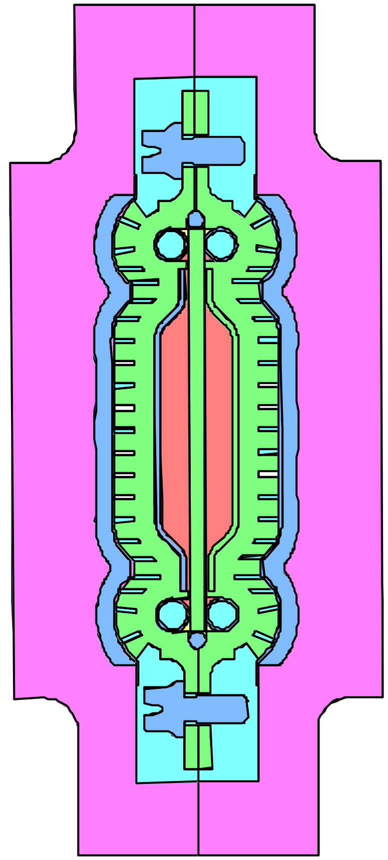
Cross Section Through Test Section



Early Configuration

-Ceramic Block Support

-Water Cooled Housing

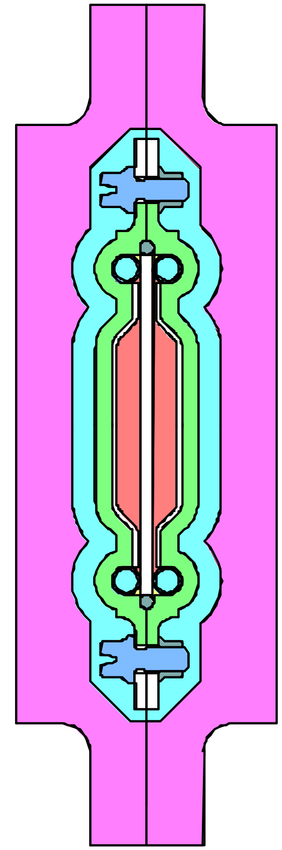


Interim Configuration

-Air Cooled Tube Support

-Water Cooled Housing

-Longer Test Specimens



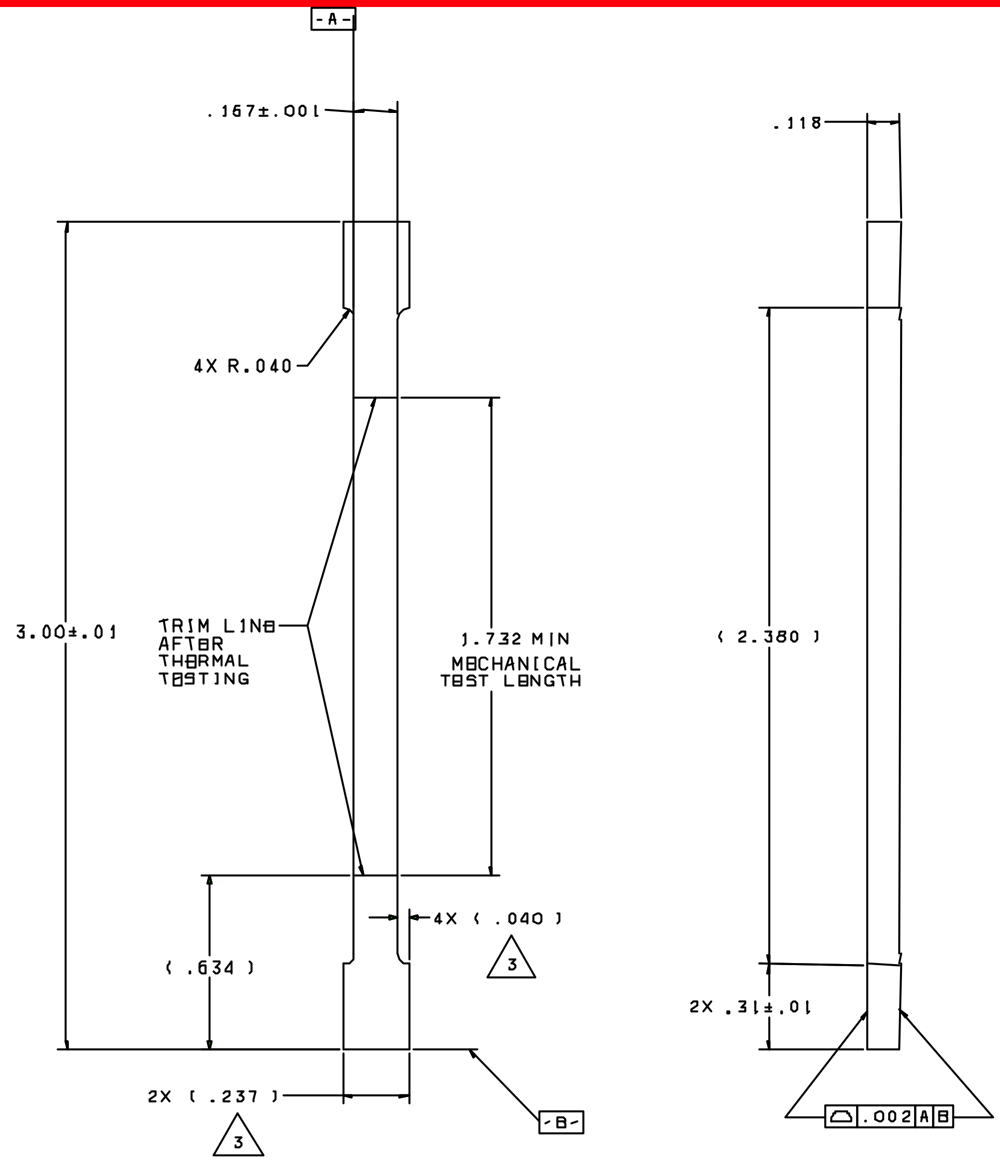
Current Configuration

-Air Cooled Tube Support

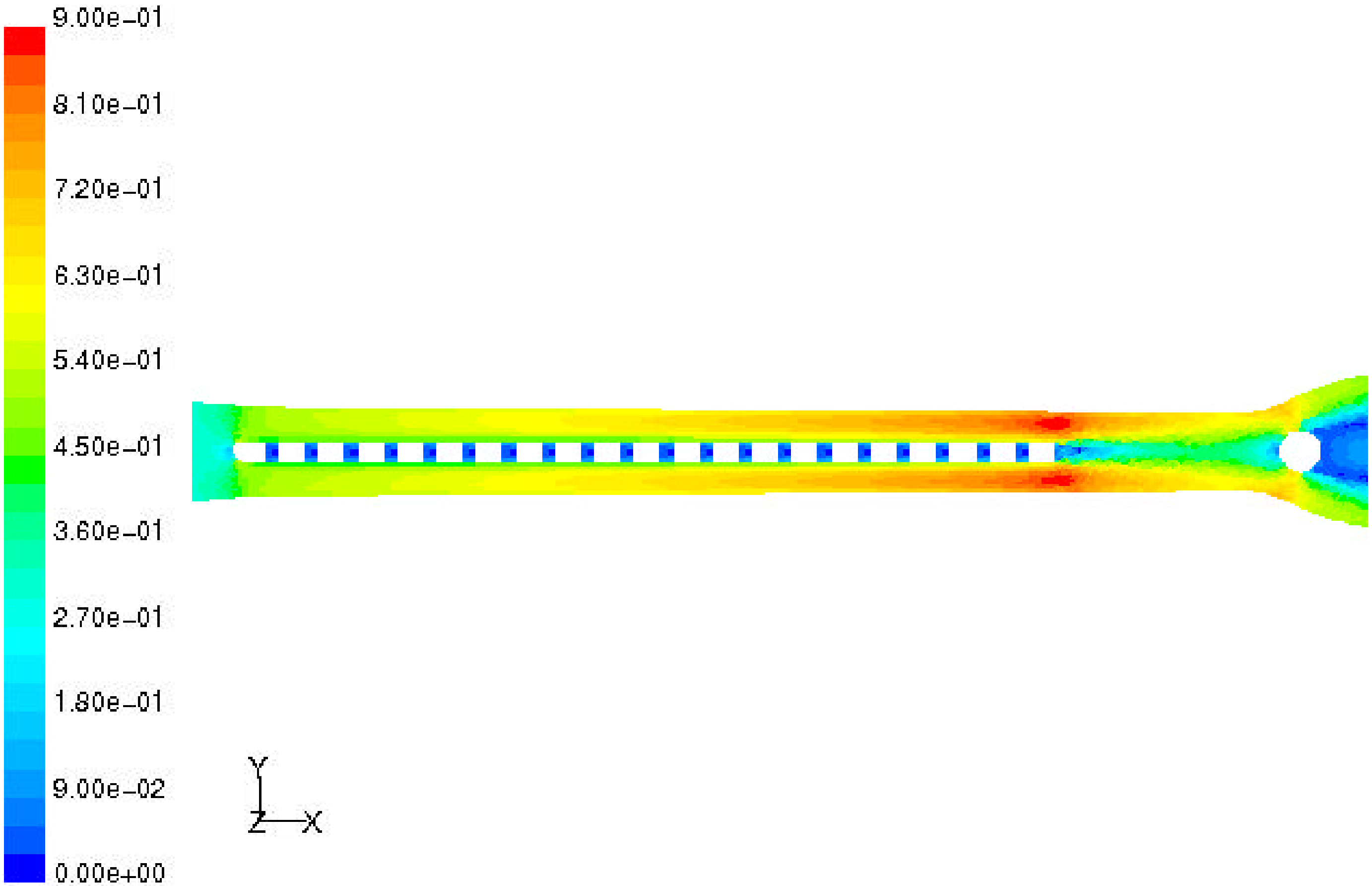
-Air Cooled Housing

-Longer Test Specimens

Specimen Geometry

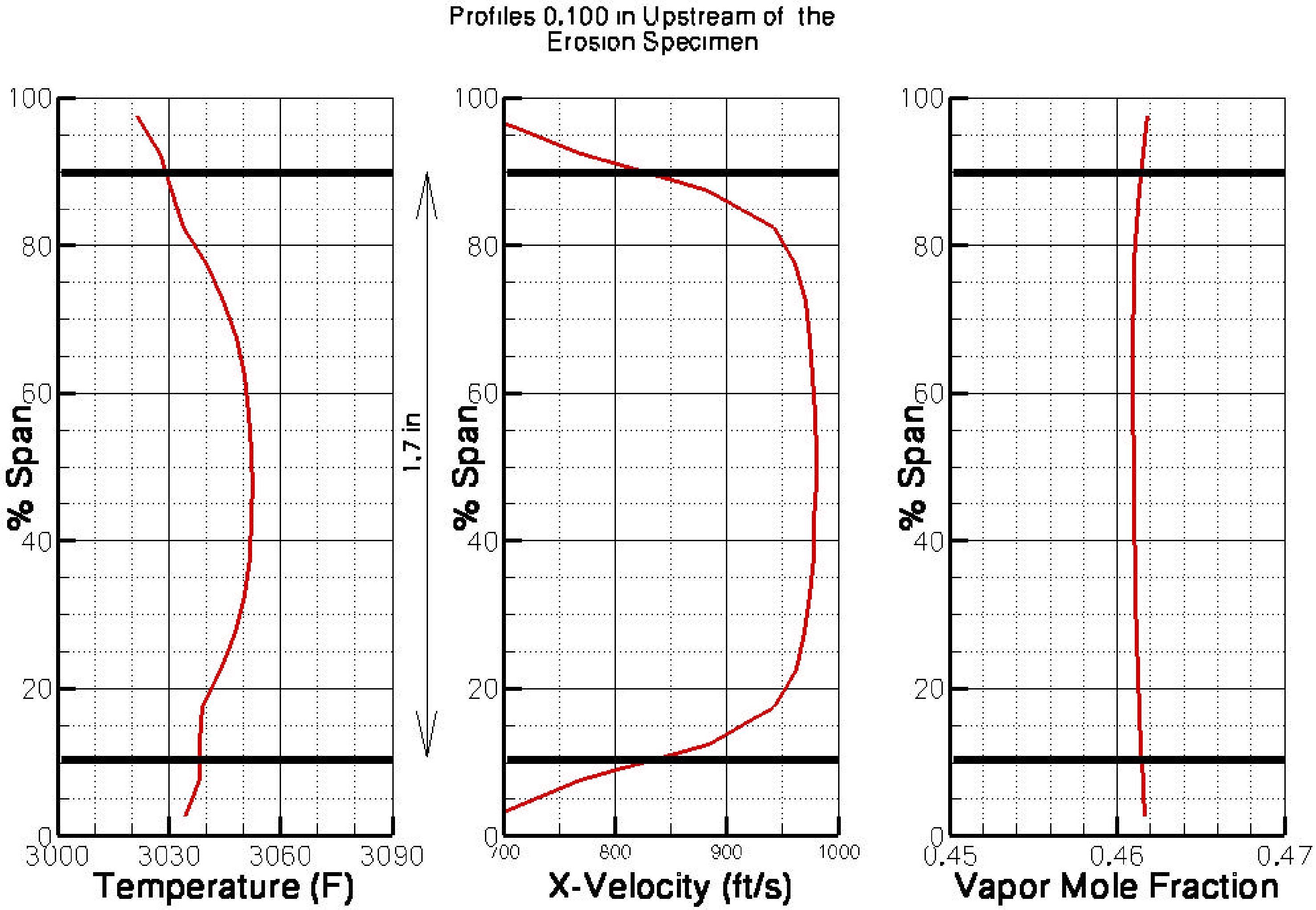


Test Section Mach Number



run11
Contours of Mach Number
Sep 16, 2002
FLUENT 5.5 (3d, segregated, spe6, ke)

Profiles



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Summary

- Ta_2O_5-based coatings inhibit water vapor induced volatilization of silica scale
- Ta_2O_5-based coatings not sufficient as stand-alone EBC
  - further optimization as potential interlayer is value-added
- Improved understanding and extended set of requirements resulted from first generation EBC development
- Focus shifted to
  - non-line-of-sight deposition methods
  - control of interface chemistry
  - systematic development and evaluation of candidate systems
  - coating deposition process optimization
  - substrate material optimization (substrate can be EBC life determining)
- Current coating concepts are industry-wide all just life-extending, non-prime-reliant "band aid" solutions
  - graded substrates as well as graded coatings development being worked as mid-term solution