# MELT INFILTRATED CMCs (HiPerComp®) for Gas Turbine Applications

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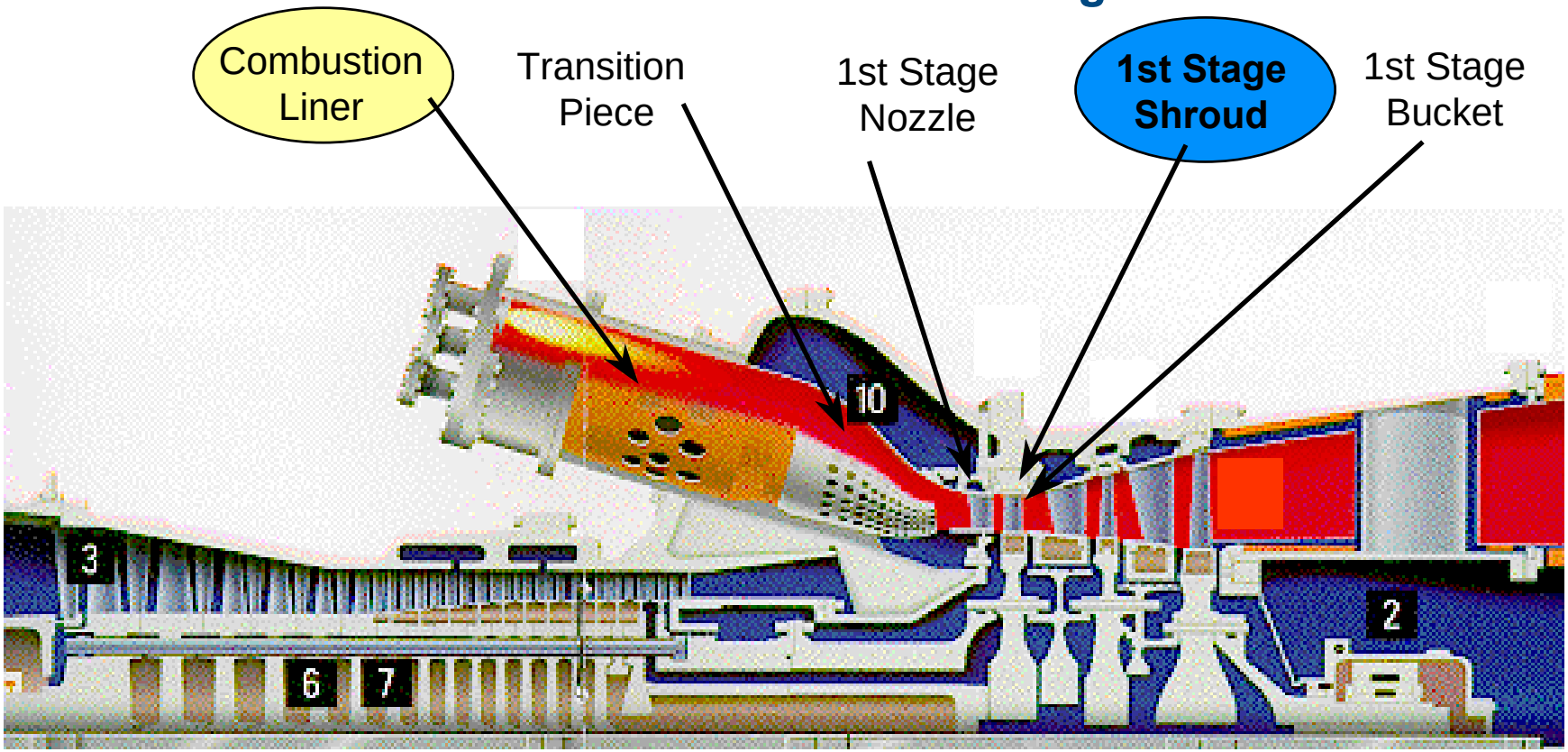
imagination at work

# Outline

- **Introduction**
- Material System & Properties
- Engine Test Experience
- Risks and Challenges
- Summary and Conclusions

# Applications

## Industrial Gas Turbine Engine




Stationary components represent best short-term opportunity

# Outline

- Introduction
- **Material System & Properties**
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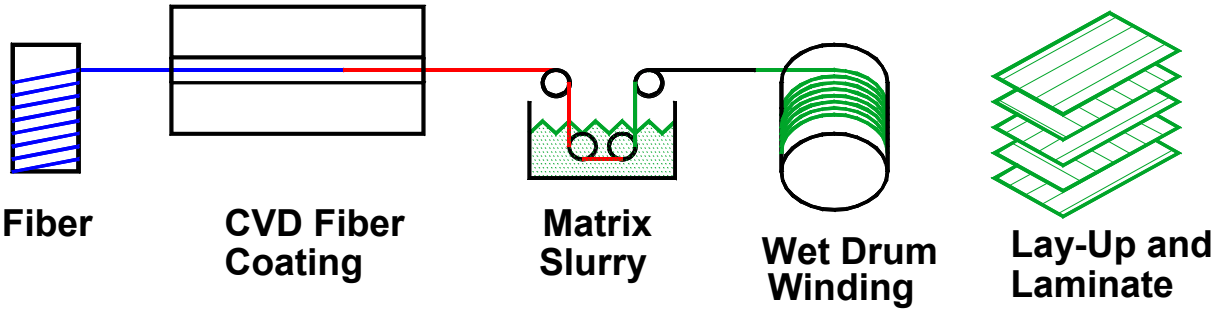
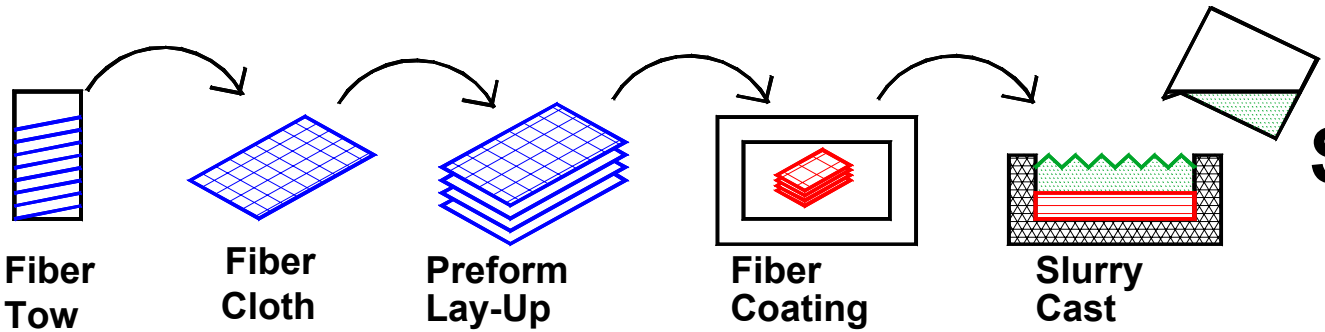
# Melt Infiltration (M.I.) Composites (HiPerComp®)

## Preform Fabrication

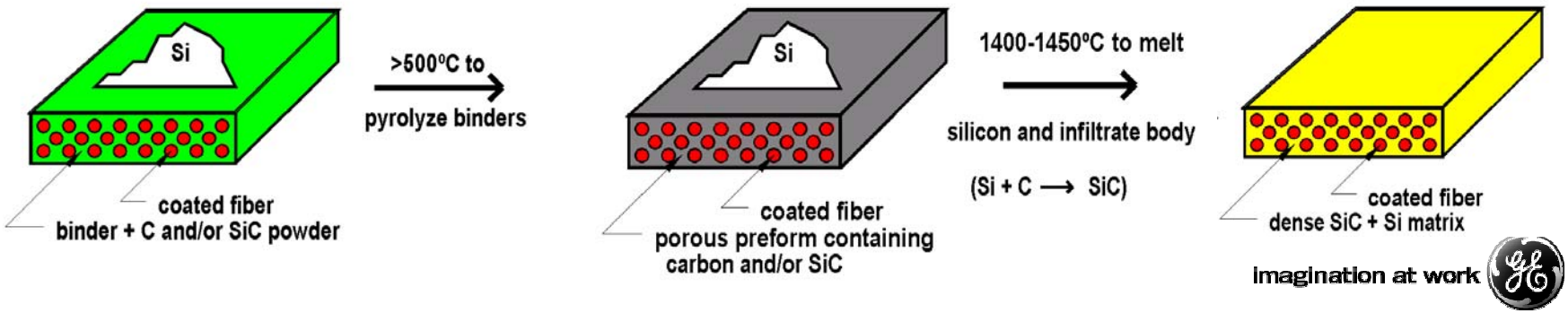



**Prepreg MI**




**Slurry Cast MI**

## Melt Infiltration

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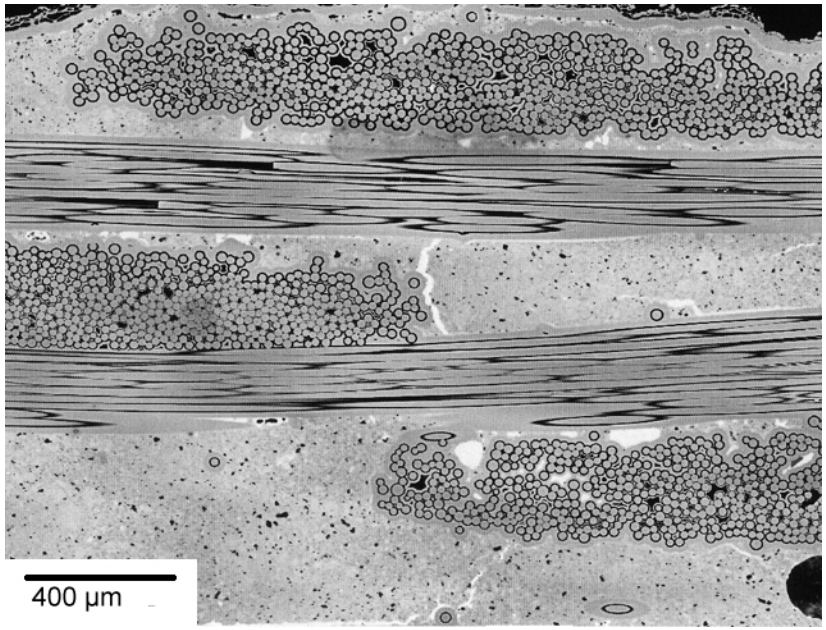
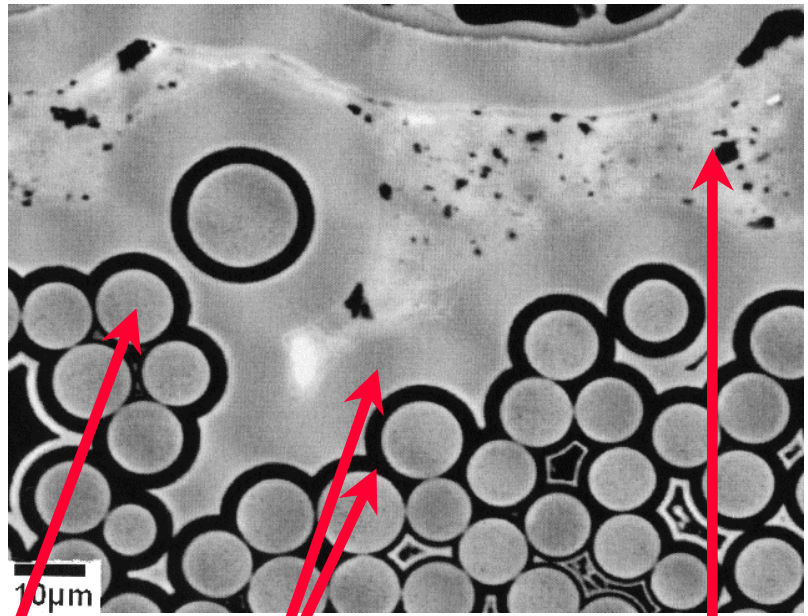
# Microstructure of Slurry Cast MI Composites




**Fiber**

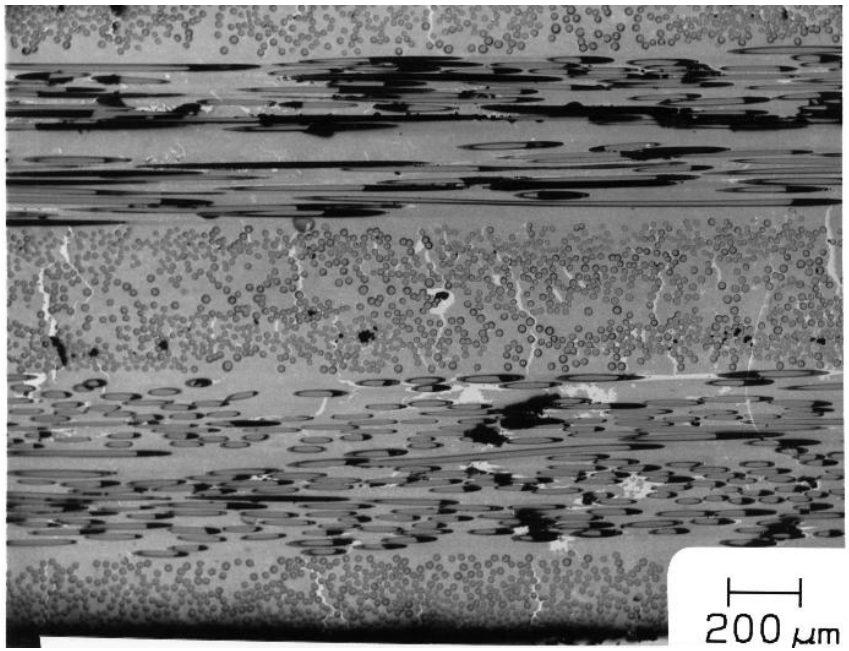
**Fiber Coatings**

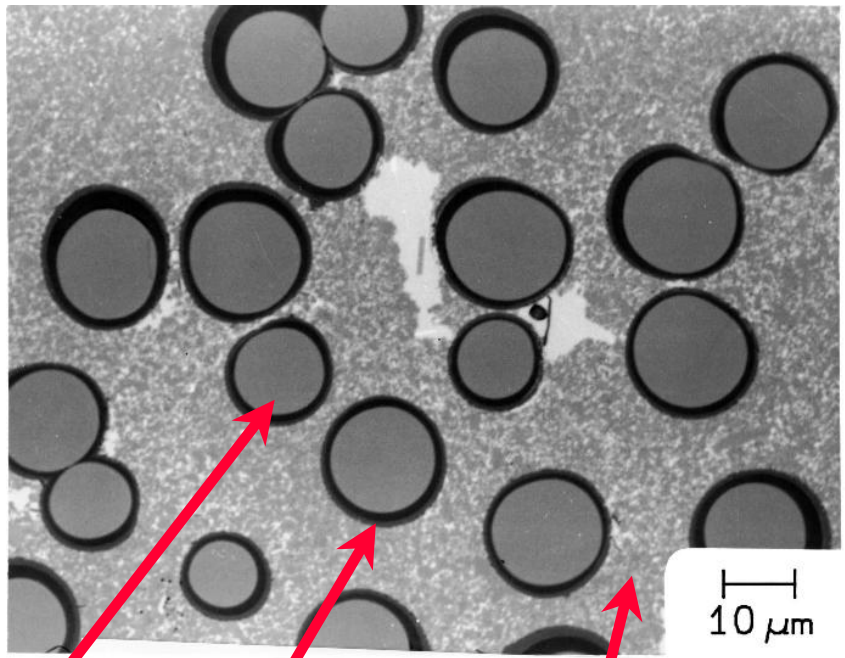
**SiC-Si Matrix**

***Fibers Bunched Together and Interconnected Fiber Coatings***

***~5-6% matrix porosity***

# Microstructure of Prepreg MI Composites




**Fiber**

**Fiber Coating**

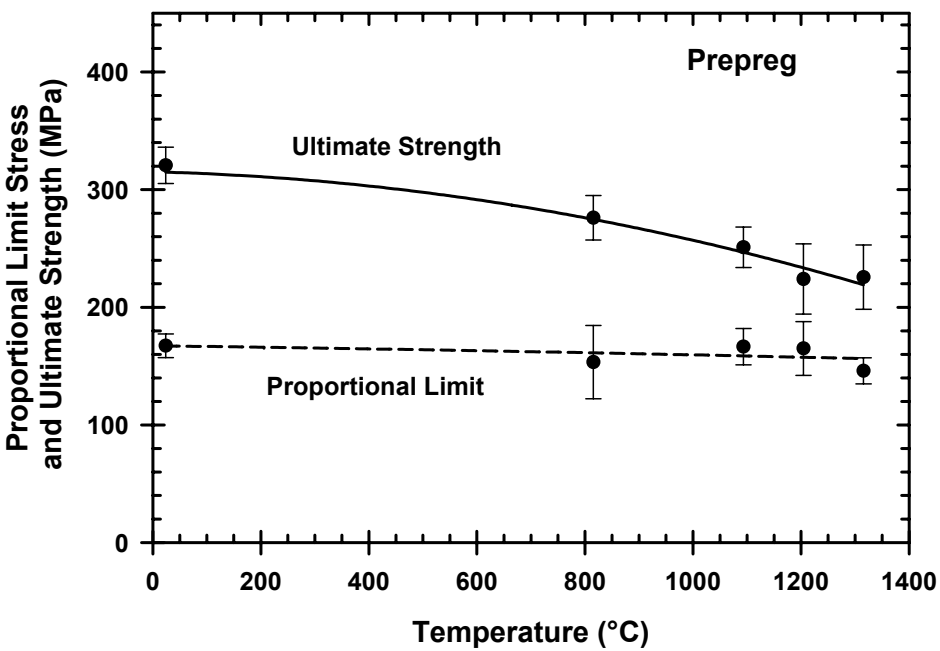
**SiC-Si Matrix**

***Separated Fibers and Fiber Coatings***

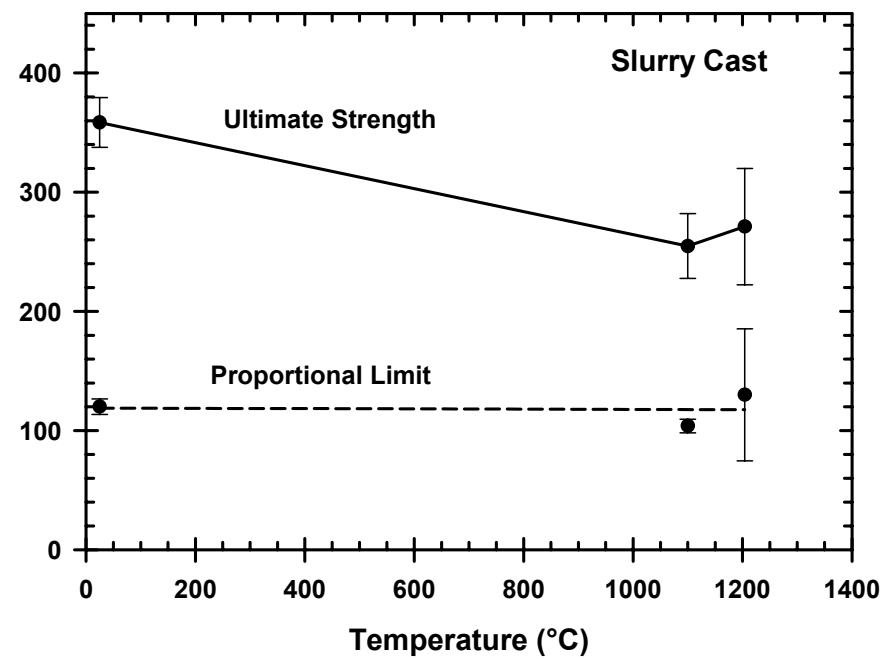
***~2-3% Matrix Porosity***

# HiNicalon Reinforced MI Composites

## Prepreg




## Slurry Cast

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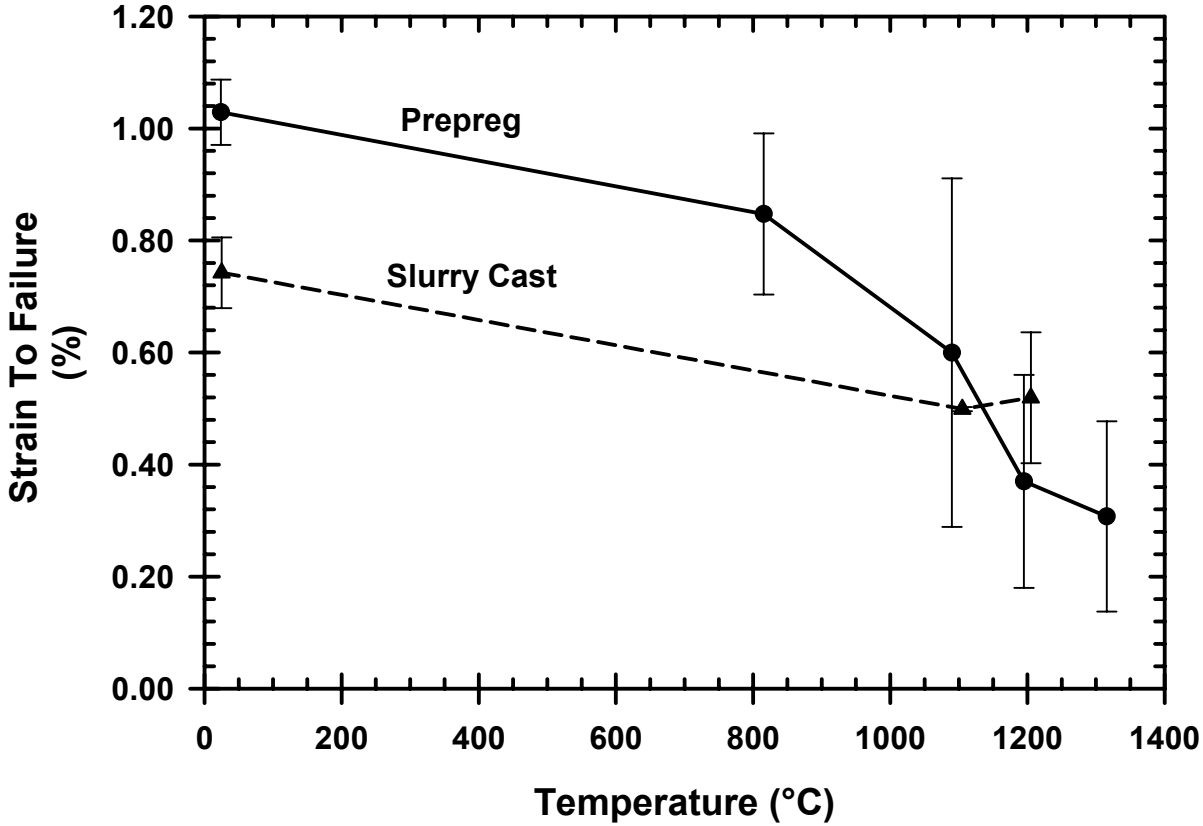
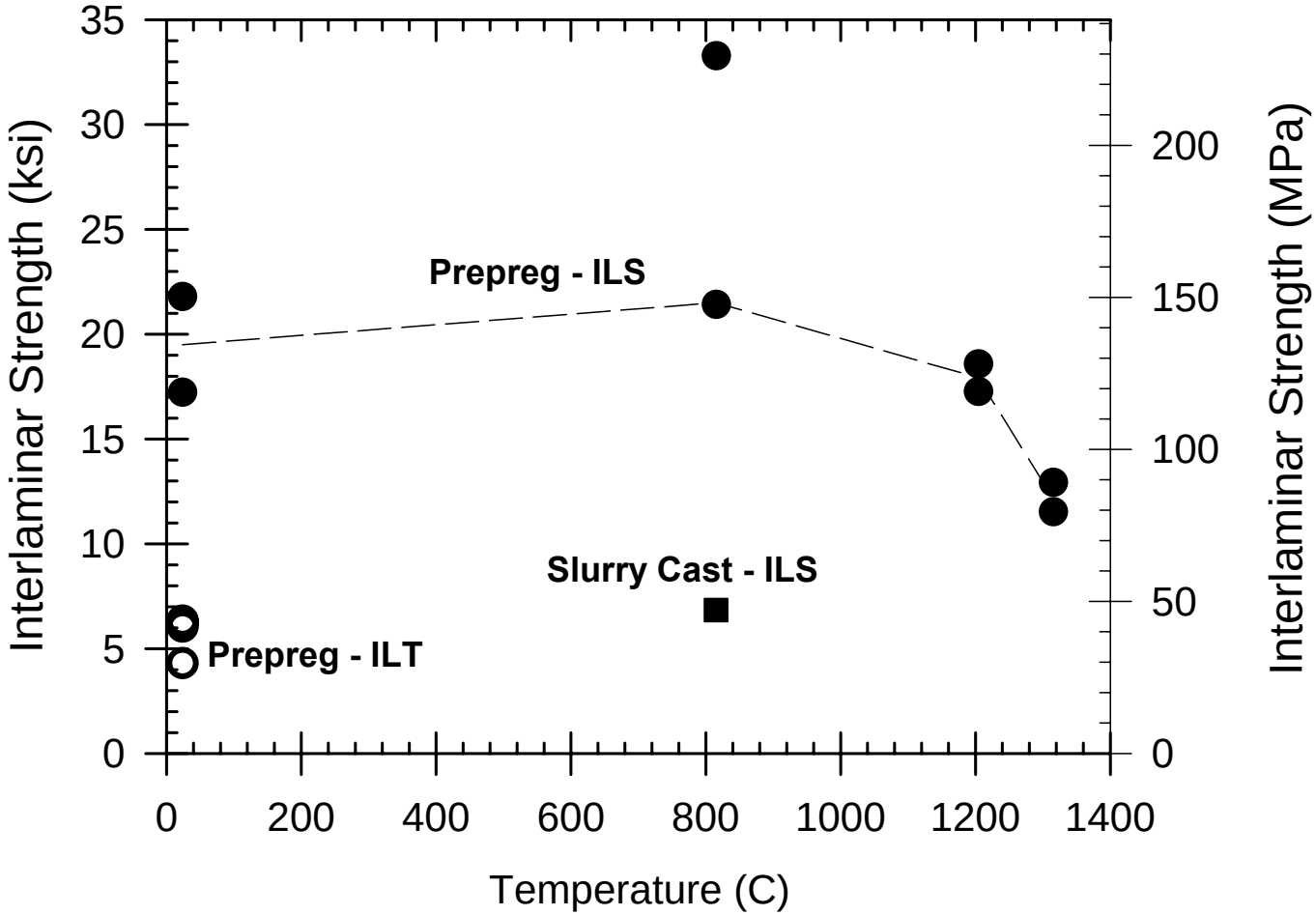
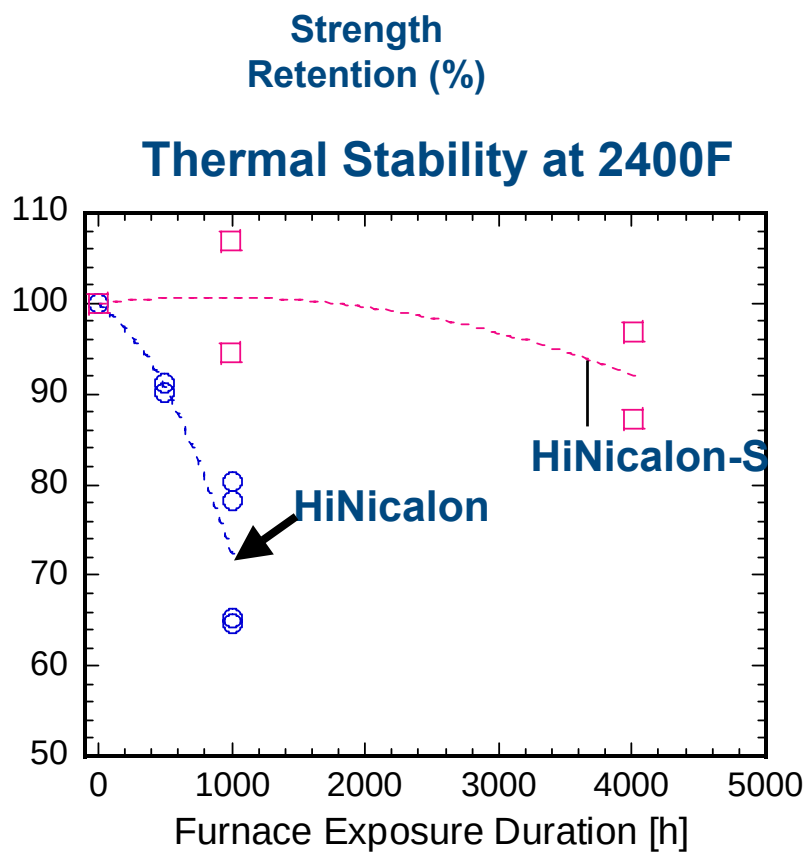
# HiNicalon Reinforced MI Composites

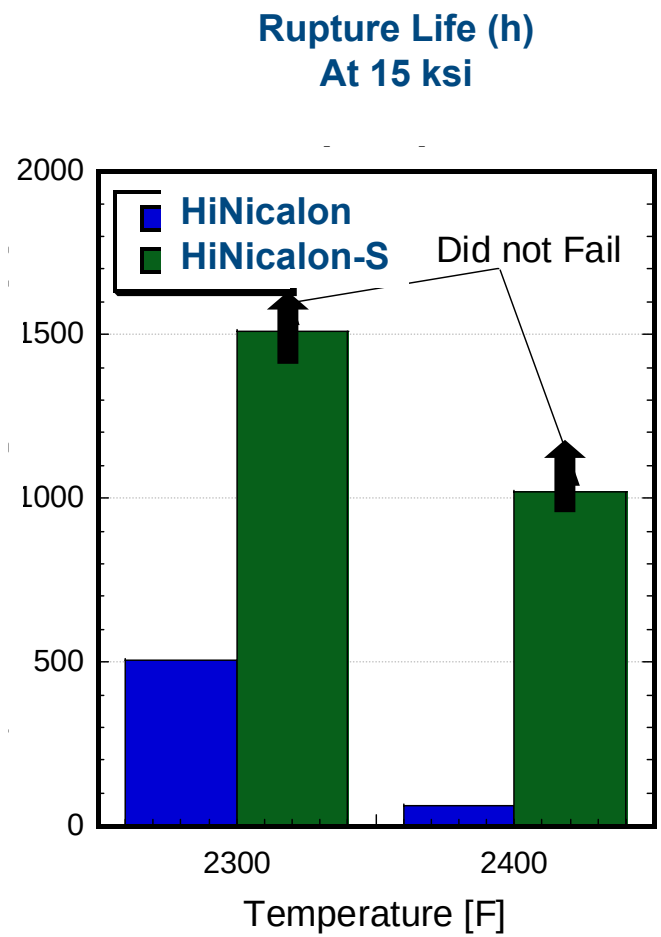


# HiNicalon Reinforced MI Composites



# Prepreg MI Composites



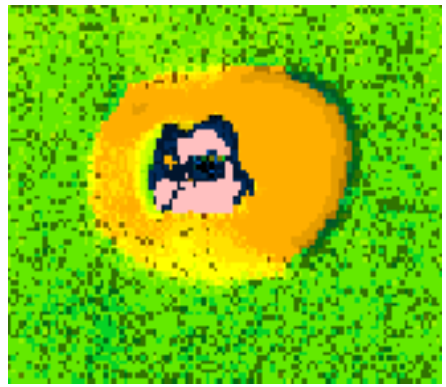



# Foreign Object Damage

- **Use ballistic impact to simulate foreign object damage**
  - 0.175” chrome steel ball bearing at 310m/s (18J)
  - damage localized to impact site
  - impacted sample exposed in shroud rig for 100 hours

**Entrance**

**Exit**

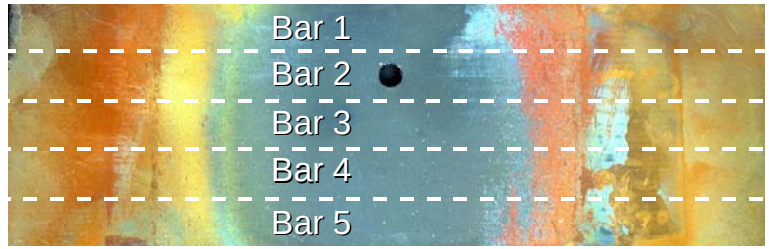


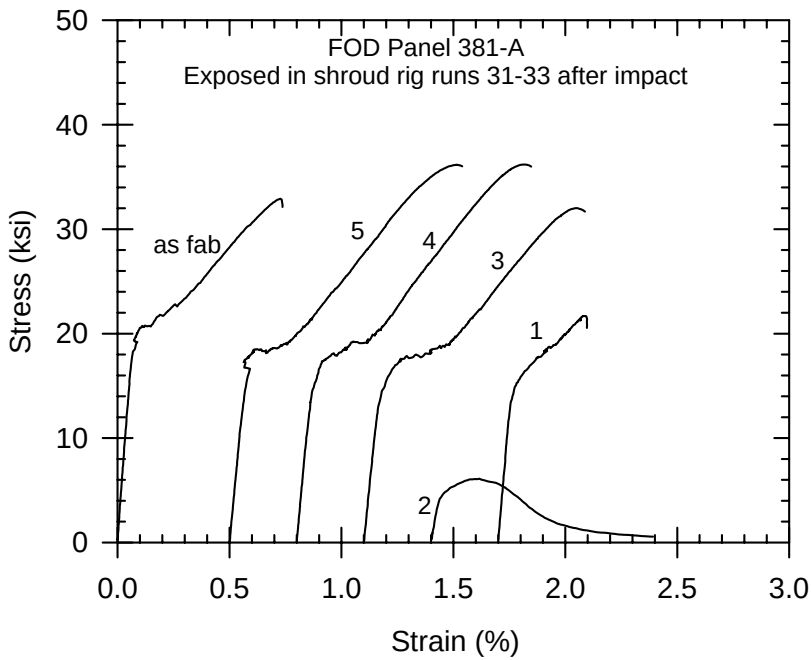
**NDE**

# Foreign Object Damage

**Panel exposed in high pressure shroud test rig**

- 50 hours at 1425°C + 50 thermal shock cycles + 100 hours at 1315°C
- Panel sectioned and residual tensile strength properties measured
- No growth of impact damage zone
- Degradation of Bar #1 due to end-on oxidation effects

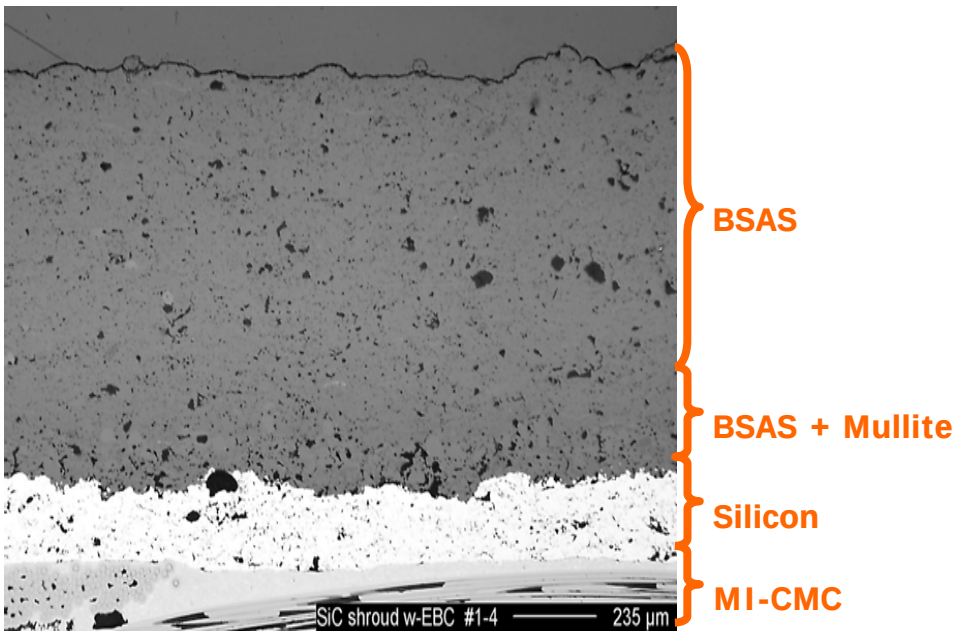


# Material System

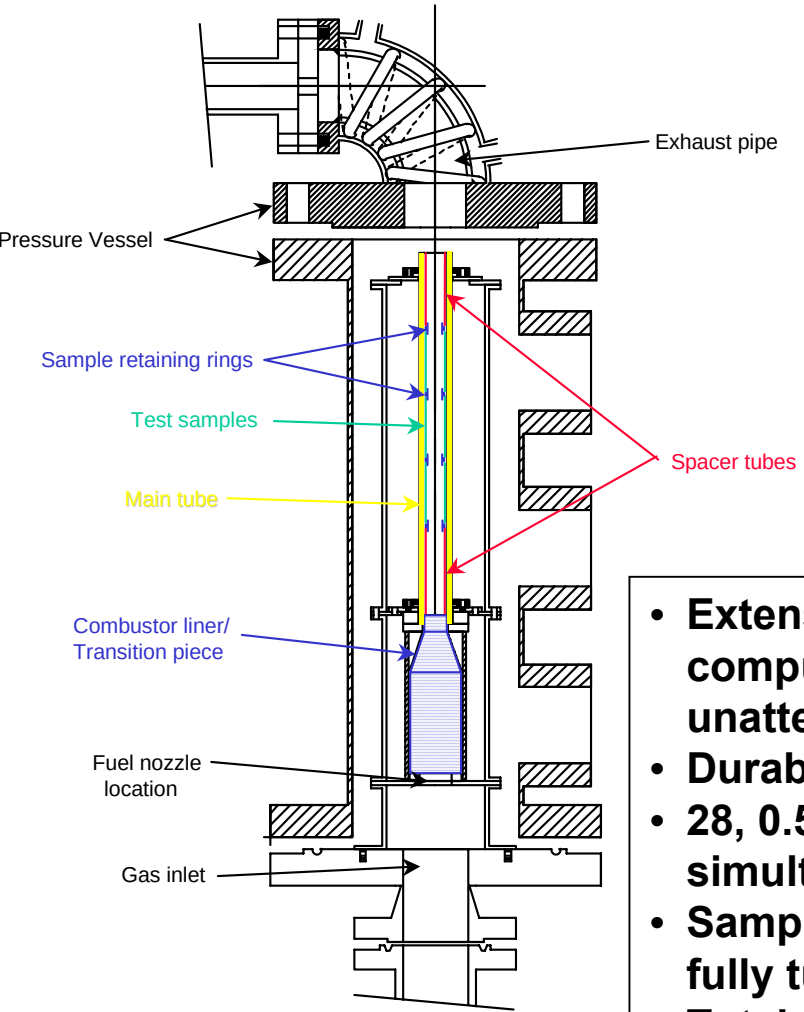
Environmental Barrier Coating (EBC) needed for turbine applications to prevent silica volatilization and surface recession from water vapor in combustion gas

$$SiO_2 + H_2O \rightarrow Si(OH)_x \text{ (gas)}$$

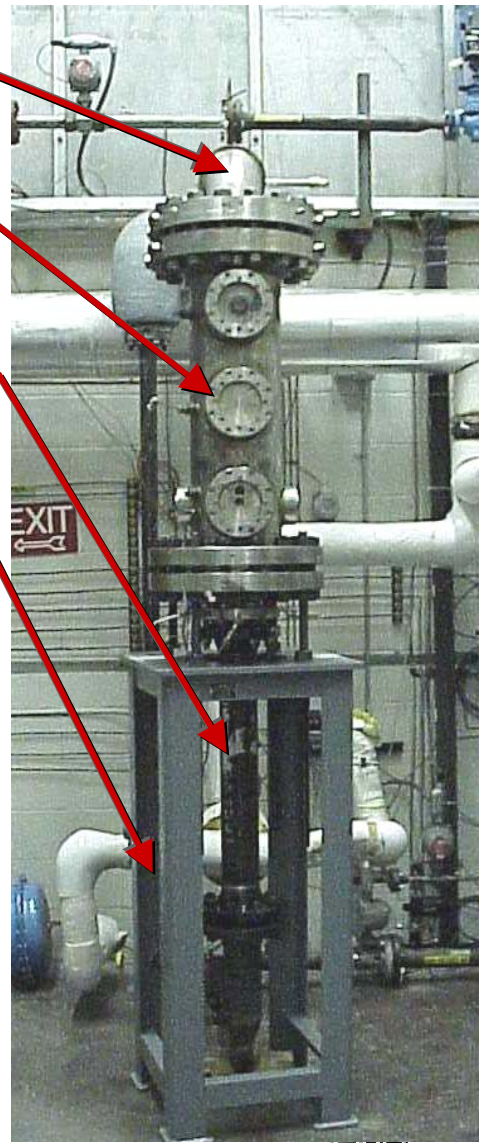



- 3-layer EBC system
- Application by thermal spray techniques
- BSAS – water vapor recession resistance
- BSAS + mullite – transition layer for CTE match
- Silicon – oxidation resistance

# Combustion Rig Testing of EBC Coatings



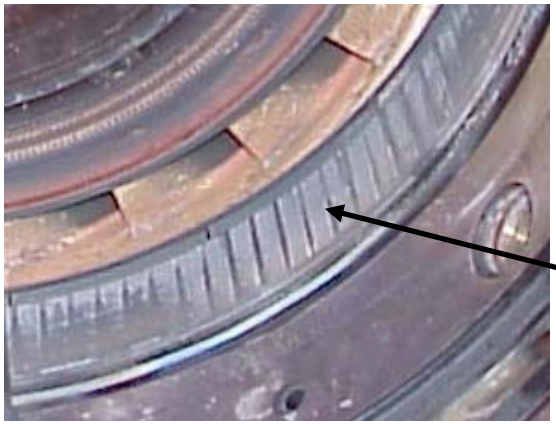

- **Extensive process monitoring & computer control for unattended operation**
- **Durable CMC hardware**
- **28, 0.5” x 4” coupons are tested simultaneously**
- **Sample surfaces exposed to fully turbulent flow**
- **Total run time > 8000 h**
- **BSAS EBC’s exposed → 3922 h**



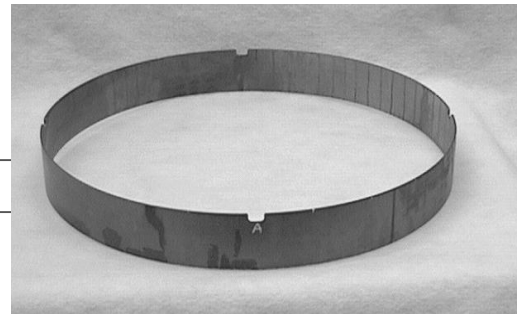
# Outline

- Introduction
- Material System & Properties
- **Engine Test Experience**
  - > **2 MW S1S & S2S**
  - > **7FA S1S**
  - > **Solar Combustor Liner**
- Risks and Challenges
- Summary and Conclusions

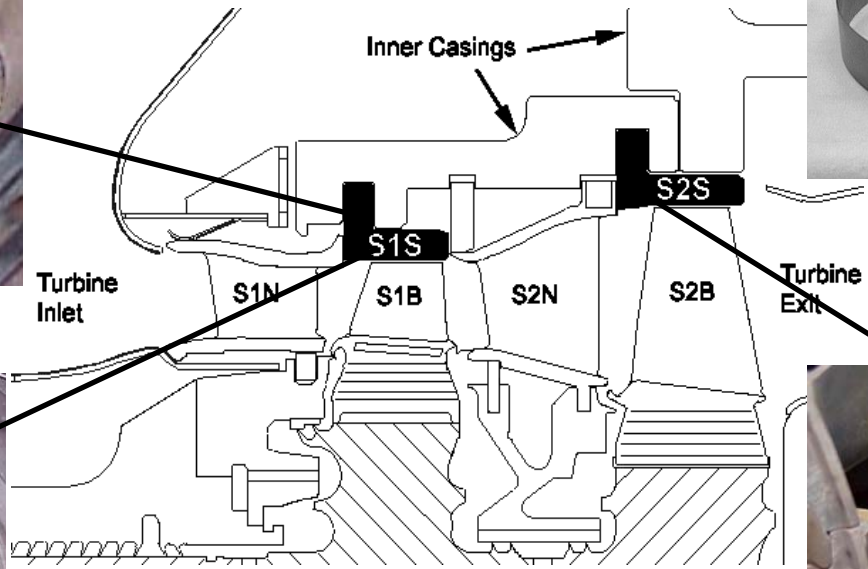
# GE2 S2S and S1S Testing



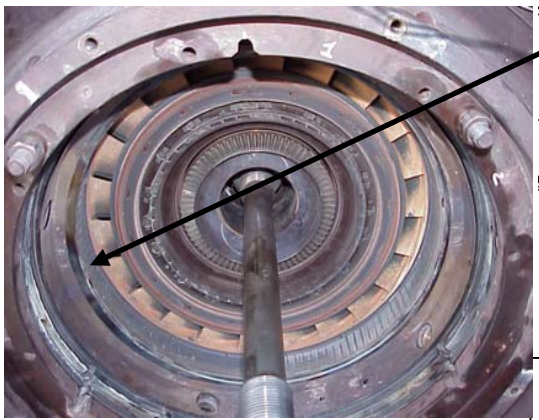
First Stage CMC Shroud



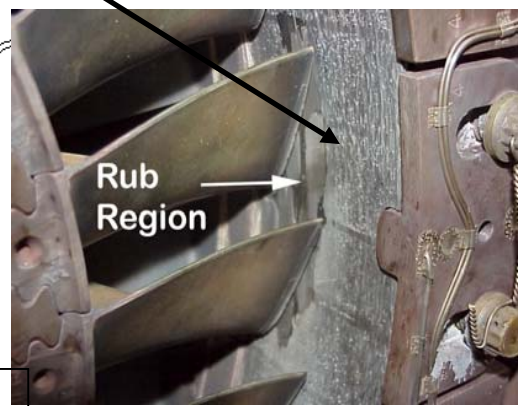
18.5" CMC Second Stage Shroud Ring




PGT-2 Turbine Cross Section Operated at Gas Temp of ~1875F



View aft looking forward

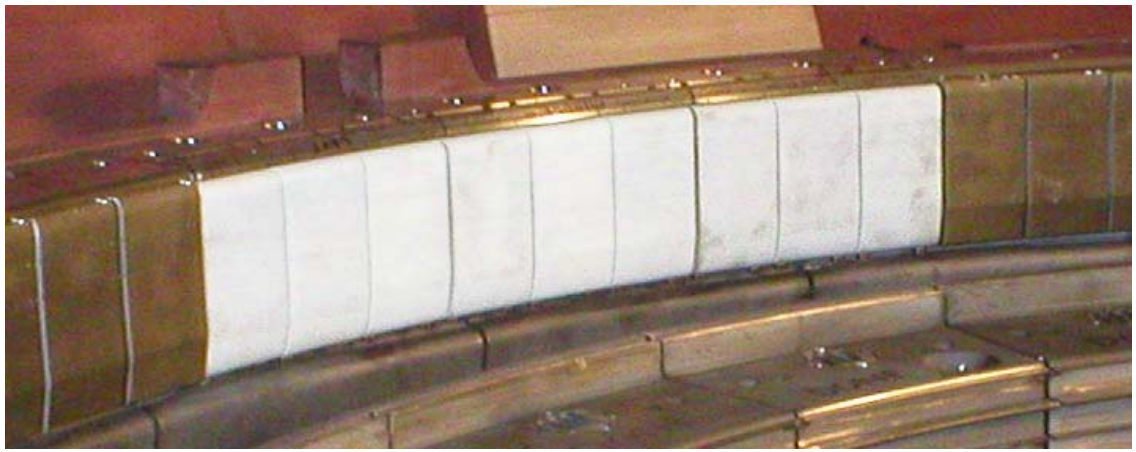


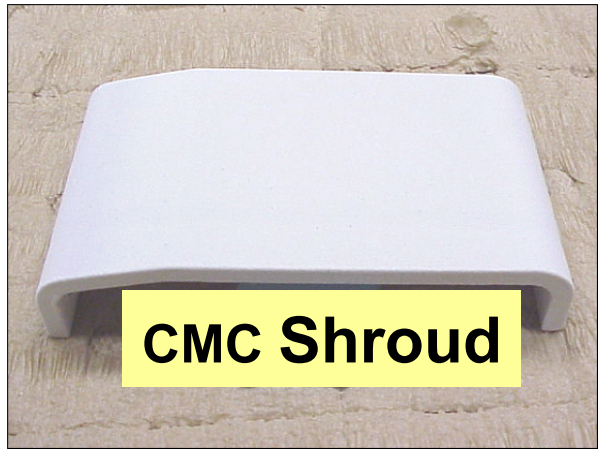

Blade Rub on Second Stage CMC Shroud

*S1S and S2S Testing:*
- 1070 hrs
- S1S had 46 starts, 24 trips, 1 blade rub
- S2S had 61 starts, 27 trips, plus over 3 blade rubs

**Successful Testing of Prepreg CMC Shrouds**

# 7FA Field Engine Rainbow Test



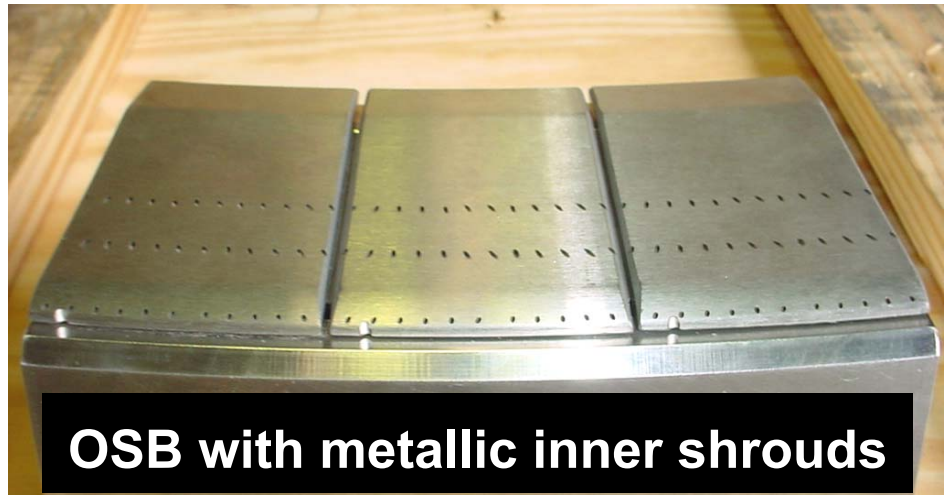



- Shrouds exposed for 5000+ fired hours and 10+ start/stop cycles with no shroud failures, engine operation issues or instrumentation anomalies
- Engine firing temperature range 2250-2350°F (1232-1288°C) on daily cycle
- CMC inner shroud maximum surface temperature ran 2200° to 2300°F

**Field Engine Test Was A Success !**

# Shroud Block Assembly / Instrumentation

- Three outer shroud blocks, each containing 2 Pre-Preg and 1 Slurry Cast CMC inner shroud were assembled and instrumented
- CMC shrouds replicate metal shroud hot gas path profile
- 49 thermocouples used for monitoring outer shroud block and attachments - CMC inner shroud temperature inferred from OSB measurements and thermal models



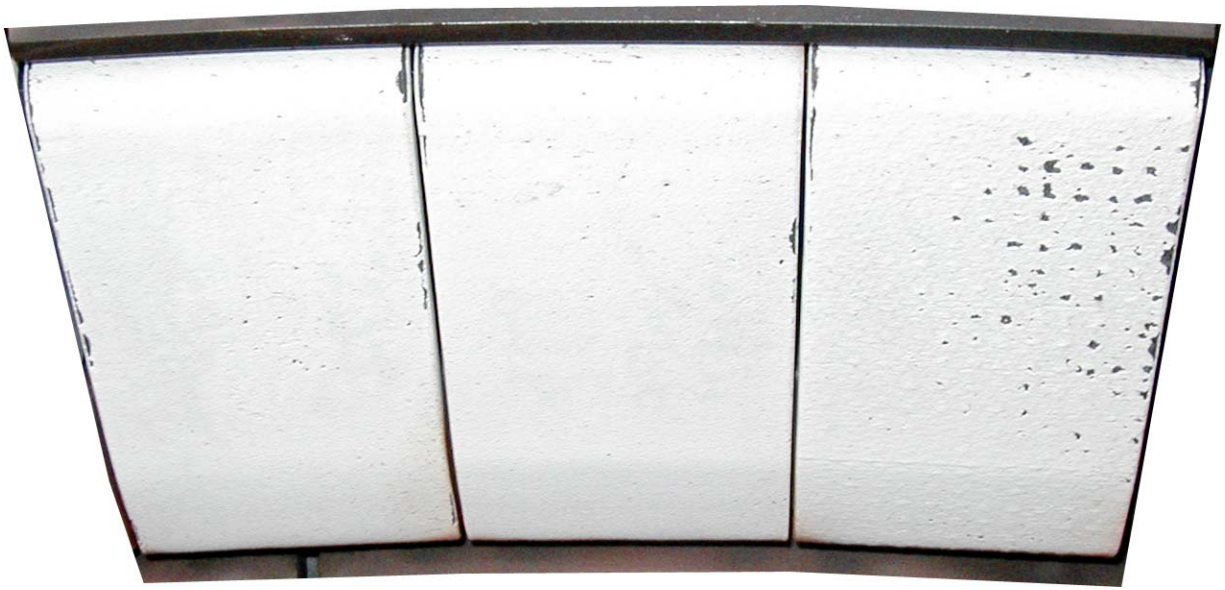
OSB with metallic inner shrouds

OSB with CMC inner shrouds

# Unsealed 7FA Shroud Rainbow Engine Test

**Post-test inspection shows no structural damage to CMC inner shrouds**

- No cracking or mechanical wear of CMC
- No damage to CMC inner shroud, to outer shroud block or to attachments
- Cracking/chipping of EBC along shroud edges was common
- CMC recession in areas of EBC spallation



- **No CMC or metallic hardware failures**
- **Design processes validated**

# Slurry Cast Shrouds Characterization

**Characterization of EBC Damage**

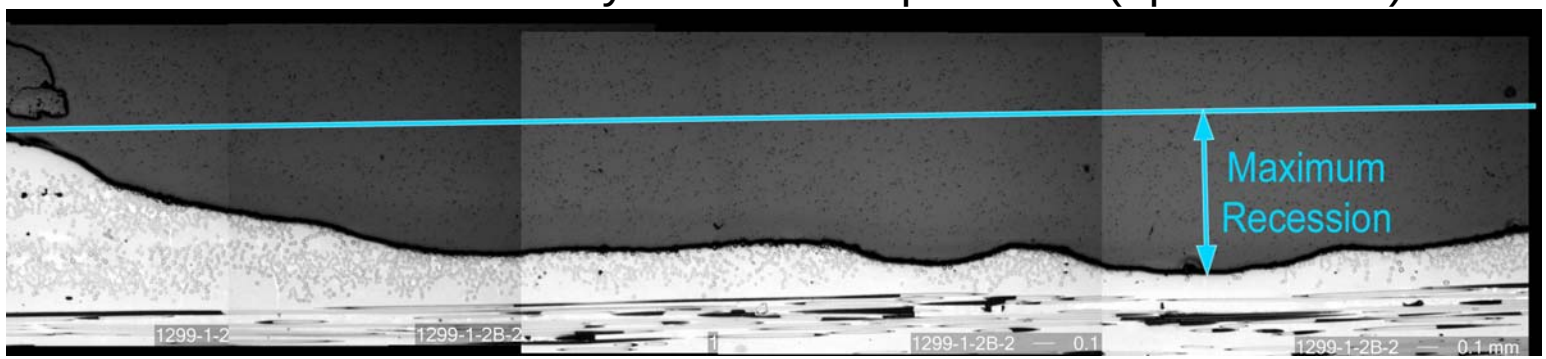
- **EBC cracking along edges leads to eventual EBC chipping**
- **Pin holes**
  - **correspond to "tooling bumps" on slurry cast shrouds**
  - **pits "grew" and "linked up" with continued exposure**
  - **pin hole growth and link-up lead to larger spall**
  - **localized CMC recession below holes**
- **EBC spallation observed**
  - **accompanied by CMC recession**

**Durability improvements to 1st generation EBC are in process**

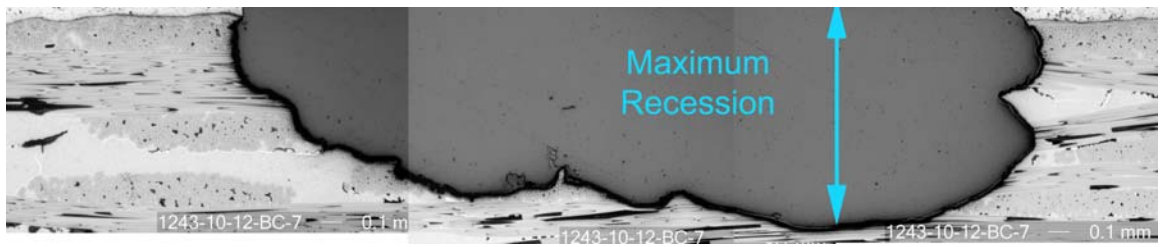
# CMC Recession

- EBC spall noted on prepreg shroud during borescope inspections
- CMC exposed to combustion gases following EBC failure
- Observed maximum recession in this region (~0.8mm) was 20% to 70% of prediction
  - prediction dependent on specific values of the local surface temperature, gas flow, humidity and exposure time
- Deeper recession found under slurry cast shroud pin holes (up to 1.3mm)

**Prepreg**
recession at
EBC spall

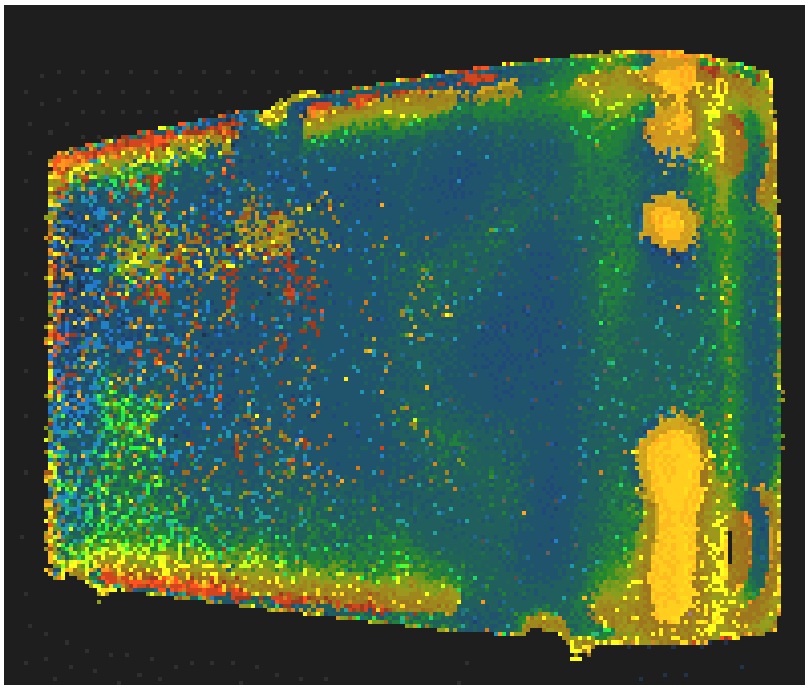



**Slurry Cast**
recession at
EBC pit

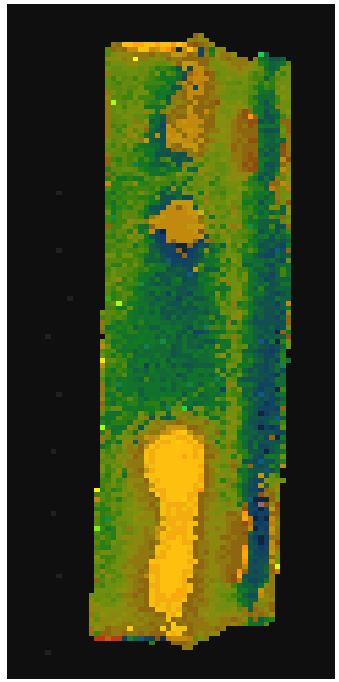



**Prepreg HiPerComp™ CMC recession resistance was better than predicted**

# Post-test NDE of Prepreg Shrouds



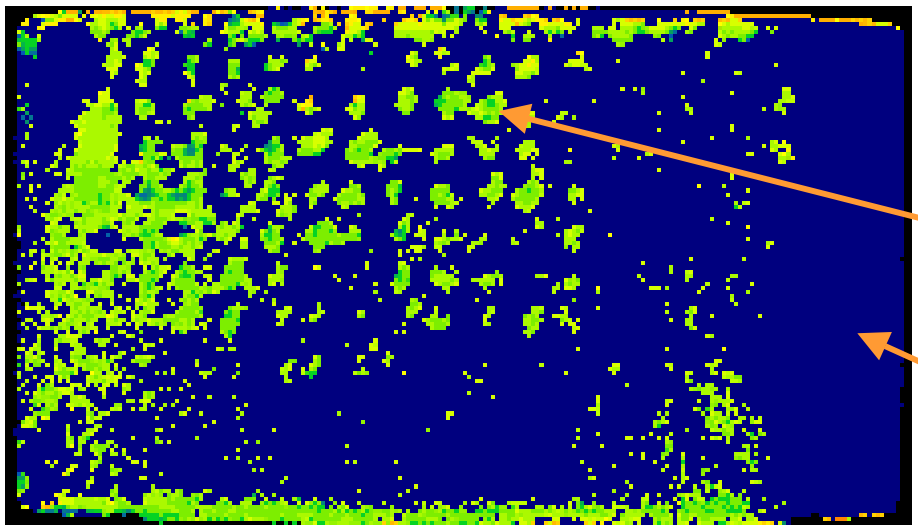
as machined



post engine test
***(coating removed)***

**Defects did not grow in Engine test**

# Post-test NDE of Slurry Cast Shrouds

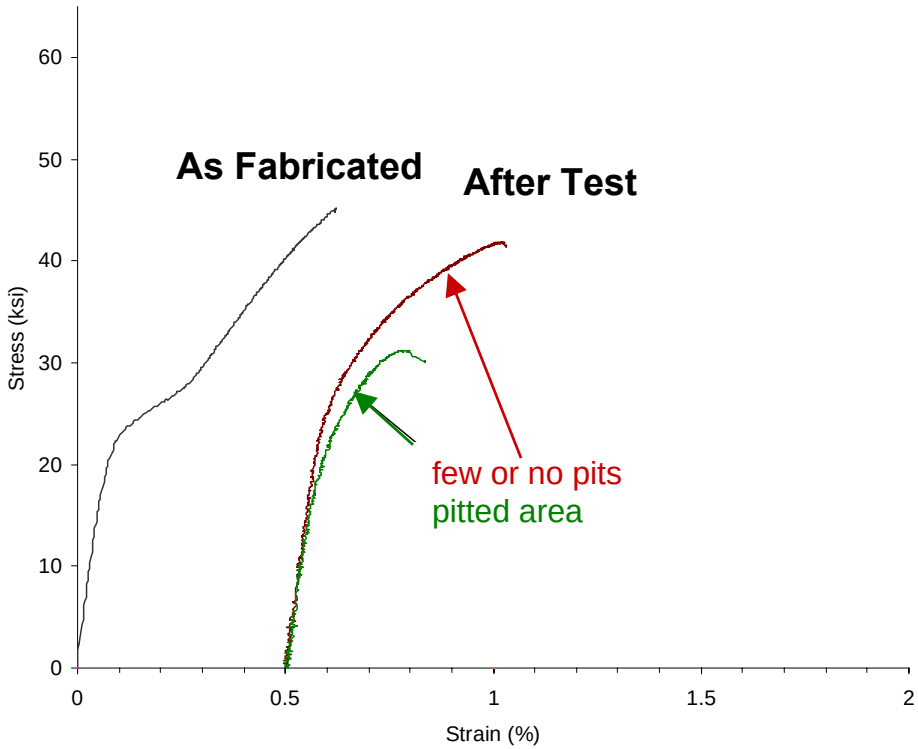


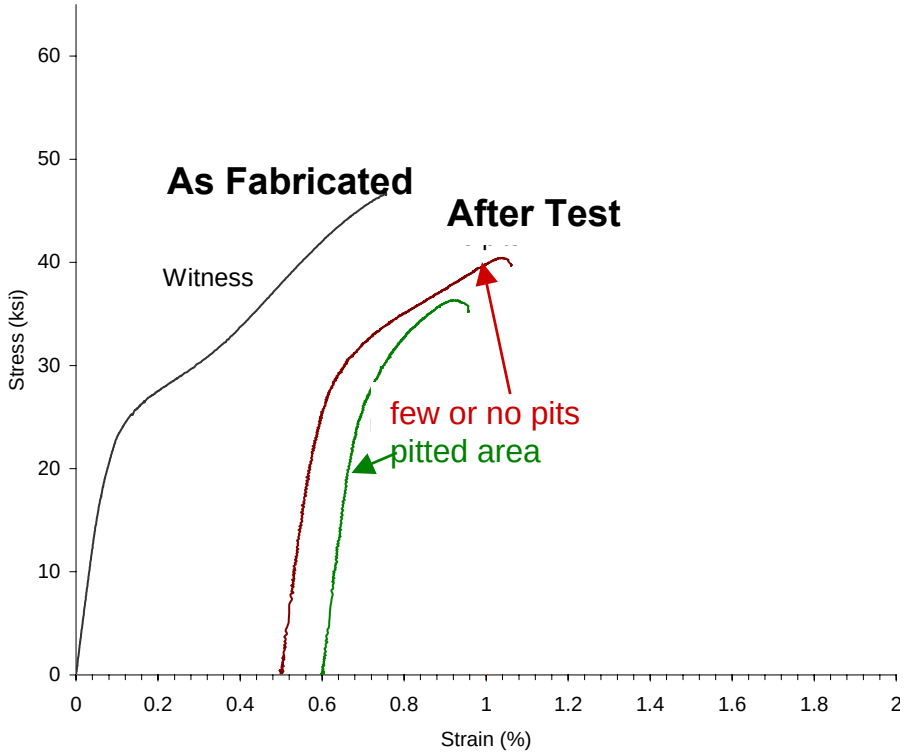
IR NDE showed undercutting of EBC tooling bump pits

**Green - EBC delaminated or undercut by oxidation**

**Blue - EBC is intact or missing**

# Slurry Cast CMC Residual Strength

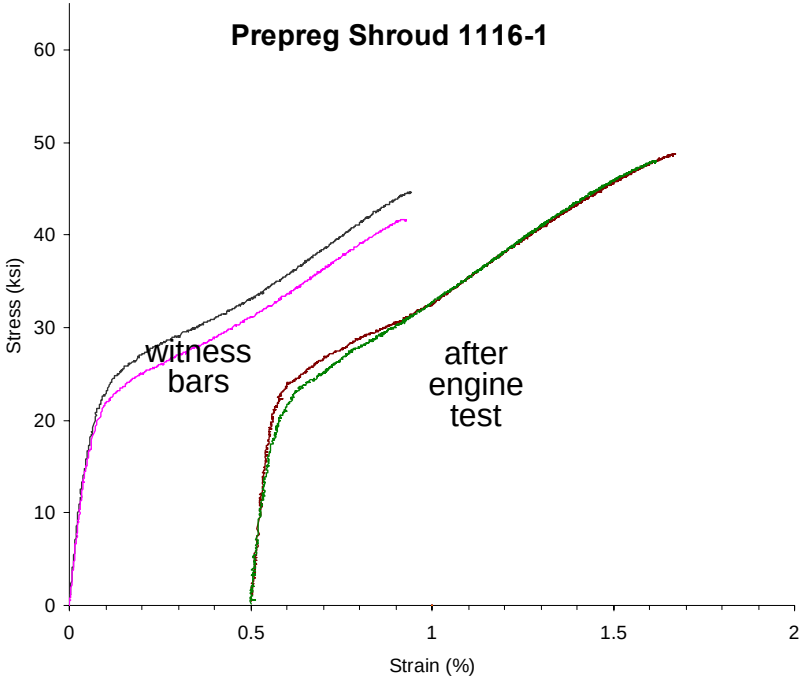


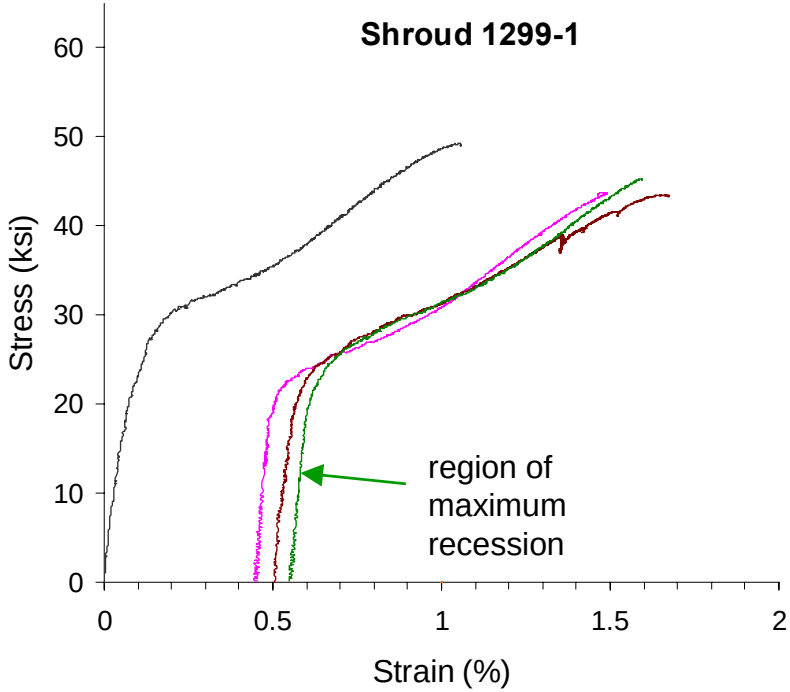

Slurry cast shrouds show loss of strength and strain in regions with EBC damage

# Prepreg CMC Shroud Residual Strength

**Prepreg Shroud**
without EBC spallation




**Prepreg Shroud**
with EBC spallation




**No degradation in mechanical properties for Prepreg system**

# Rig Testing of Sealed Shroud Design

Rig testing was conducted on new sealed shroud design

- During 1st test a compressor trip caused a combustion gas temperature excursion in excess of 3000°F (1650°C) – well above Si melting point
- CMC shrouds survived the accidental excursion, but EBC spallation occurred due to Si bond coat melting
  - Post-test destructive analysis showed CMC shrouds retained strength and toughness despite overtemp condition

# Prepreg CMC Combustor Liner in Solar CSGT Engine

**Combustor liner fabricated in late 2004**

**In service in Solar Centaur 50 CSGT engine at Chevron/Texaco site in Bakersfield, CA since January 2005**

- Liner has accumulated >7500 hours and >20 cycles as of April 17, 2006

**Borescope inspections performed at 3983 and 5706 hours**

- No distress on CMC
- EBC adherent even on pre-existing fabrication flaws
- Some preliminary evidence of EBC cracks and one minor spall at 5706 hours – possibly related to bond coat or CMC oxidation
- Test Ongoing

# Outline

- **Introduction**
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# Barriers and Risks

Life of MI-CMC Components

- Requires tens of thousands of hours
- Damage propagation after FOD damage
- Requires minimization of processing defects in components

Design of Components

- Adequate attachment compliance to account for thermal expansion mismatch
- Adequate part sealing to realize cooling air flow and leakage goals

Coating Life

- Required minimum of 24,000 hours
- Damage propagation after FOD or otherwise localized damage

Component Cost

- Target is 1.5 - 2 times the metallic component cost
- Current cost 5 - 20 times metallic component costs

# Summary and Conclusions

- Melt Infiltrated SiC/SiC composites are attractive for high temperature applications in gas turbines
  - >High thermal conductivity; low matrix porosity, high proportional limit
- Feasibility of fabricating a wide variety of composites demonstrated
- Successful field engine test of CMC shroud system for >5000 hours and >10 cycles at shroud material temperature up to ~1250$^0$C
- Additional engine test planned on CMC shrouds
  - >With sealing in between shrouds
  - >Material improvements based on first engine test
- EBC life and CMC cost represent the highest risks in commercialization of CMC components
- Technology being transitioned to GE Ceramic Composite Products for Scale up, Cost Reduction, and Commercialization