EBC Development for Turbomachinery

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**New Developments in Silicon Nitride and Environmental
Barrier Coatings for Microturbine and Industrial Gas
Turbine Hot-Section Components Workshop
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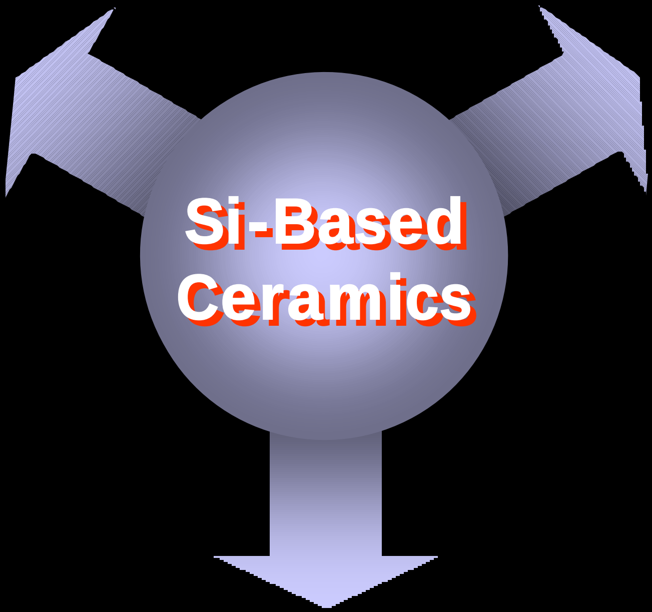
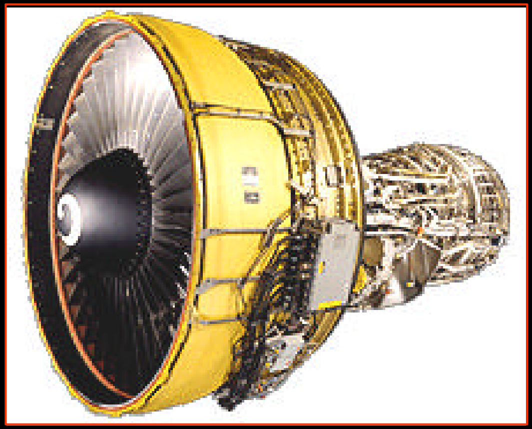
Si-based structural ceramics for advanced applications

Industrial Gas Turbines

- ***SiC/SiC CMC***
- Shrouds
- Combustor liners
- Buckets
- Nozzles



Aircraft Engines



- ***SiC/SiC CMC***
- Combustor liners
- Vanes
- Blades

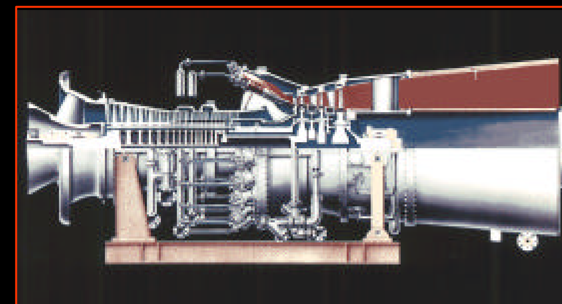
Microturbines

- ***Monolithic Si_3N_4***
- Combustor
- Rotor
- Nozzle
- Scroll

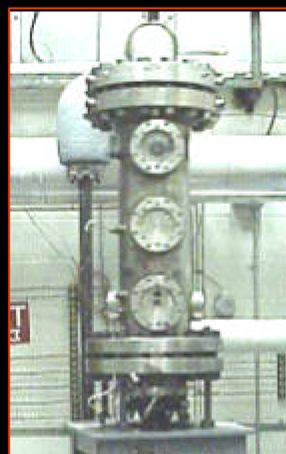
Si-based ceramics offer increased firing temperatures and reduced cooling, for greater efficiency and lower emissions!

Progressive development approach for CMC & EBC technology

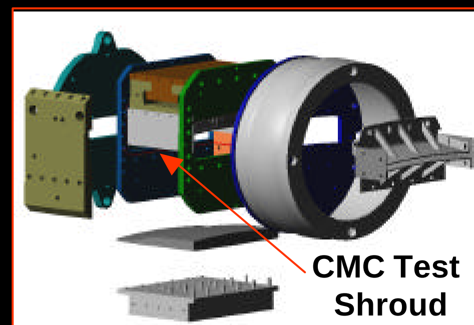
GEPS 7FA Industrial Gas Turbine



High-Pressure, High Velocity Burner Rig



Shroud Combustion Rig



Isothermal and Cyclic Steam Oxidation Furnaces

1996-Present

Lab Tests

600+ cycles & 4000+ hrs

1998-Present

Rig Feasibility Tests

30+ cycles & 1300+ hrs

2001-2003

Rig Qualification Tests

50+ cycles & 300+ hrs

2003

Large Engine Validation Test

4000 - 8000 hrs At Customer

Progressive testing provides risk reducing "stepping stones" to engine test

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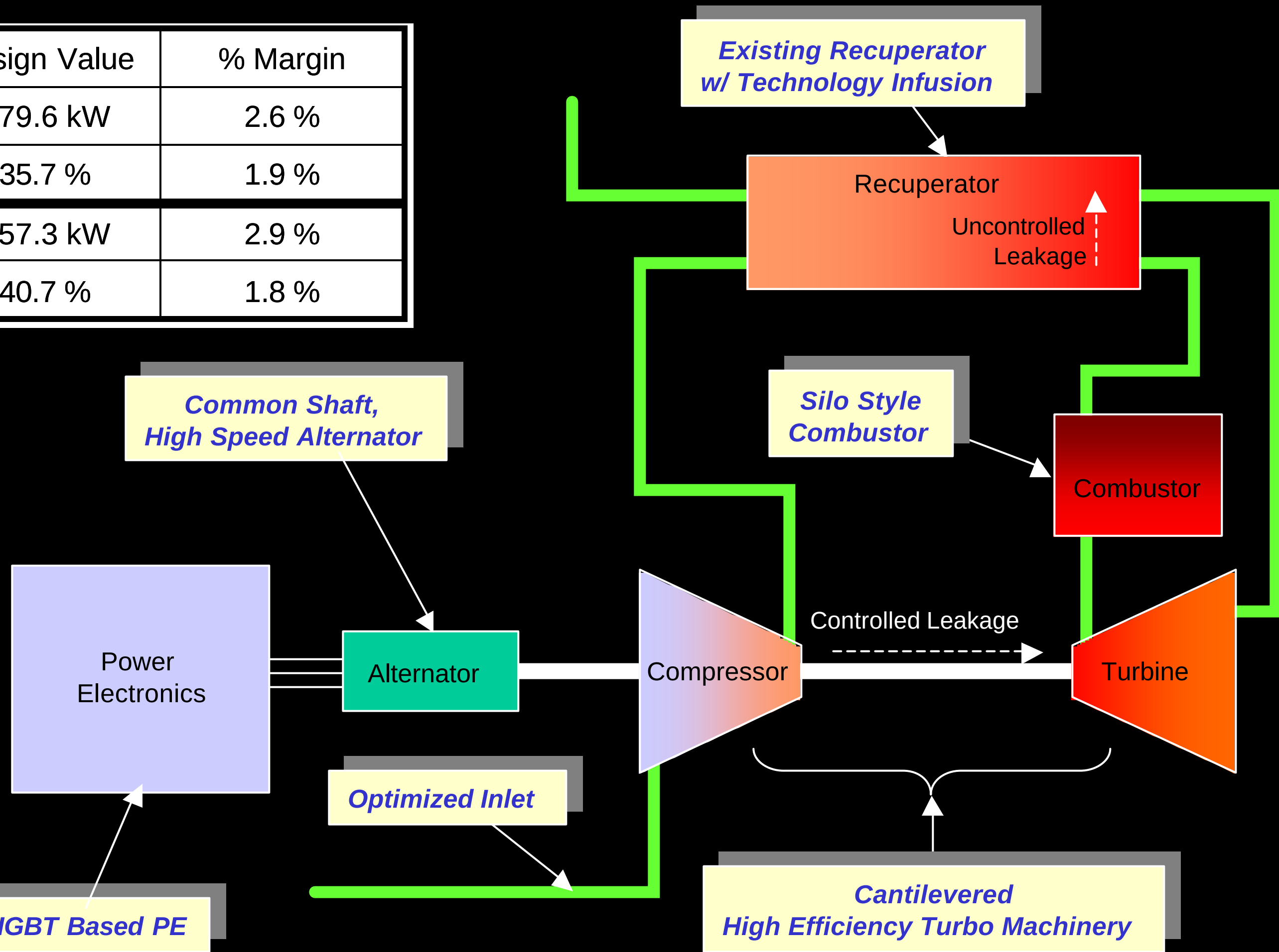
Progressive development approach for AIMS technology

- 35% efficient all-metallic design
- 40% efficient design utilizing advanced materials
- Both designs based on single-stage radial inflow recuperated cycle

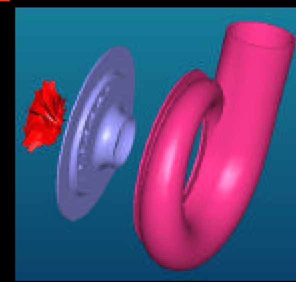
	Target Value	Design Value	% Margin
Cycle Output	175 kW	179.6 kW	2.6 %
Cycle Efficiency	35 %	35.7 %	1.9 %
Cycle Output	250 kW	257.3 kW	2.9 %
Cycle Efficiency	40 %	40.7 %	1.8 %



Progressive development enables building advanced technology on a solid design foundation

Ceramic component development for AIMS

Microturbine design for best use of ceramics
- Select component
- Highest payoff and lowest risk
- Combustor, scroll, nozzle, rotor, …



Ceramic property database for selected materials
- Focus on Kyocera SN-282 Si_3N_4
- Supplement ORNL database
- Conduct combustion rig testing

Ceramic Components for AIMS

Probabilistic design capability for ceramic component
- NASA CARES/LIFE
- Honeywell CERAMIC/ERICA
- GE extensions

Component Demonstration
- Fabricate prototype parts
- Test in lab or microturbine

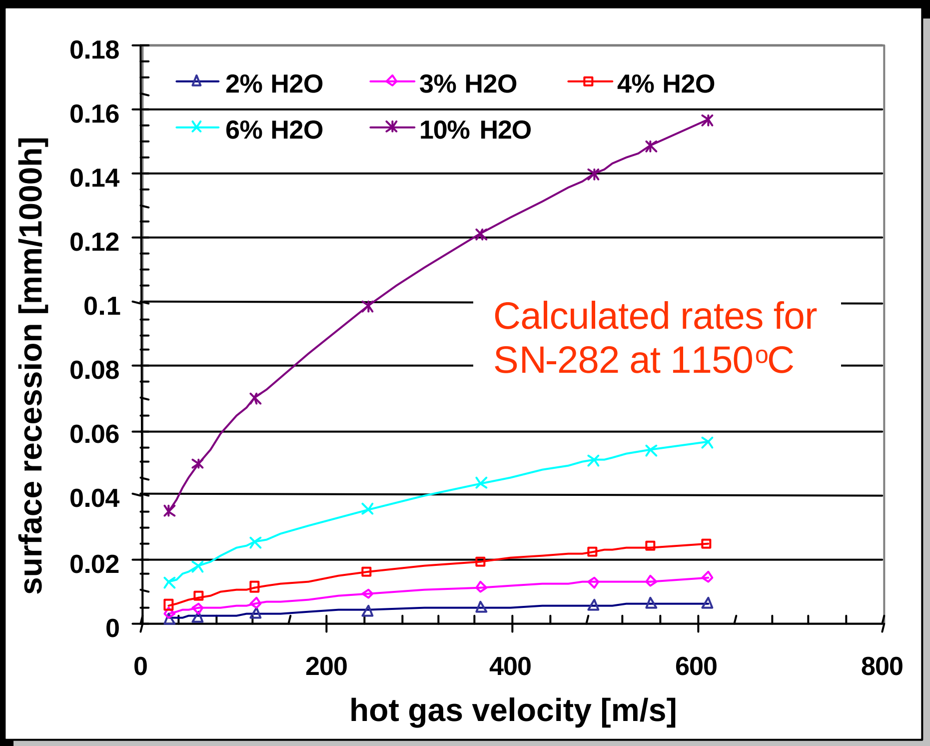
Incorporation of ceramic components requires innovative ceramic application engineering

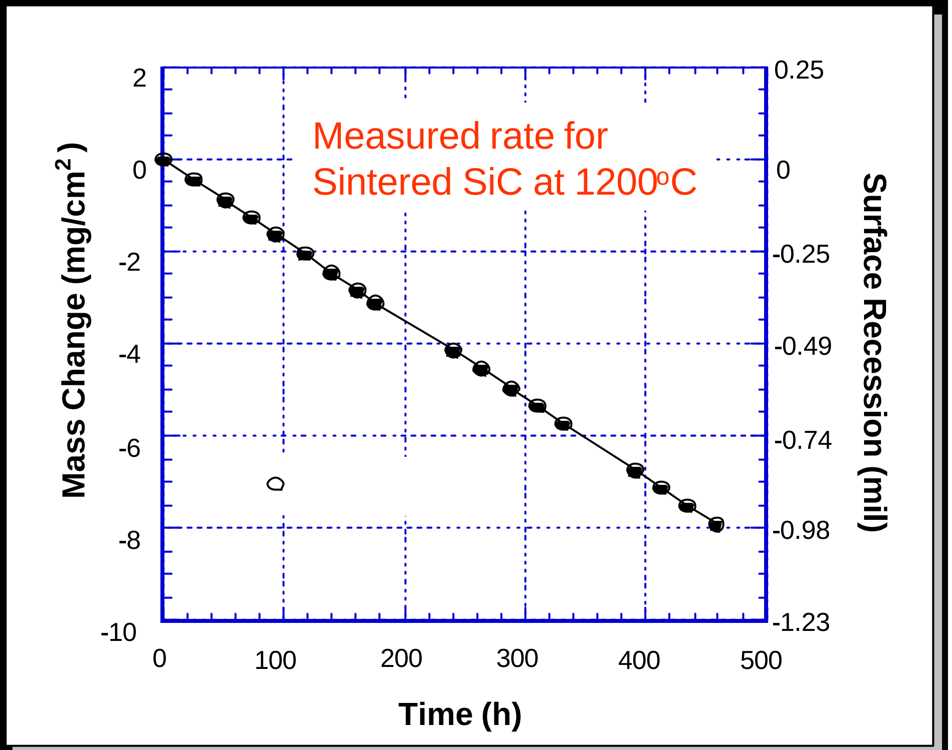
Environmental durability of Si-based ceramics

- **Water vapor present in combustion gas results in degradation of Si-based ceramics**
- **Mass loss and surface recession observed in furnace and engine tests**
- **Recession rate is often unacceptably high, such that**

EBC is needed for protection against volatilization!

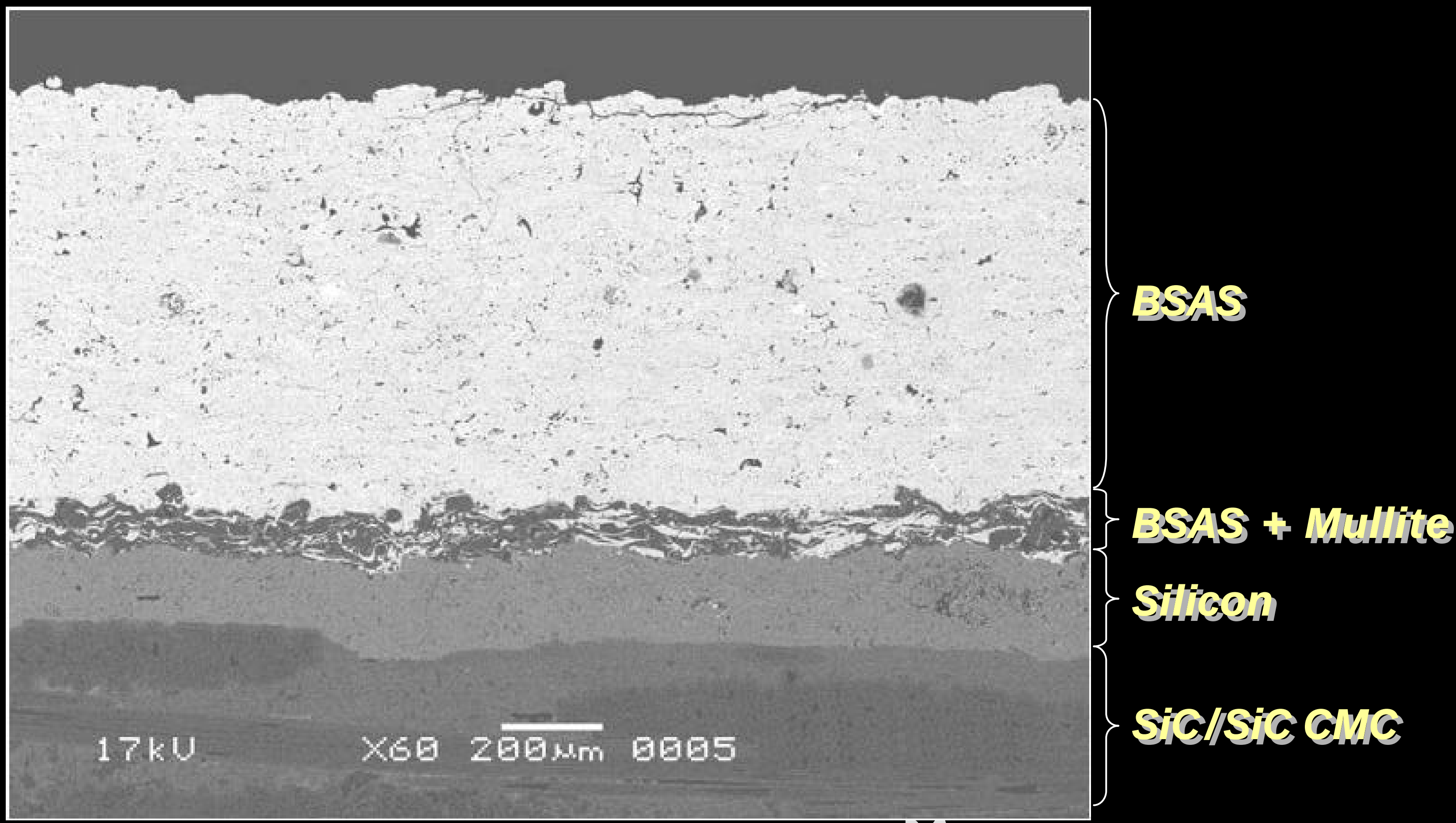
Si_3N_4 | **SiC**



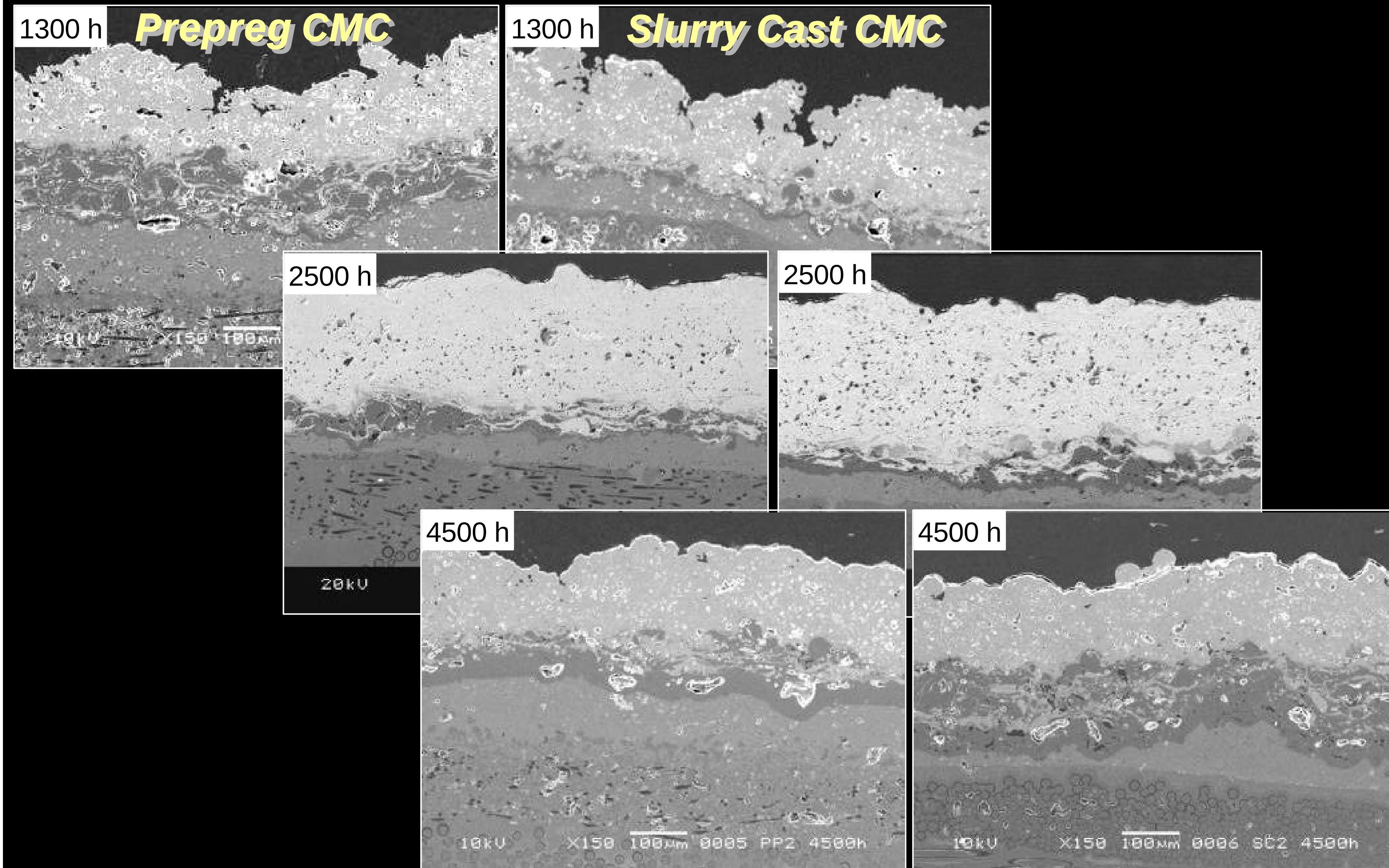


Environmental barrier coating (EBC) microstructure

- Environmental Barrier Coating was developed jointly by NASA, GE and UTRC under the NASA HSCT/EPM program
- Long-term EBC durability furnace, rig and engine tests are in progress



Isothermal steam-oxidation exposure test



No spallation of EBC has been observed

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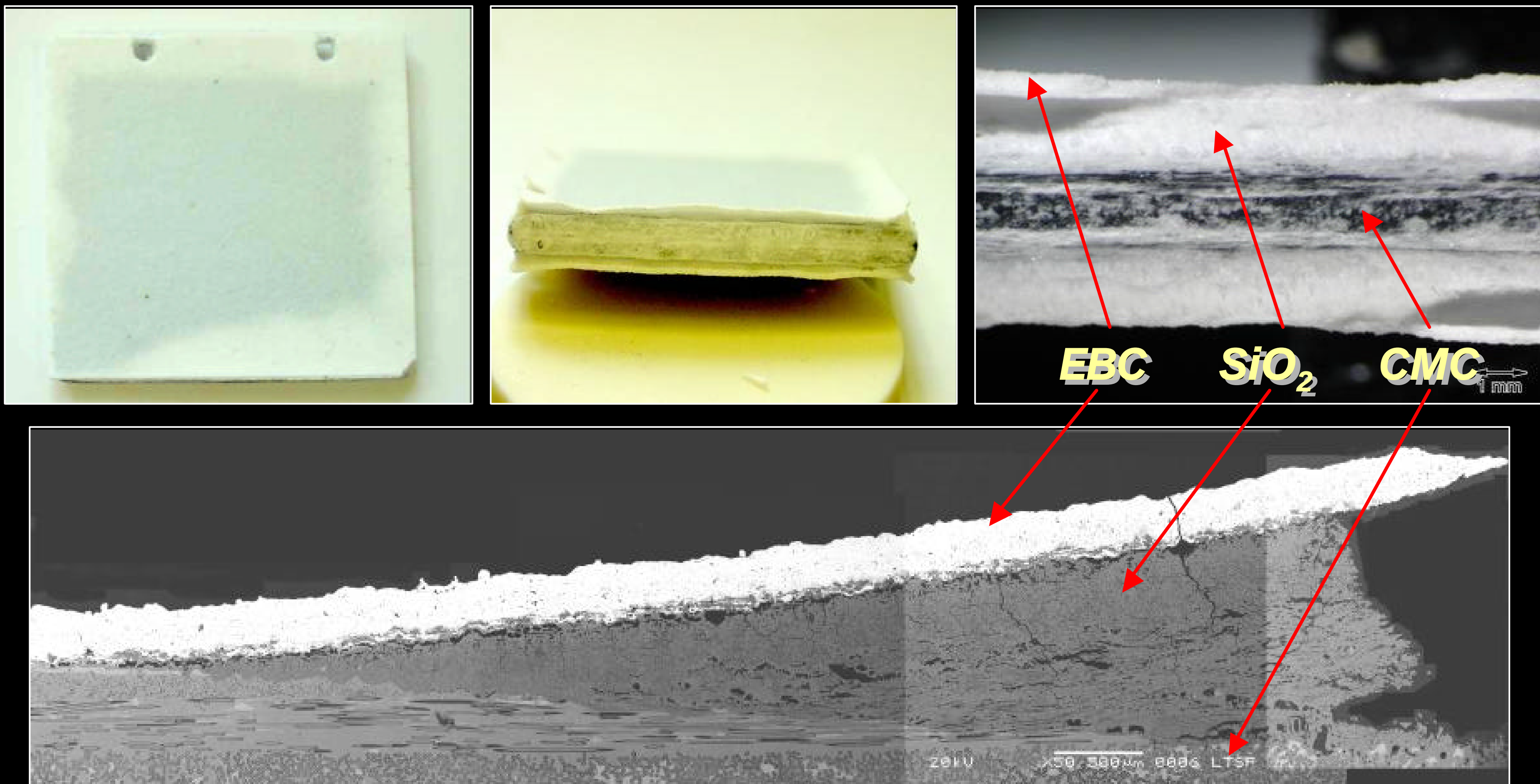
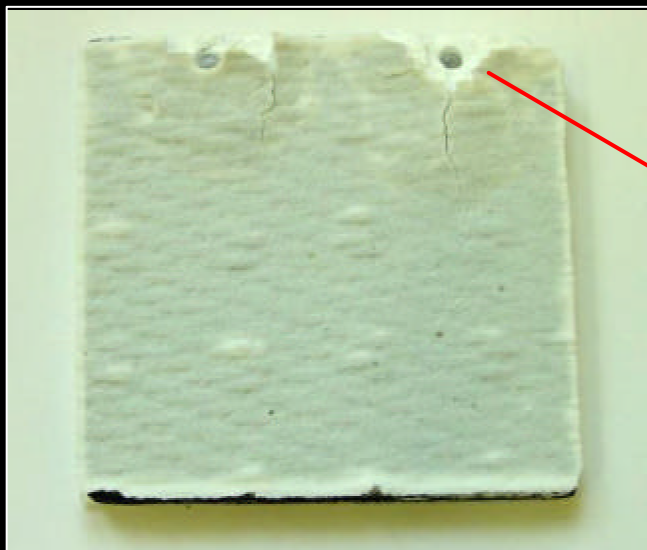
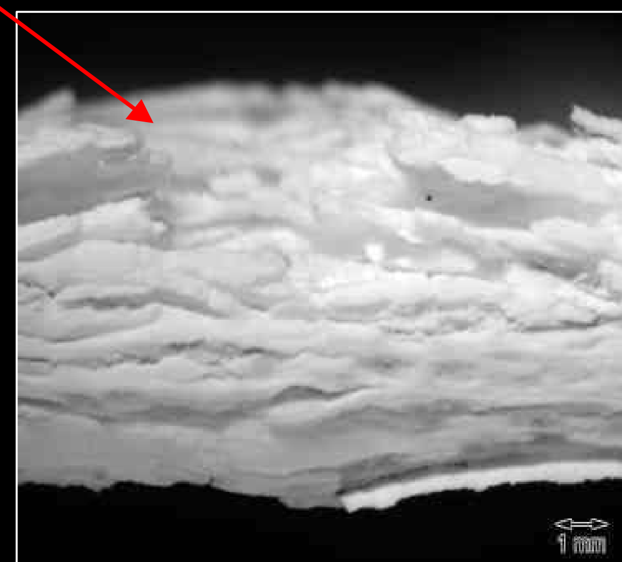
Edge-on oxidation of prepreg CMC during steam furnace testing



- **Exposed CMC and silicon bond coat are oxidized from the uncoated edges.**
- **Oxidation reaction results in a volume increase which acts to lift the EBC and allow further penetration of the steam atmosphere.**

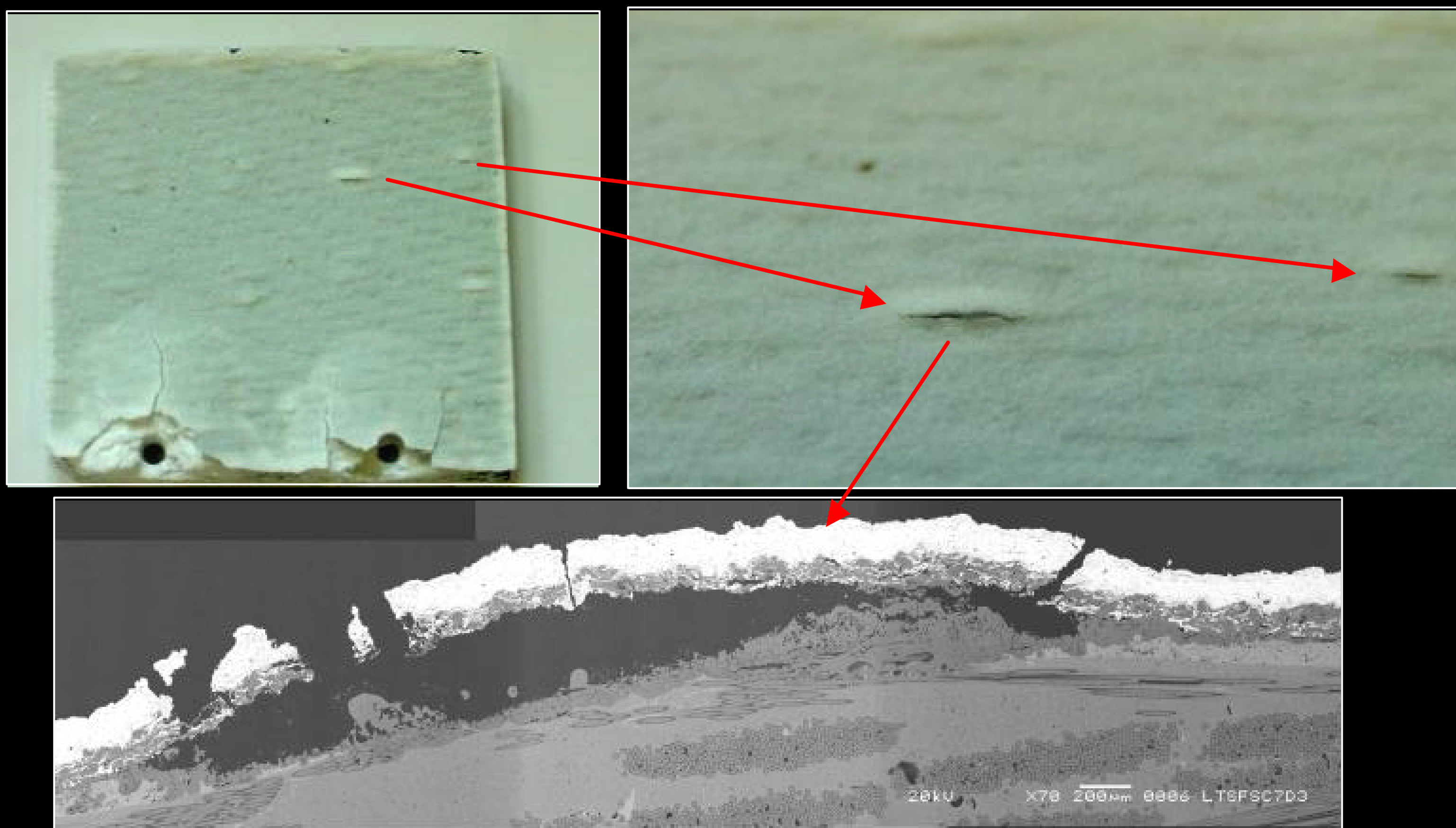
Edge-on oxidation of slurry cast CMC during steam furnace testing





- **Extensive oxidation around the holes is causing lifting and cracking of the EBC.**
- **Oxidation damage occurred preferentially in the hole regions relative to the uncoated edges.**

The effect of surface asperities on EBC degradation



- **There are discontinuities in the EBC where it covers tool bumps in the slurry cast CMC.**
- **The discontinuities occur in as-deposited coatings when the coating does not bridge the region between the top of the tool bump and the adjoining CMC surface.**
- **Oxidation in the gaps created by the discontinuities can be more severe than in regions of continuous coating, similar to edge effects.**

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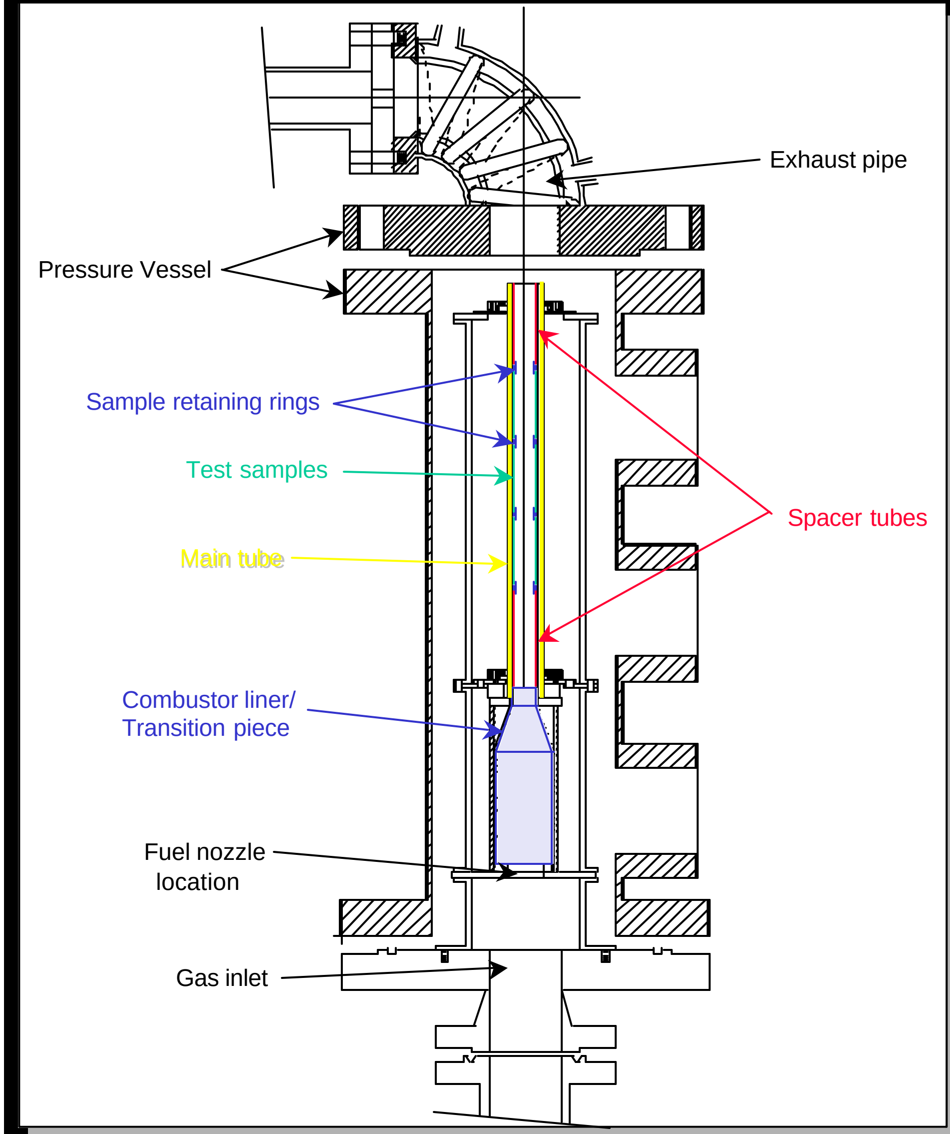
High pressure/high velocity combustor rig

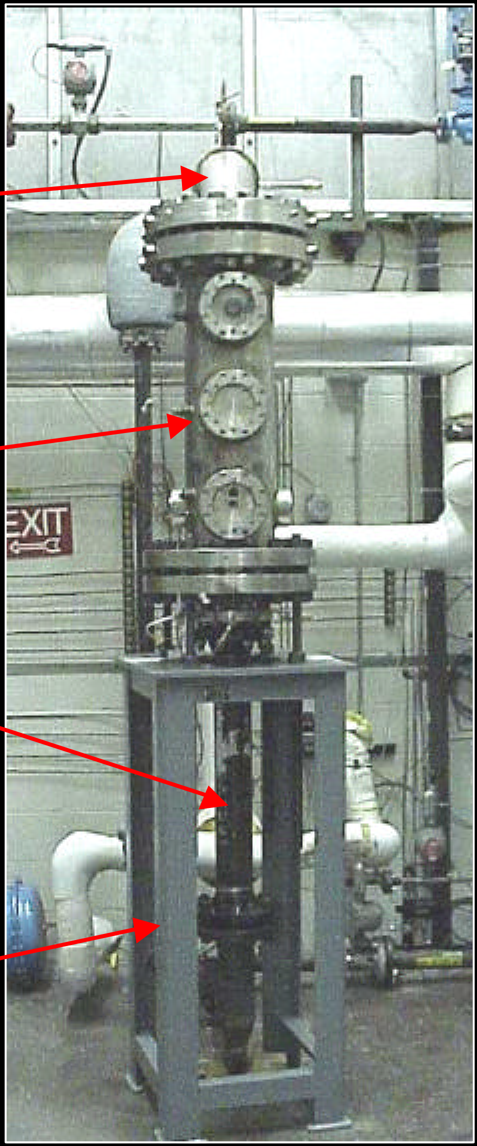


Exhaust piping

Pressure vessel

Air inlet piping

Stand



High pressure/high velocity combustor rig

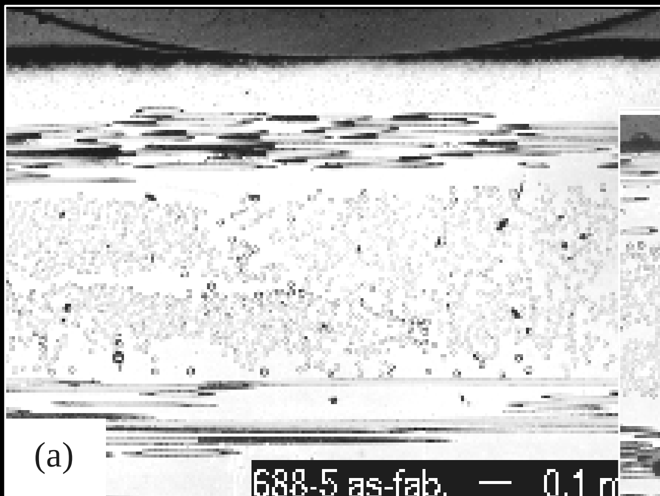
- Allows testing of mechanical properties test coupons for 1000's of hours under conditions similar to those in a turbine
- Runs largely unattended with extensive computer control, data acquisition, and safety monitoring
- Uses CMC hardware (combustor liner, transition piece, sample tube, sample retaining rings)
- Capacity: up to 28, 4" x 0.5" mechanical properties test bars
- Unique facility!

- *Typical IGT test conditions*
  - Material = MI SiC/SiC
  - Fuel = natural gas
  - T = 2200 °F (1205 °C)
  - P_{TOT} = 130 psia (8.8 bar)
  - P_{H2O} = 13.2 psia (0.9 bar)
  - Linear gas flowrate = 430 ft s^{-1} (130 m s^{-1})
- *Post-test evaluation*
  - Surface recession rate
  - EBC bondcoat oxidation rate
  - Strength vs. time
  - Strain capability vs. time

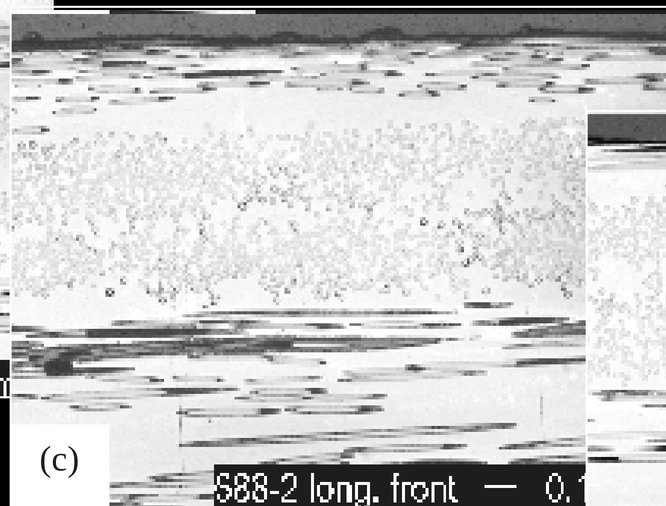
- *Initial AIMS test conditions*
  - Material = monolithic Si_3N_4 (SN-282)
  - Fuel = natural gas
  - T = 1900-2100 °F (1037-1150 °C)
  - P_{TOT} = TBD
  - P_{H2O} = TBD
  - Linear gas flowrate = 430 ft s^{-1} (130 m s^{-1})
- *Post-test evaluation*
  - Surface recession rate
  - Strength vs. time
  - Weibull modulus vs. time

EBC eliminates recession of SiC/SiC CMC

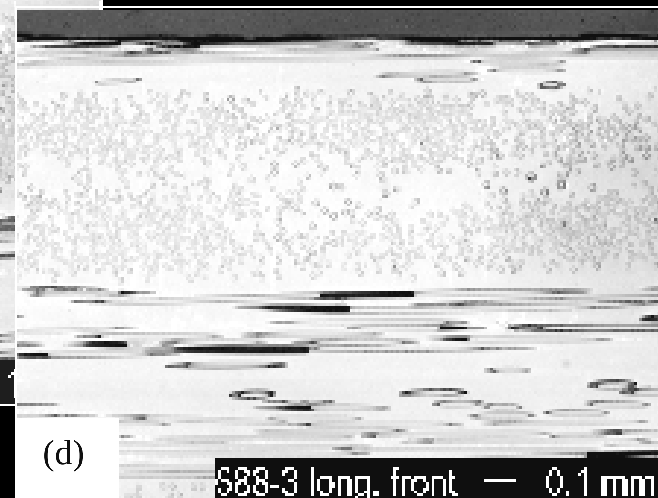
as fabricated



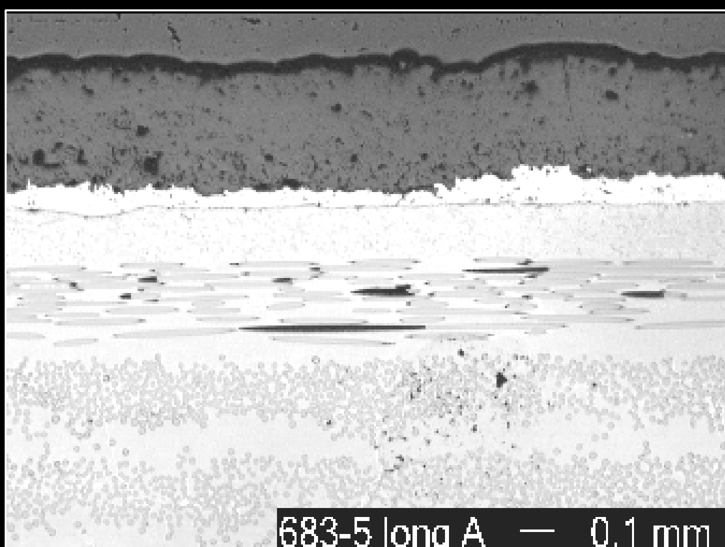
500 hr rig exposure



1000 hr rig exposure



1000 hr rig exposure with EBC



The EBC eliminates CMC recession under turbine engine conditions!

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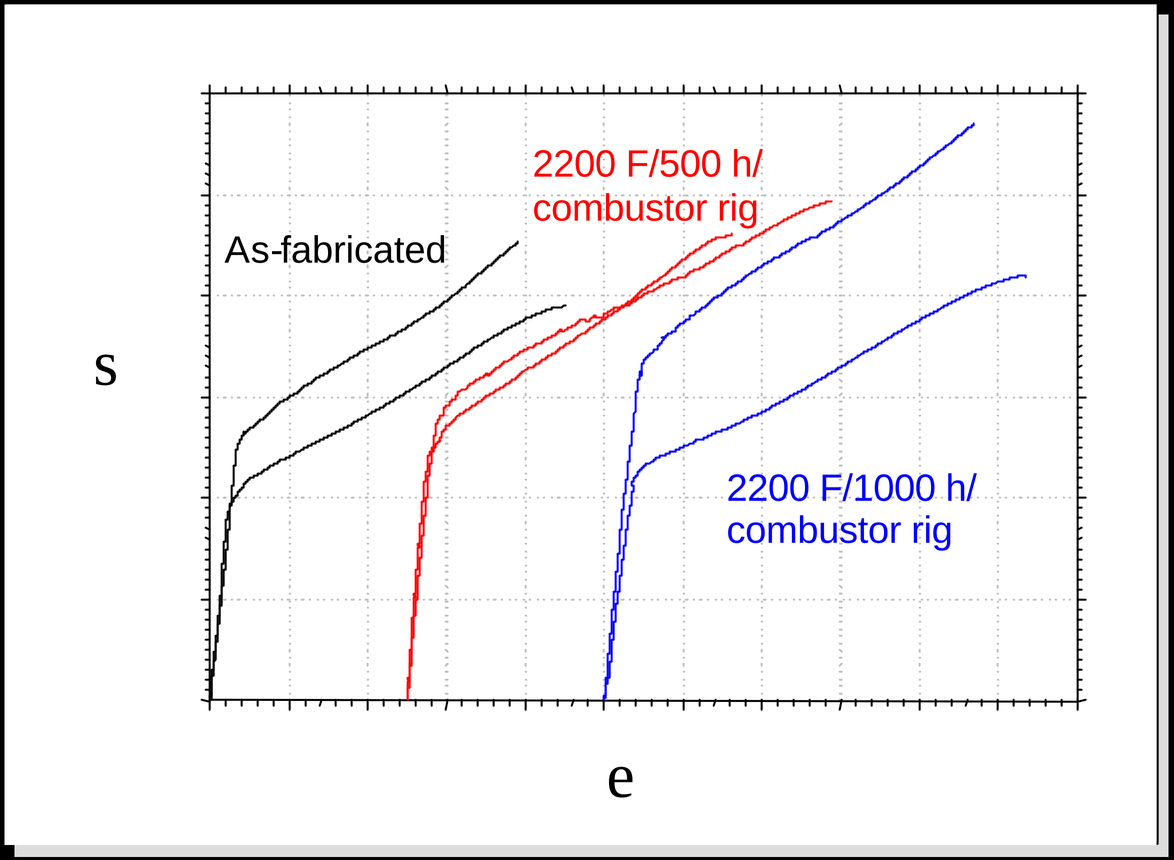
EBC protects mechanical properties

EBC coated CMC run 1000 h in the combustor rig

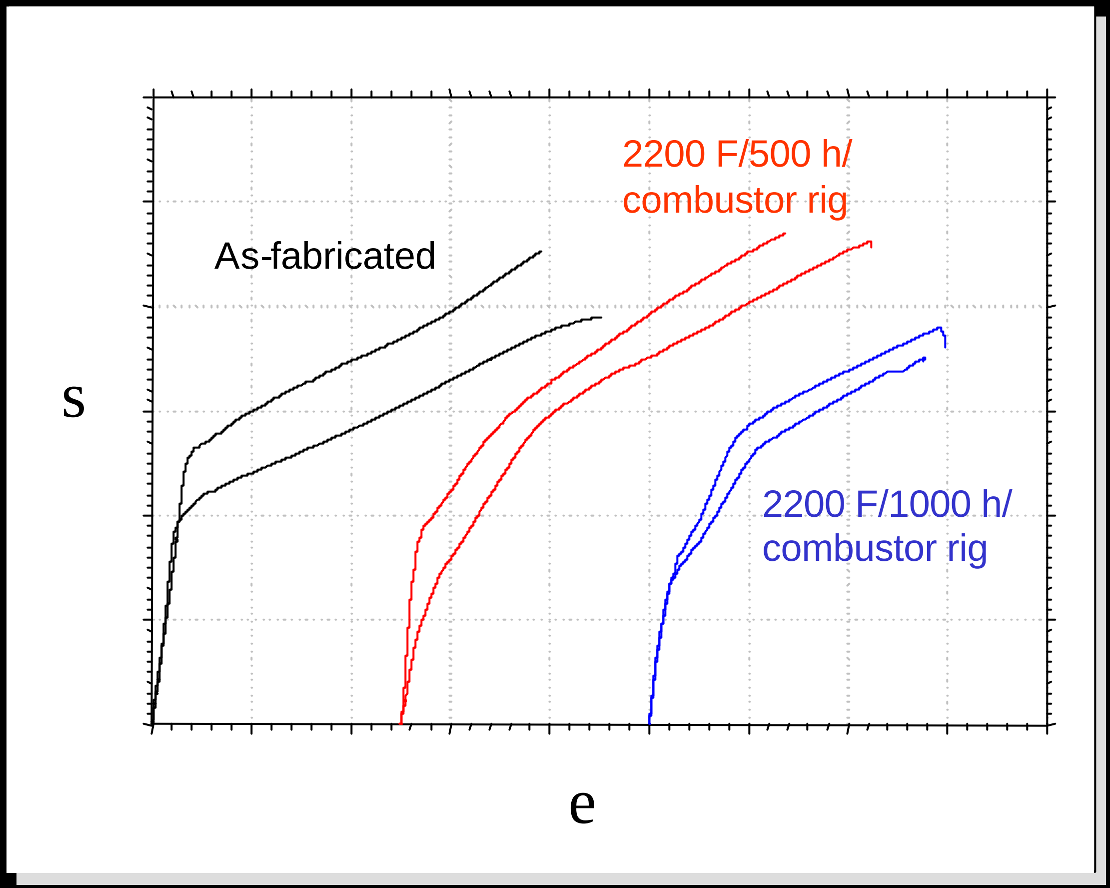
Residual mechanical properties of EBC coated CMC samples after combustor rig exposure



The EBC effectively protects the CMC substrate, preventing environmental degradation of mechanical properties!

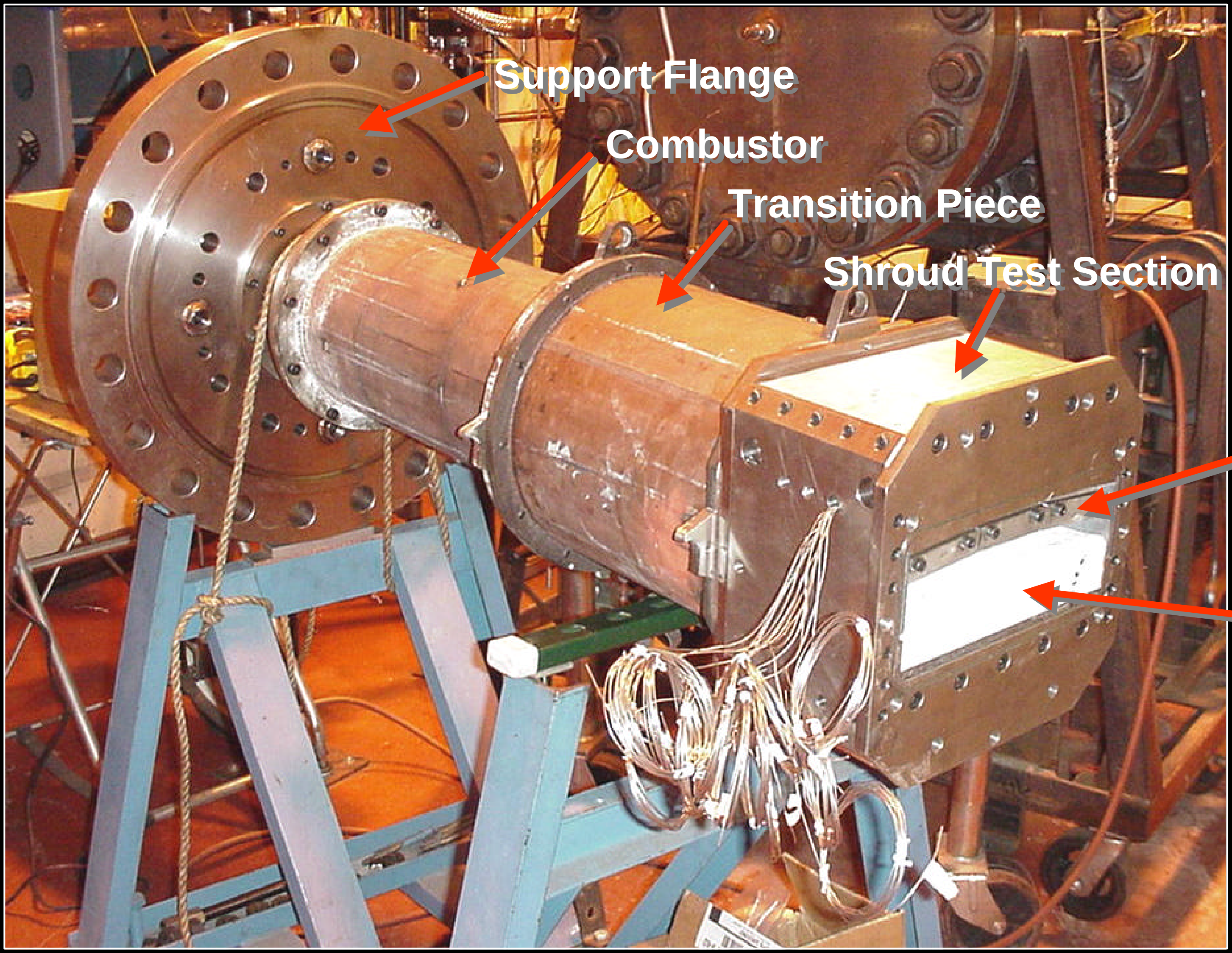
EBC protection reduced after cracking

Residual mechanical properties of precracked EBC coated CMC samples after combustor rig exposure



Environmental attack through fine cracks causes continuing degradation of CMC mechanical properties

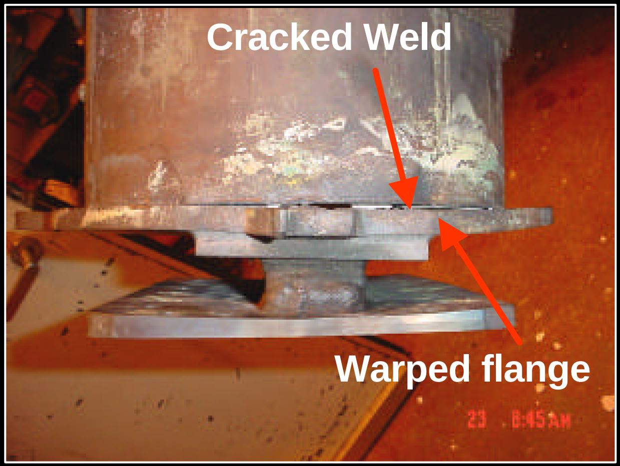
Shroud combustion rig

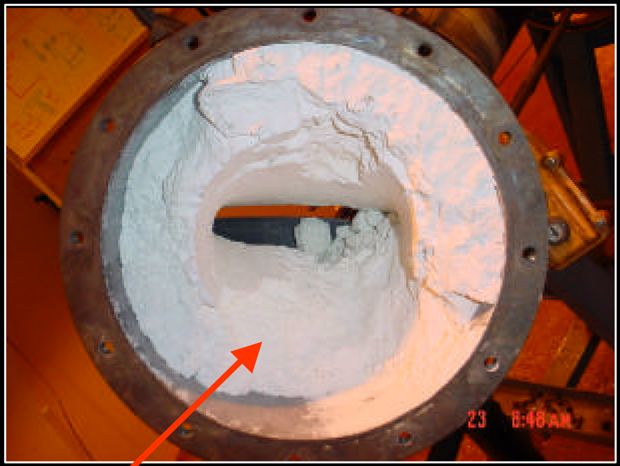


Surrogate metallic shrouds

Cast ceramic bottom channel wall

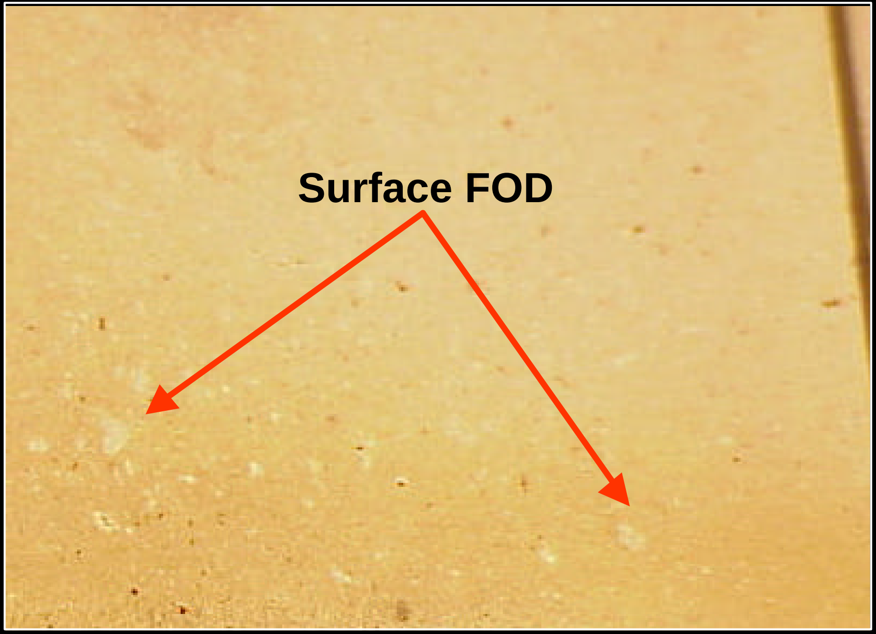
Transition Piece Damage





Cast ceramic transition piece failure generates FOD

Effect of FOD on Shroud EBC Surface

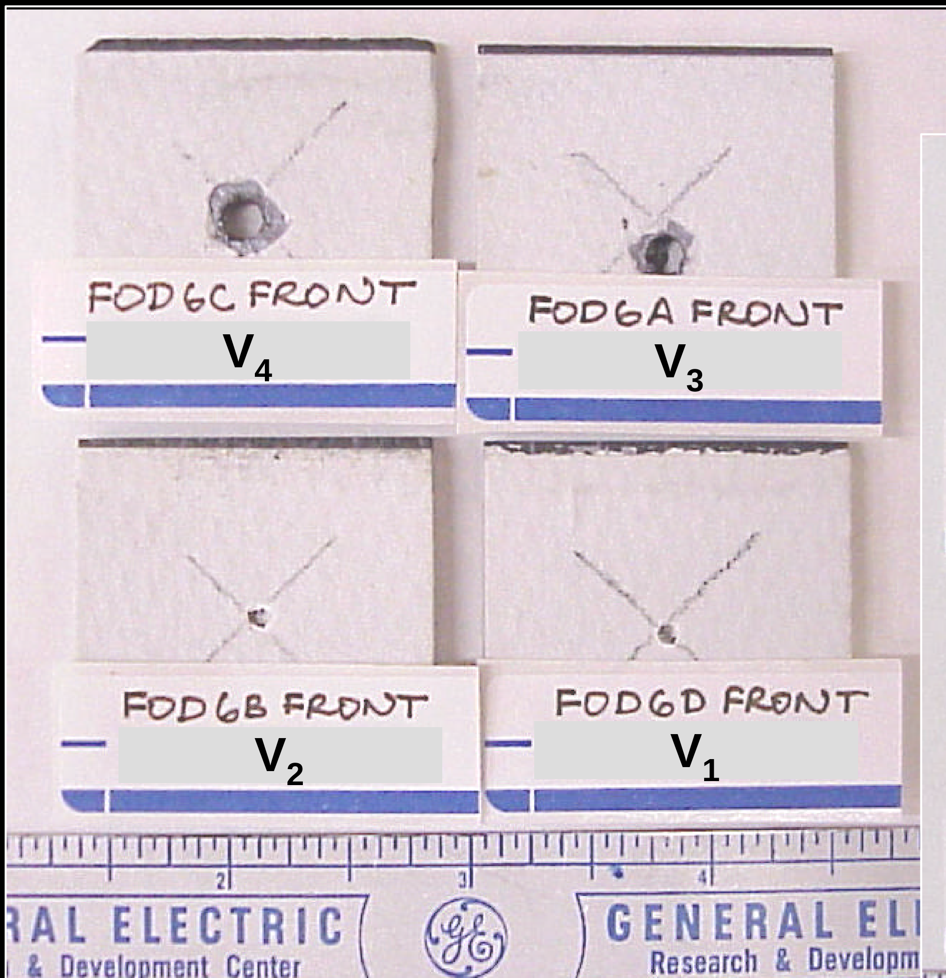


EBC and CMC are FOD resistant!

FOD testing by ballistic impact

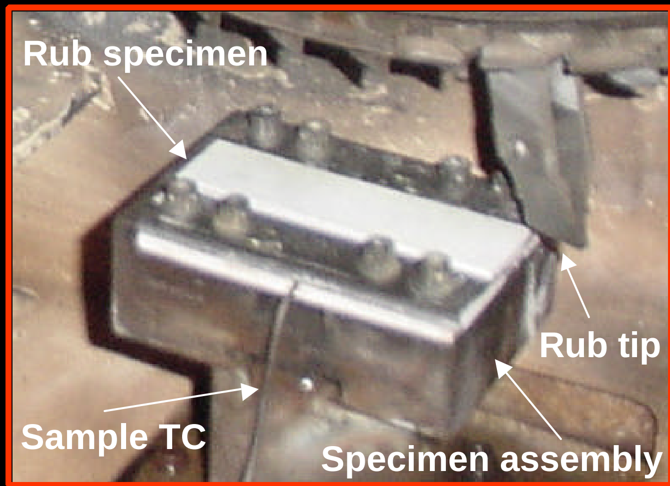
Impact velocity increases from V_1 to V_4

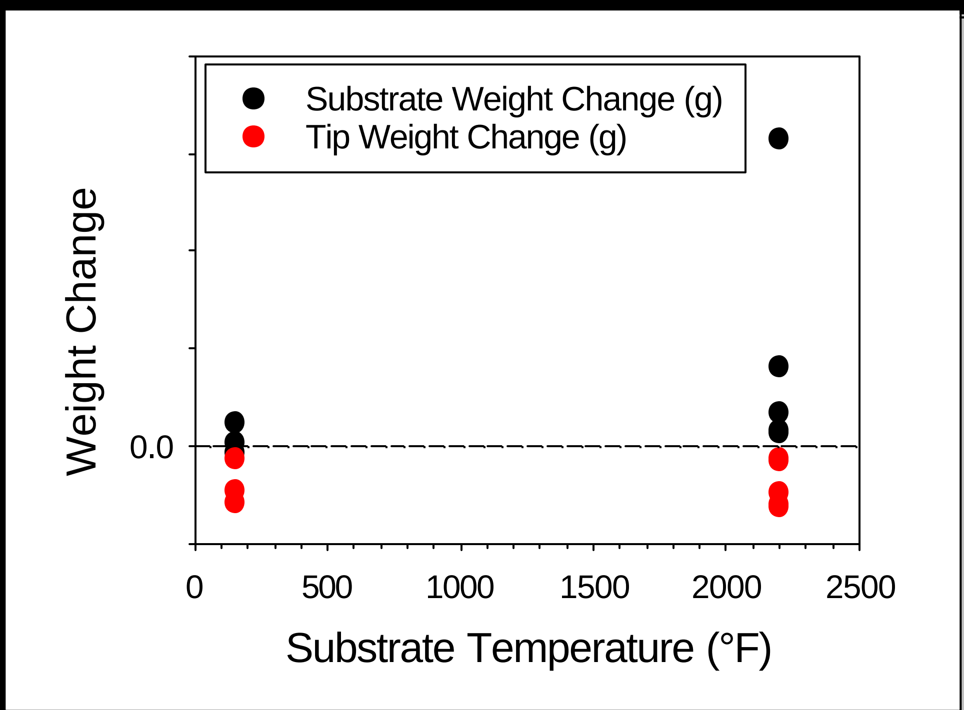
Frontside

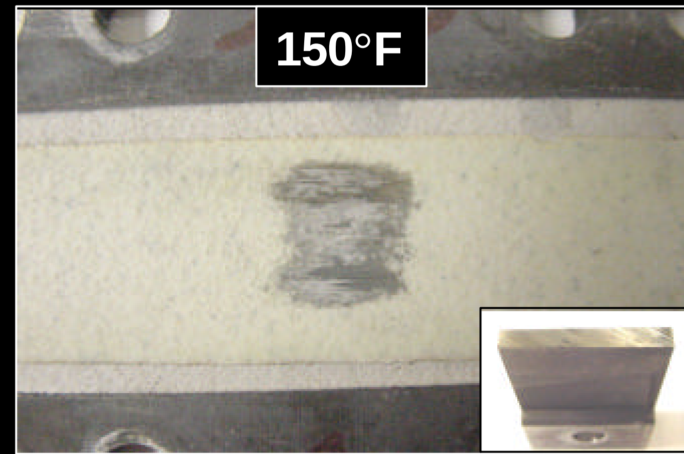


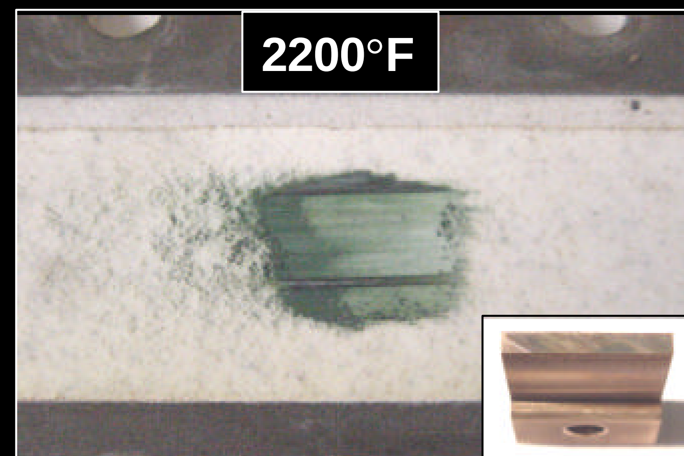
Backside

Backside damage is always more significant than frontside









EBC not damaged by rub with superalloy blade material at ambient or high temperature!

Summary

- A progressive approach is being applied to CMC and EBC development and testing in order to reduce the risks associated with commercial introduction
- A progressive approach is being employed in the development of a 35% efficient all-metallic material microturbine design and a 40% efficient design utilizing advanced materials
- EBC eliminates surface recession of Si-based ceramics in combustion environments
- EBC protects σ/ε properties of CMC in the uncracked state
- EBC protection of σ/ε diminishes as cracking occurs
- EBC and CMC are resistant to FOD and rub events

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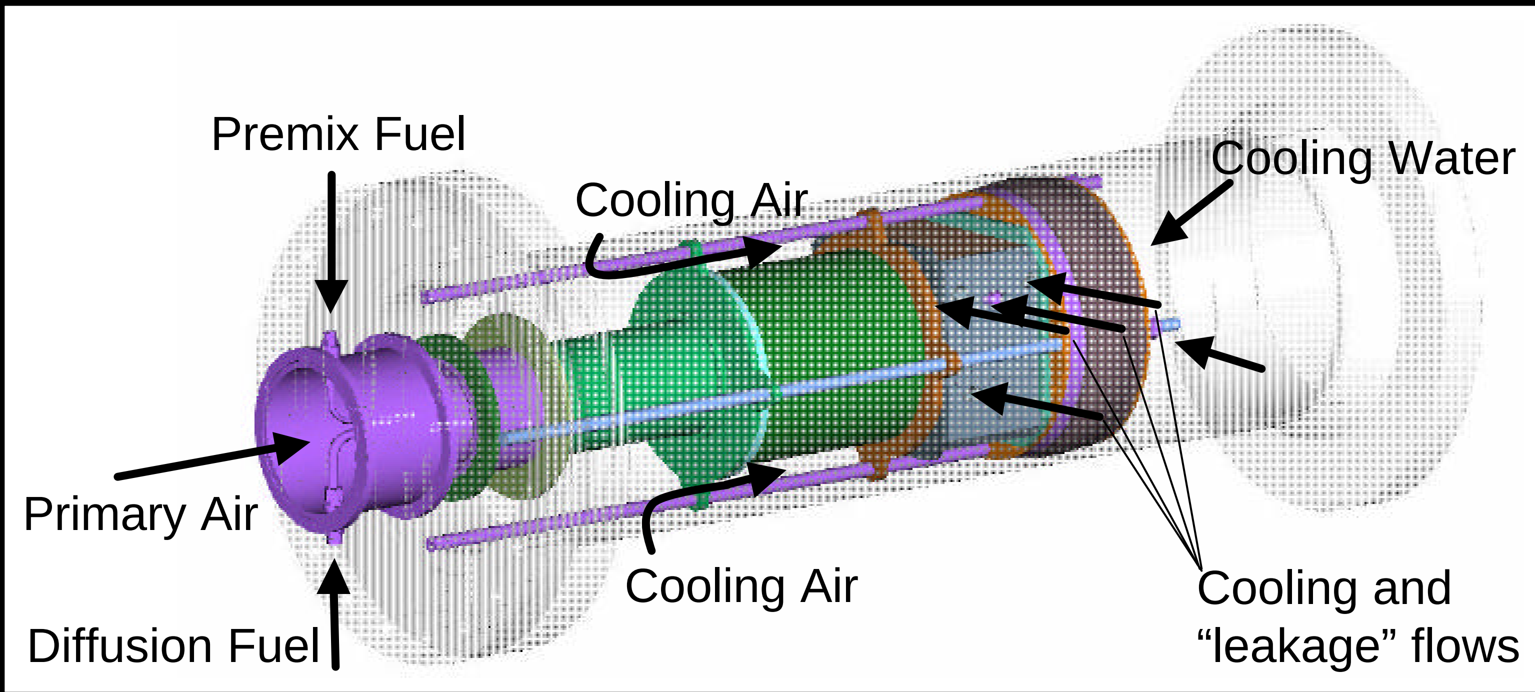
Shroud combustion rig



- Primary Air - T = 700F; P = 200 psi; Wa = 6 lbs/s
- Main Cooling Air - T = 100F; P = 200 psi; Wa = 1.2 lbs/s
- Leakage Air - T = 700F; P ≅ 200 psi; Wa = 0.25 lbs/s
- Fuel - T = 100F; P ≅ 200 psi; Wa ≅ 0.2 lbs/s