Keynote Lecture

Advanced Ceramic Matrix Composites (CMCs) for High Temperature Applications

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Abstract

Advanced ceramic matrix composites (CMCs) are enabling materials for a number of demanding applications in aerospace, energy, and nuclear industries. In the aerospace systems, these materials are being considered for applications in hot sections of jet engines such as the combustor liner, vanes, nozzle components, nose cones, leading edges of reentry vehicles, and space propulsion components. Applications in the energy and environmental industries include radiant heater tubes, heat exchangers, heat recuperators, gas and diesel particulate filters, and components for land based turbines for power generation. These materials are also being considered for use in the first wall and blanket components of fusion reactors. In the last few years, a number of CMC components have been developed and successfully tested for various aerospace and ground based applications. However, a number of challenges still remain slowing the wide scale implementation of these materials. They include robust fabrication and manufacturing, assembly and integration, coatings, property modeling and life prediction, design codes and databases, repair and refurbishment, and cost. Fabrication of net and complex shape components with high density and tailorable matrix properties is quite expensive, and even then various desirable properties are not achievable. In this presentation, a number of examples of successful CMC component development and testing will be provided. In addition, critical need for robust manufacturing, joining and assembly technologies in successful implementation of these systems will be discussed.

Advanced Ceramic Matrix Composites (CMCs) for High Temperature Applications

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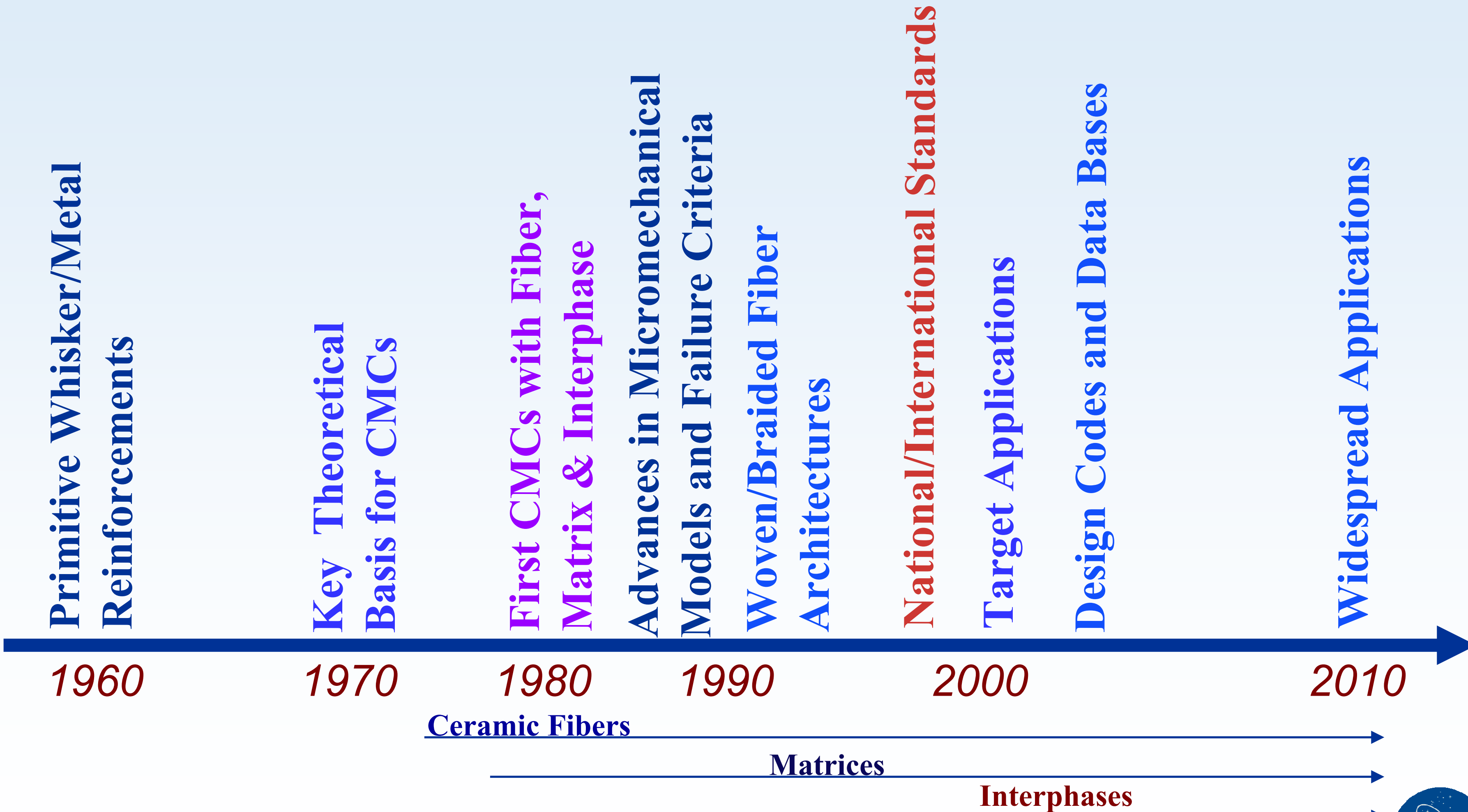
Outline

- Introduction/Background
- Current Status of CMC Technology
- Key Implementation Challenges
  - Fabrication and Manufacturing
  - Assembly and Integration
  - Design Codes, Databases, Standards
  - Life Cycle Analysis and Cost
- Concluding Remarks

Introduction/Background

As materials systems go, the time scale for *serious* development and use for CMCs has been brief.....



Ceramic Matrix Composites Components for Aerospace and Ground Based Systems

Turbine Rotor

Turbopump Stator

Turbine Rear Frame Leading Edge

Interstage Shroud

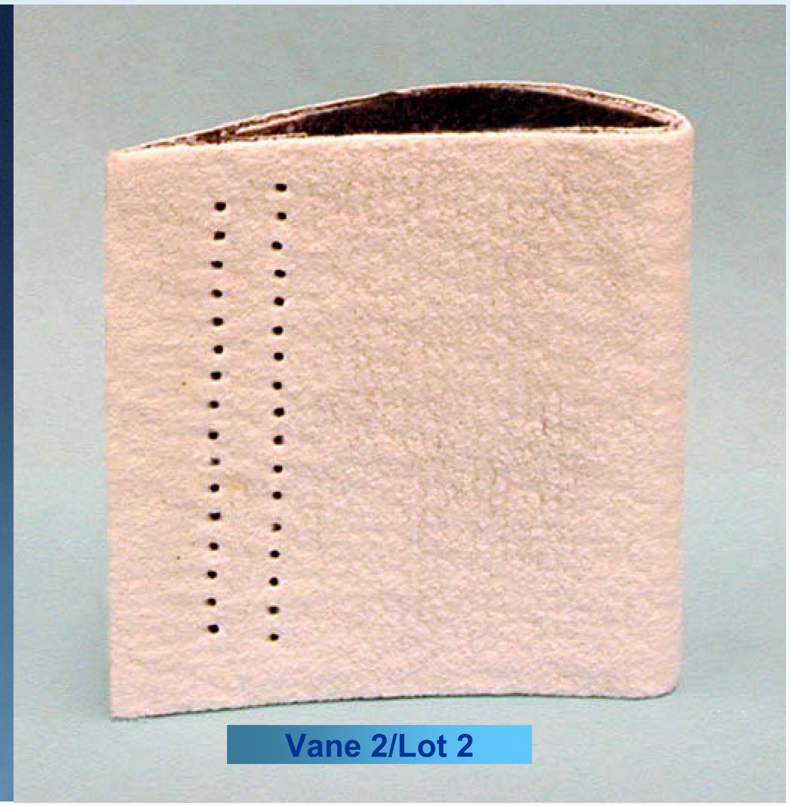
Nozzle Flaps and Seals

Combustor Liner

High Temperature SiC/SiC Composite Vanes

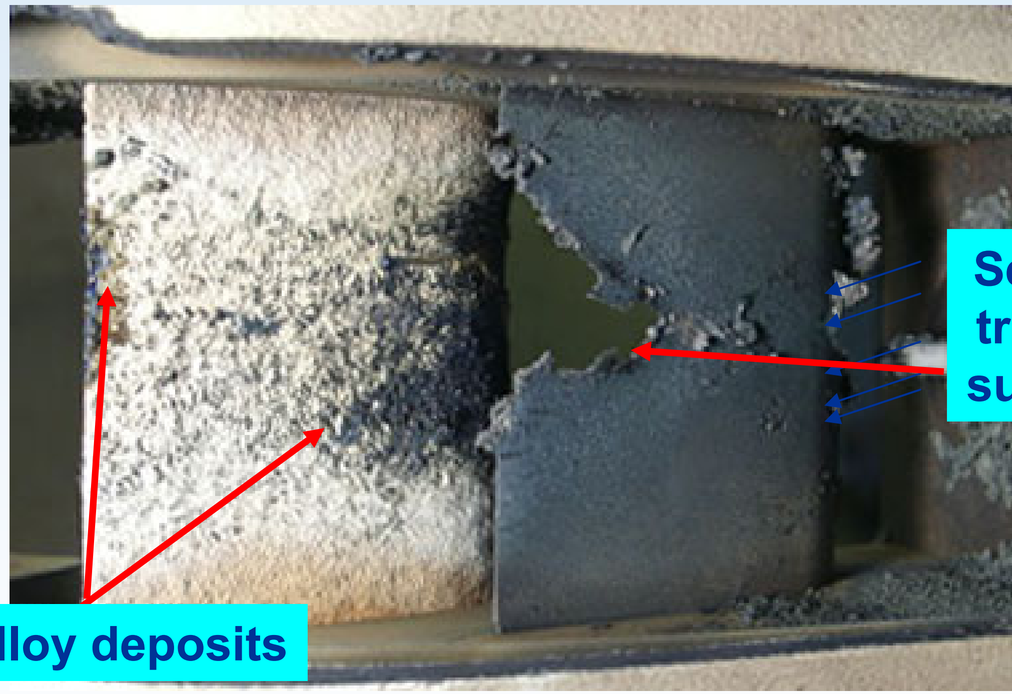
(fabricated by GE Power Systems Composites)

As-fabricated



Machined and coated vane with a Sc silicate EBC and cooling holes

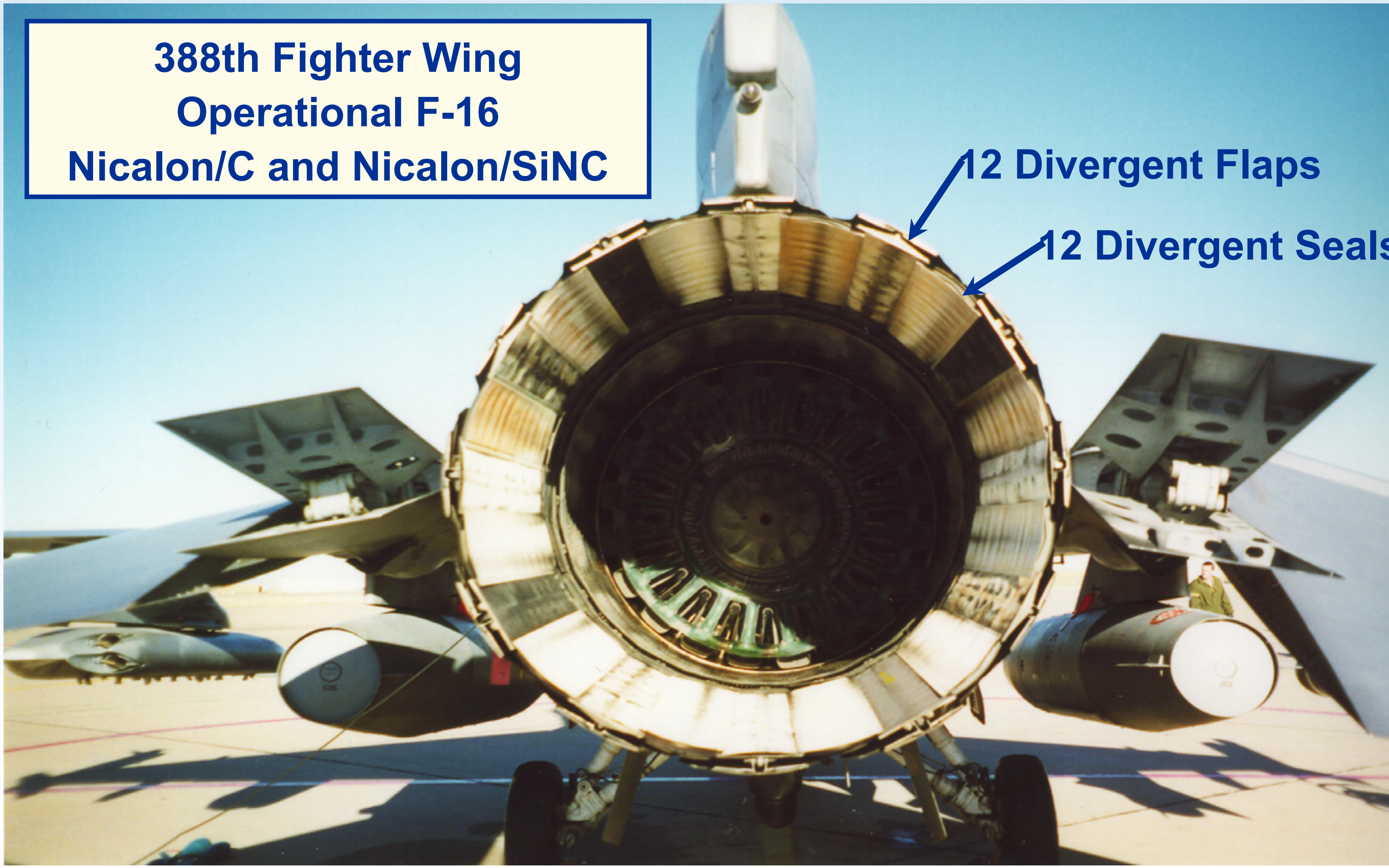
EBC Coated SiC/SiC Vane after 110 Cycles in High Pressure Burner Rig



- No obvious degradation of SiC/SiC vane after 110 cycles
- Superalloy vanes and holder sustain heavy damage.

CMC Components Have Shown Performance Benefits in Aerospace Systems

F110-GE-129 CMC Divergent Flaps



Larry Zawada, AFRL, HTCMC-5, Seattle, WA (2004)

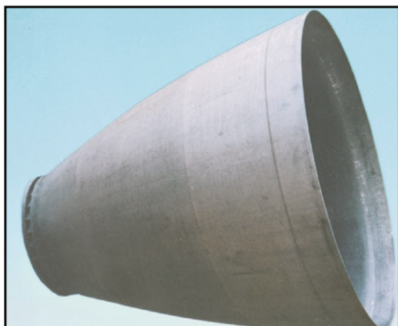
CMC Components Have Shown Performance Benefits in Aerospace Systems

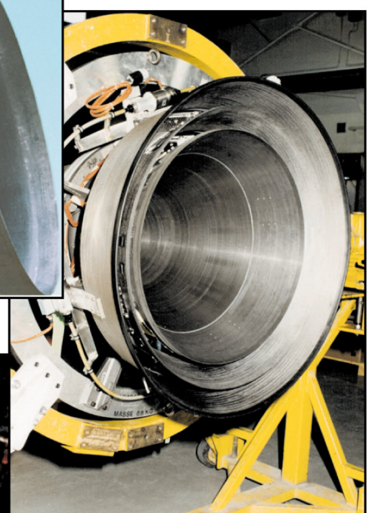
- Ground Tested SiC/C Flaps and Seals in Excess of 6000 Hrs
- Design Live Defined As 500 Engine Flight Hours
- Currently 10 Squadrons with F/A18 E/F Aircraft Flying With SiC/C Exhaust Nozzle Divergent Flaps and Seals
- Actual Service Durability of SiC/C Divergent Flaps and Seals
  - Flaps Averaging >1150 Engine Flight Hours (230% Design)
  - Seals Averaging >850 Engine Flight Hours (170% Design)
- The CMC Hardware is Performing Well in Actual Service

Larry Zawada, AFRL, Dayton, OH

CMCs are Enabling Materials for Components in Space Propulsion Systems

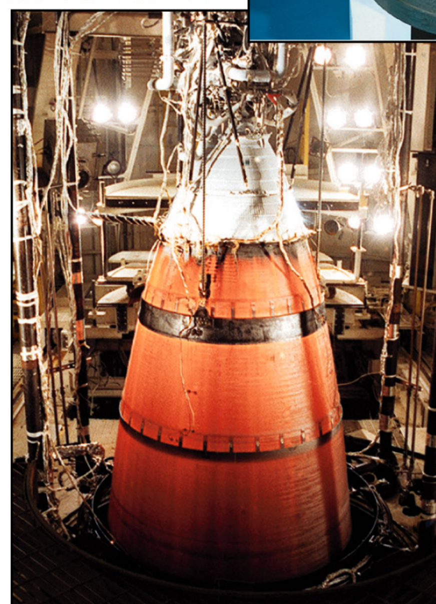
HM7 C-C/SiC nozzle extension





C-C extendible nozzle extension for SRM

C-C extendible nozzle extension for RL10B-2



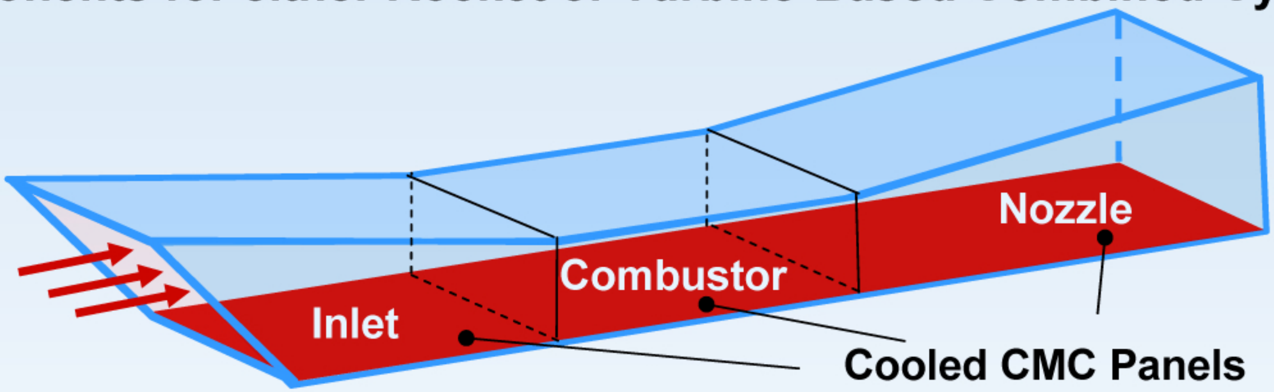
C-C throat - Ariane 5 SRM

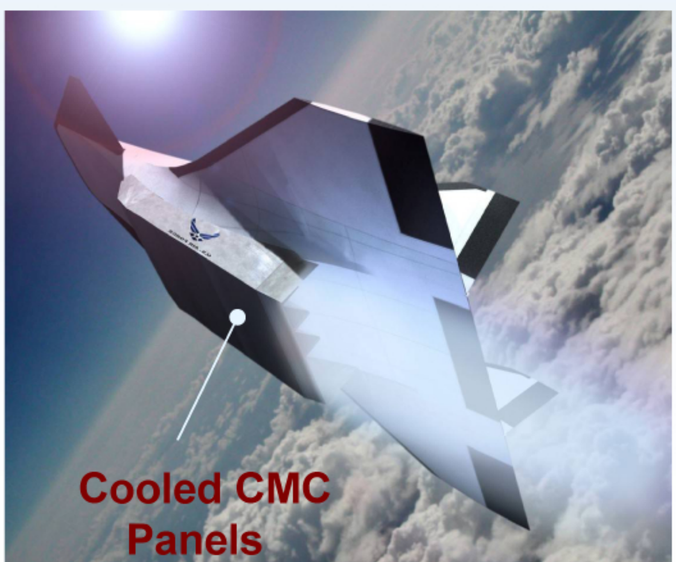
Thrust chamber

Snecma, France

Cooled CMC Panel Applications

- Current Cooled CMCs Panels targeted for hot-flow path propulsion components for either Rocket or Turbine-Based Combined Cycle vehicles



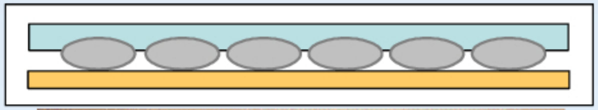


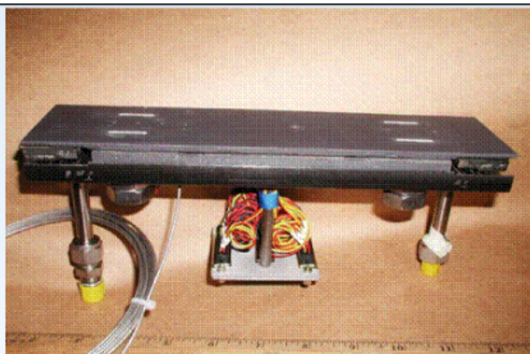
Benefits of Cooled CMCs

- Lighter weight than metallic designs
  – up to 50% weight reduction calculated
- Lower coolant flow requirements
- May eliminate re-entry cooling requirements
- Can provide higher fuel injection temperatures
- Enable vehicle and engine designs/cycles
- Increased operational margin -- translates to enhanced range and/or system payload

Cooled CMC Heat Exchanger Panels Successfully Tested in Rocket Combustion Facility

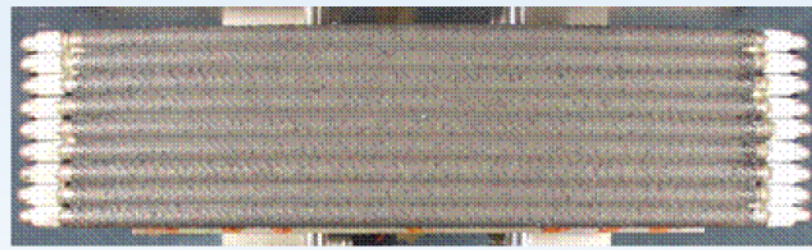
Metal tube, CMC outer

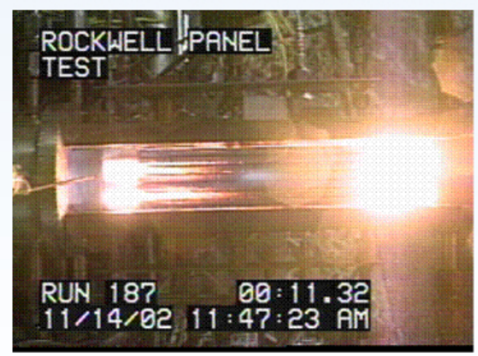




- Successfully completed 18 runs (5.5 min total)
- Max surface temperature – 2600°F, hot streak – 3000°F

Woven CMC tube

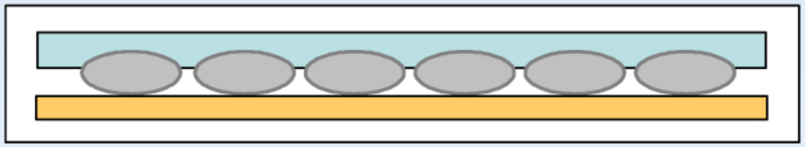


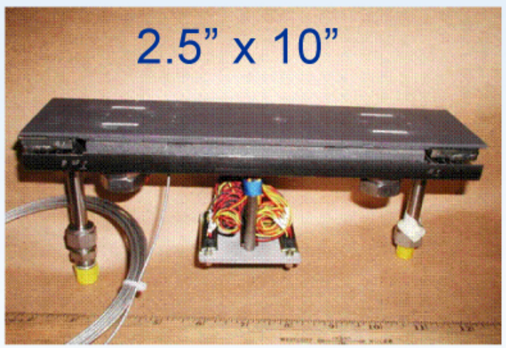


- 20 hot fire runs
- Heat fluxes up to 10.4 BTU/in^2-s

Several Cooled Panel Designs Successfully Fabricated

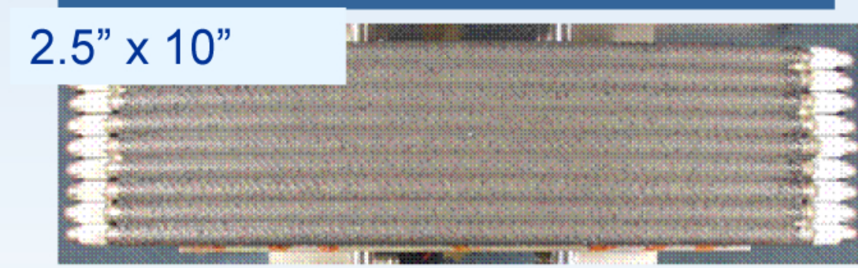
Metal Tube, CMC Outer





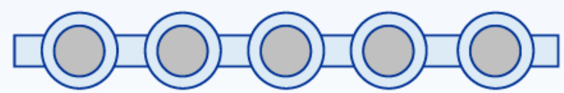
C/C CMC, Outer Seal Coat

Woven CMC tube



C/SiC

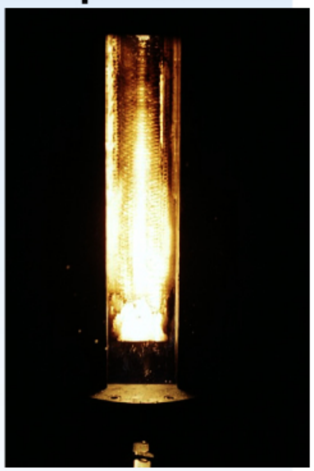
Metallic Tubes Co-Processed With CMC



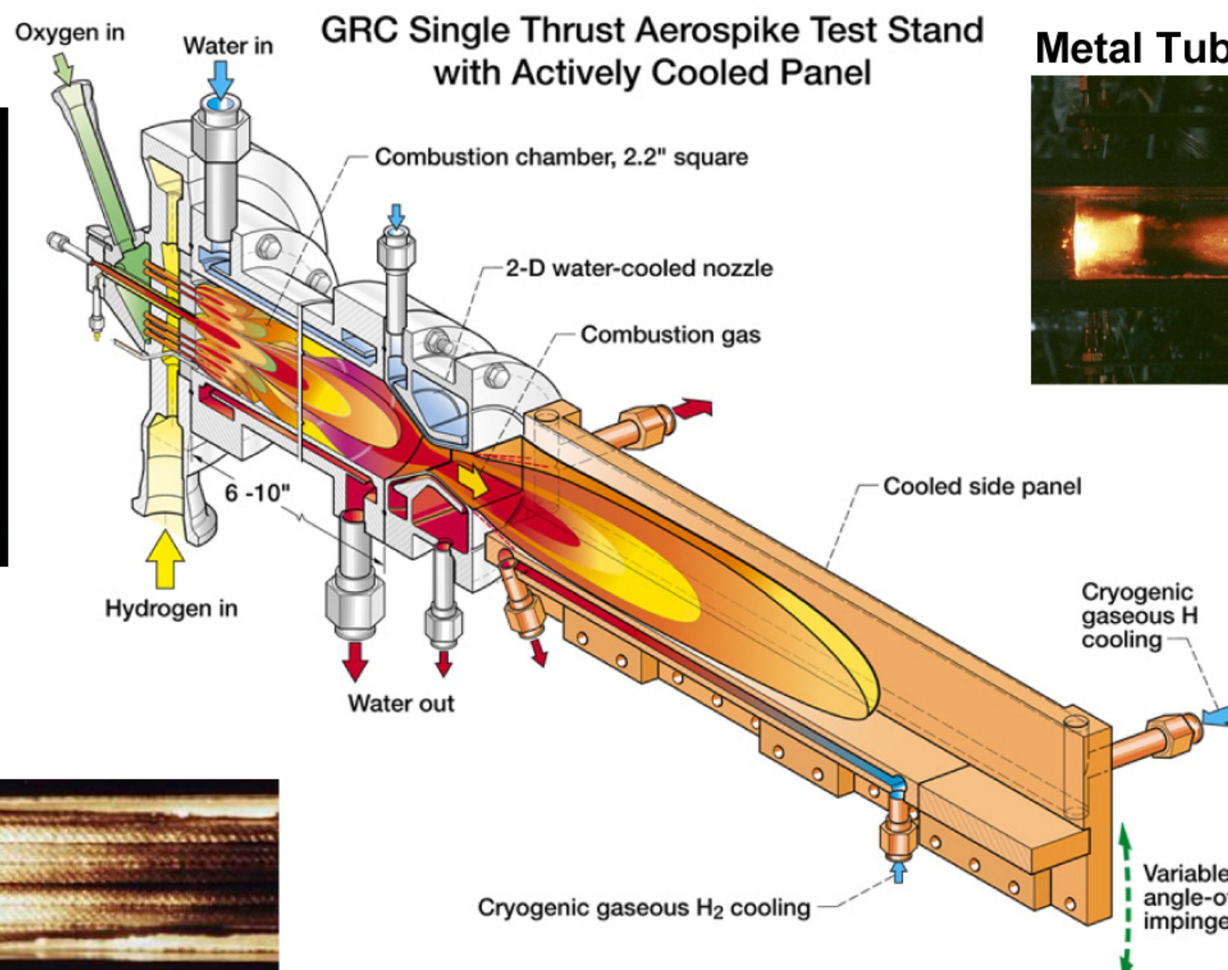
C/SiC
+
Mo-Re

Cooled CMC Panels Tested in NASA's Research Combustion Facility (Cell 22)

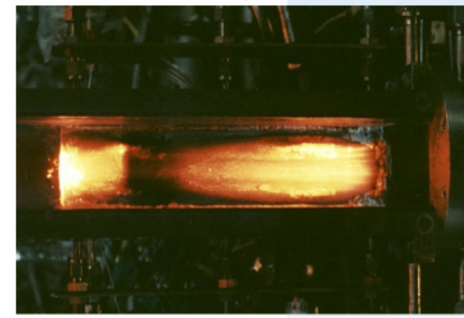
Co-processed



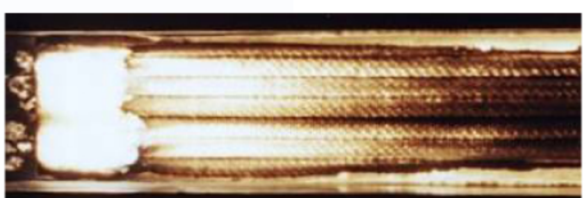
GRC Single Thrust Aerospike Test Stand with Actively Cooled Panel



Metal Tube, CMC outer

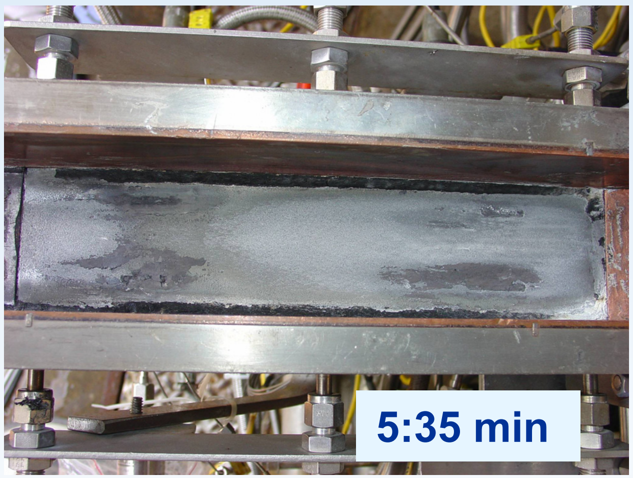


Woven CMC

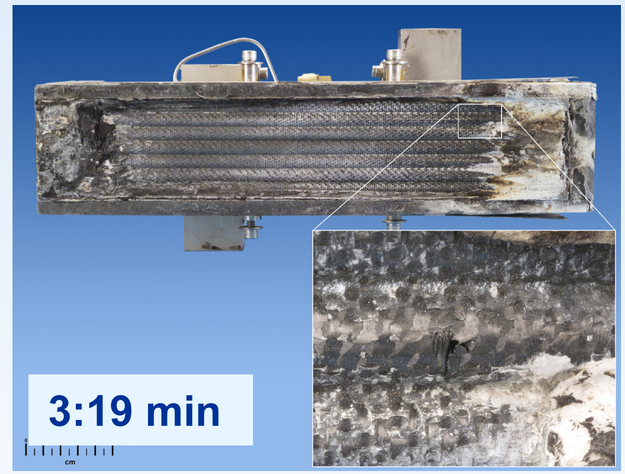


Cooled CMC Panels Survived Rig Testing Without Catastrophic Failure

Metal Tube, C/C outer with seal coat



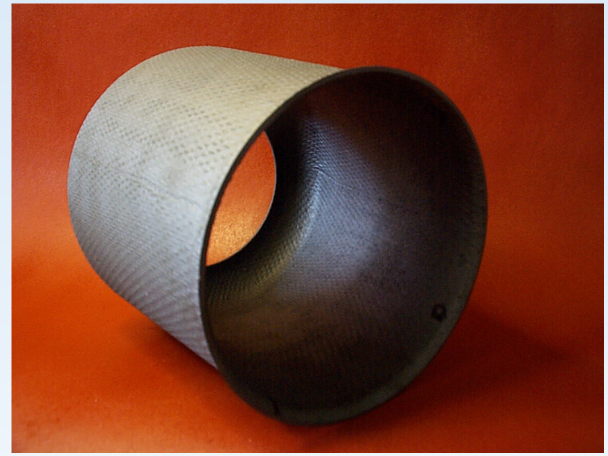
Woven CMC, C/SiC



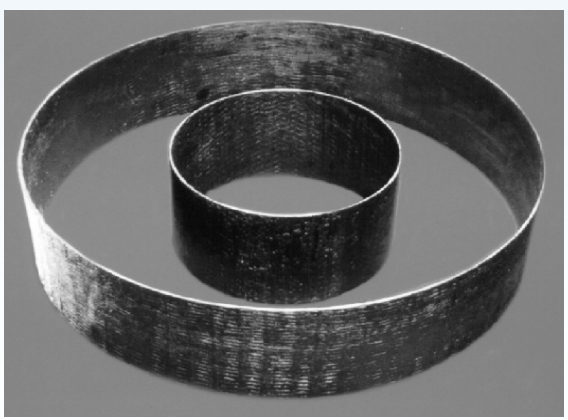
C/SiC CMC Co-processed with Mo-Re

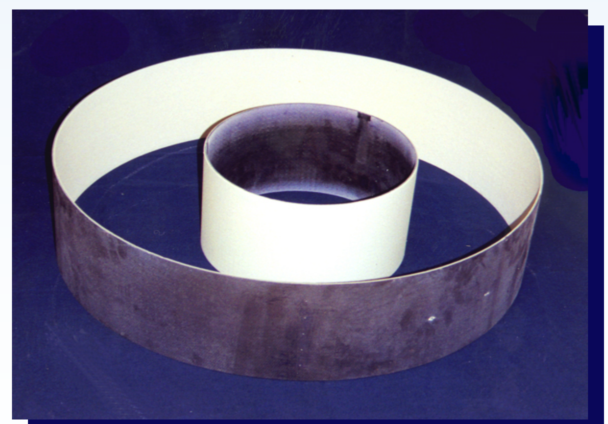
Minor damage observed for all panels after rig testing

Ceramic Matrix Composite Combustor Liners



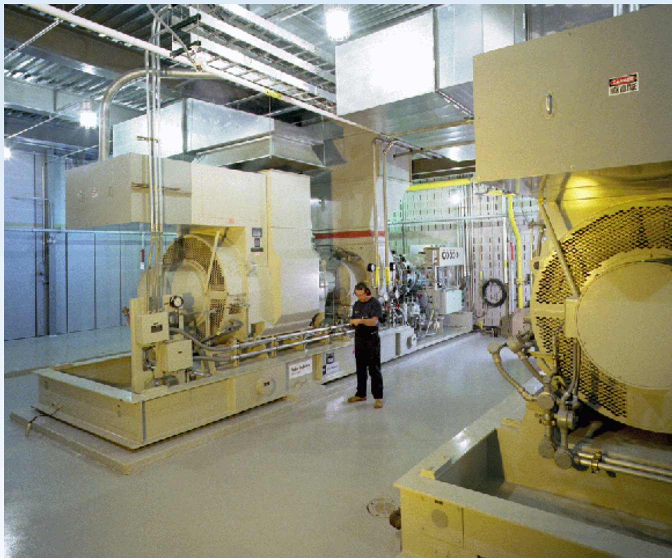
Some SiC/SiC combustor liners developed under NASA EPM program

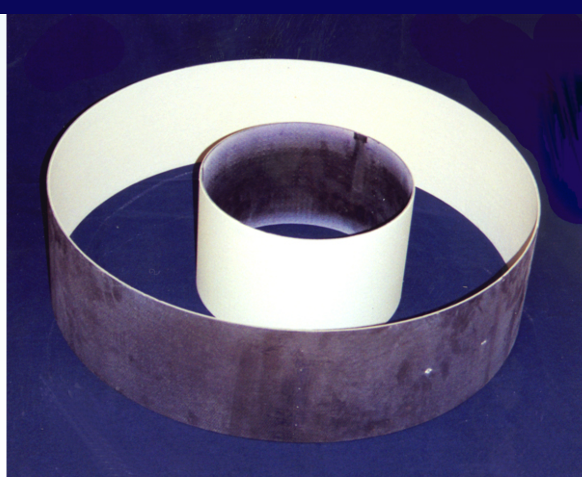




As fabricated and EBC Coated SiC/SiC Liners, Solar Turbines

CMC Combustor Liners Have Shown Tremendous Potential in Ground Based Systems





- Engine Installed in August 2000.
- Hi-Nicalon/Enhanced SiC CVI Outer Liner Made by HACI.
- Tyranno ZM/SiC-Si MI Inner Liner Made by BFG.
- Both Protected With Environmental Barrier Coatings (EBCs).
- 13,937 hrs/61 starts: 2-3 x improvement in liner life

Data from Solar Turbines

Key Technical Challenges in Implementation of Ceramic Matrix Composite Materials

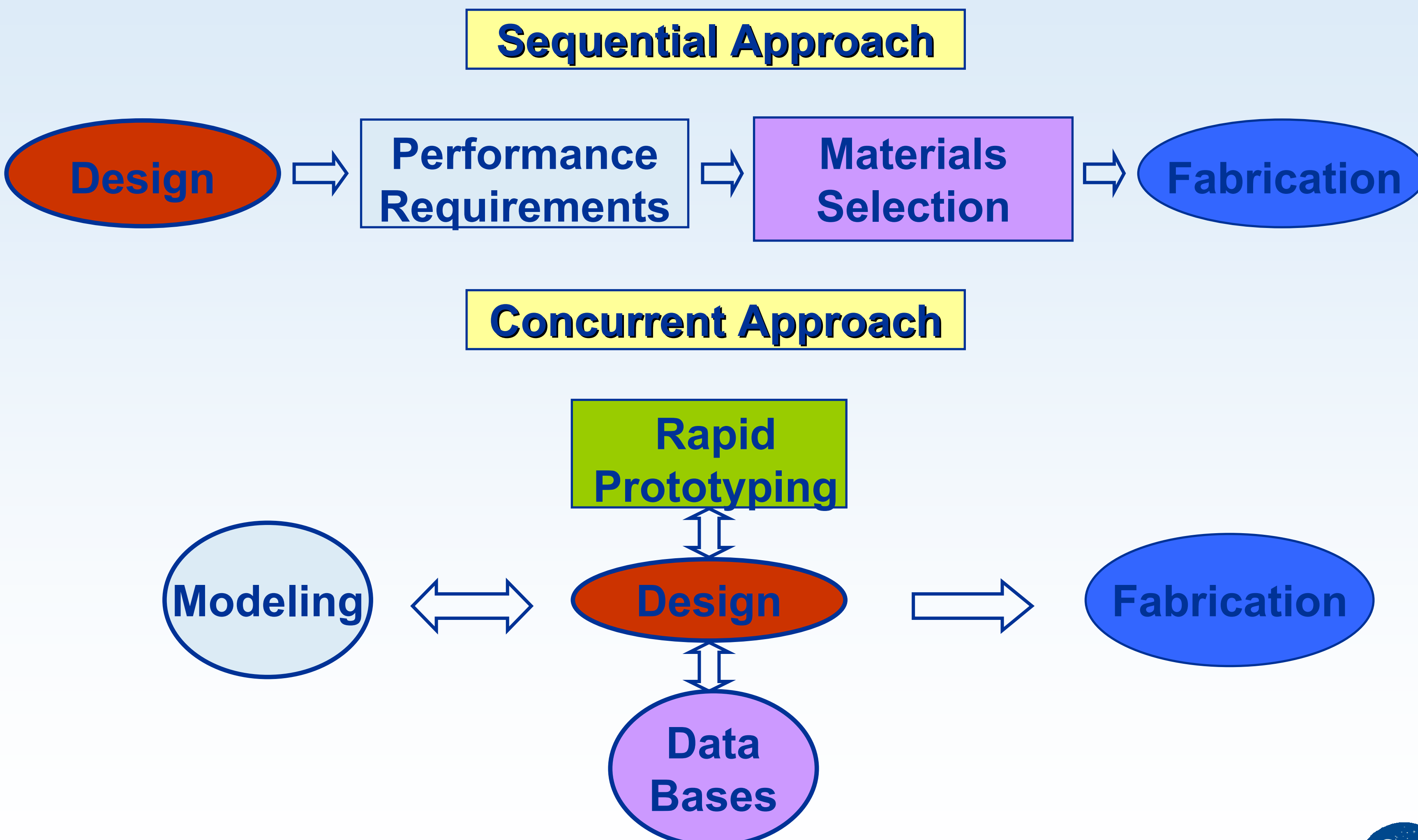
- Manufacturing
- Processing Cosistency/ Reliability
- Joining and Attachments
- Scale-up & Demos
- Machining and Repair

- Material Durability
- Degradation Mechanism
- EBCs and TBCs
- NDE and Reliability
- Life Prediction Models
- Sub-Component Tests

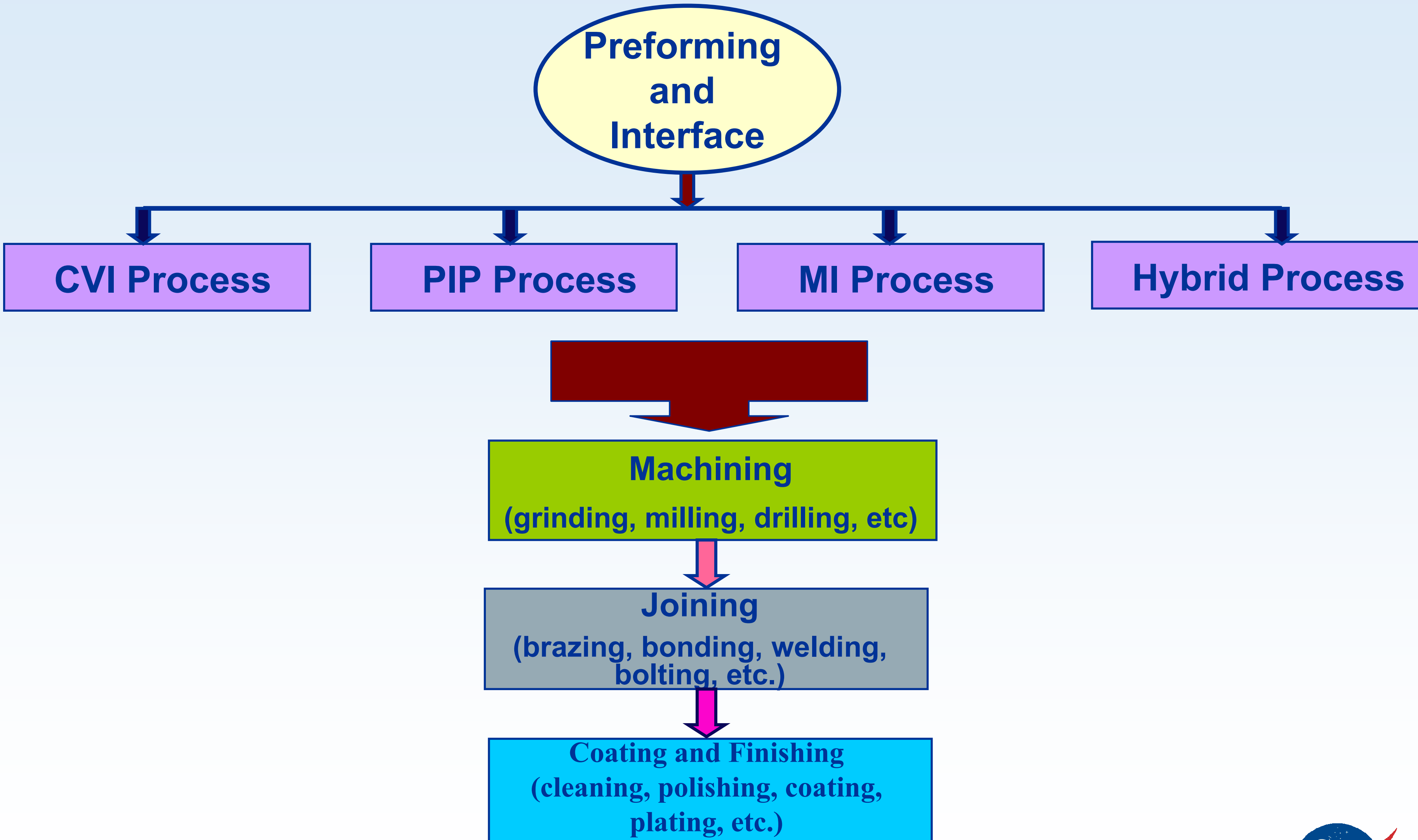
- Design Codes
- Databases
- Legal Issues
- Recycling
- Cost Reduction
- Industrial Partnerships
- Training & Education

Largest Barriers to Insertion are Acquisition and Unknown Life Cycle Costs

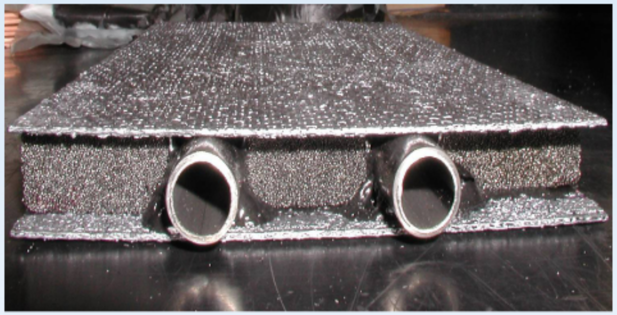
Need for Concurrent Manufacturing Approaches for Ceramic Matrix Composite Materials



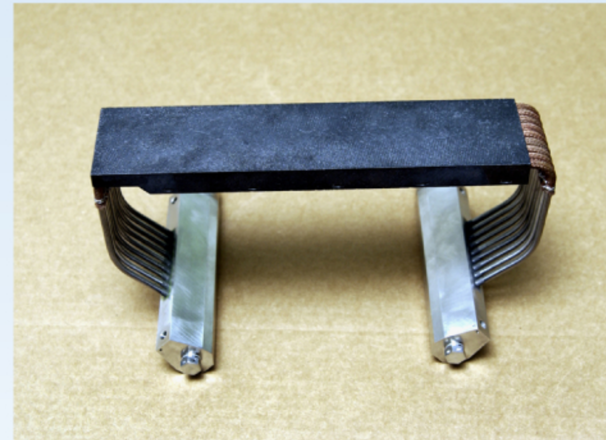
Typical Manufacturing Processes for Ceramic Matrix Composites



Need of Ceramic Composites with Varying Thickness and Hybrid Structures

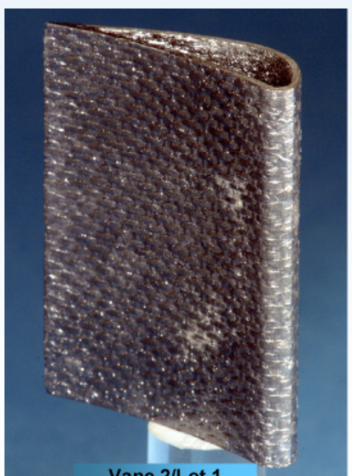


Advanced Composites for Radiators



Cooled Panels for Nozzle Ramps

Composites with varying thickness and architecture are needed

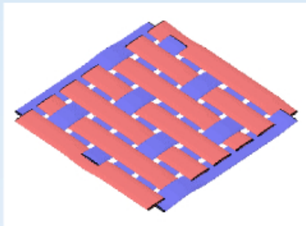


Composite Vane for Aeroengine

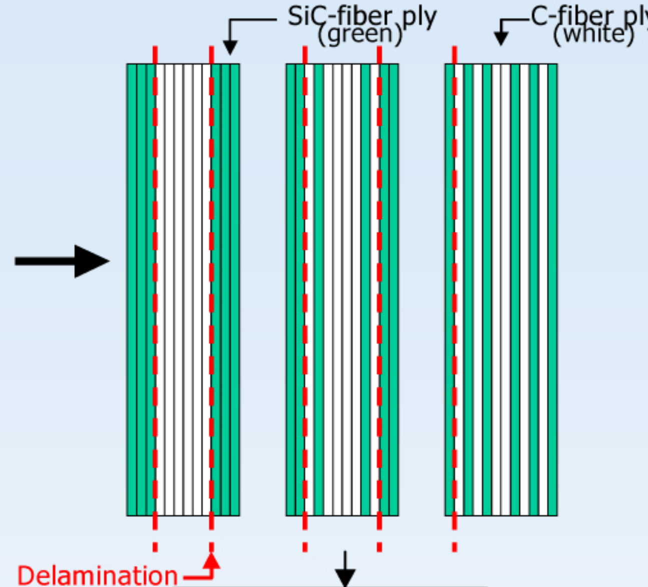
Composite Blisks

Approaches to Composite Fabrication

GE Power Systems Composites, Newark DE



← 2D lay-up fixed in tooling →



Interphase deposition, then removal from tool

Standard and epoxy-infiltrated panels:

CVI BN or C Infiltration → CVI SiC Infiltration

→ Dog Bone Tensile Bars Machined → Final CVI SiC Infiltration

8, 30, & 36 ply Standard Panels

→ Cut into Rectangular Shapes → Epoxy Infiltrate → Tensile Bars Machined

8 ply Epoxy-Infiltrated

Delaminated panels:

CVI BN or C Infiltration → CVI SiC infiltration, removal from tool, and ***delamination*** → Straight-Sided Tensile Bars Machined

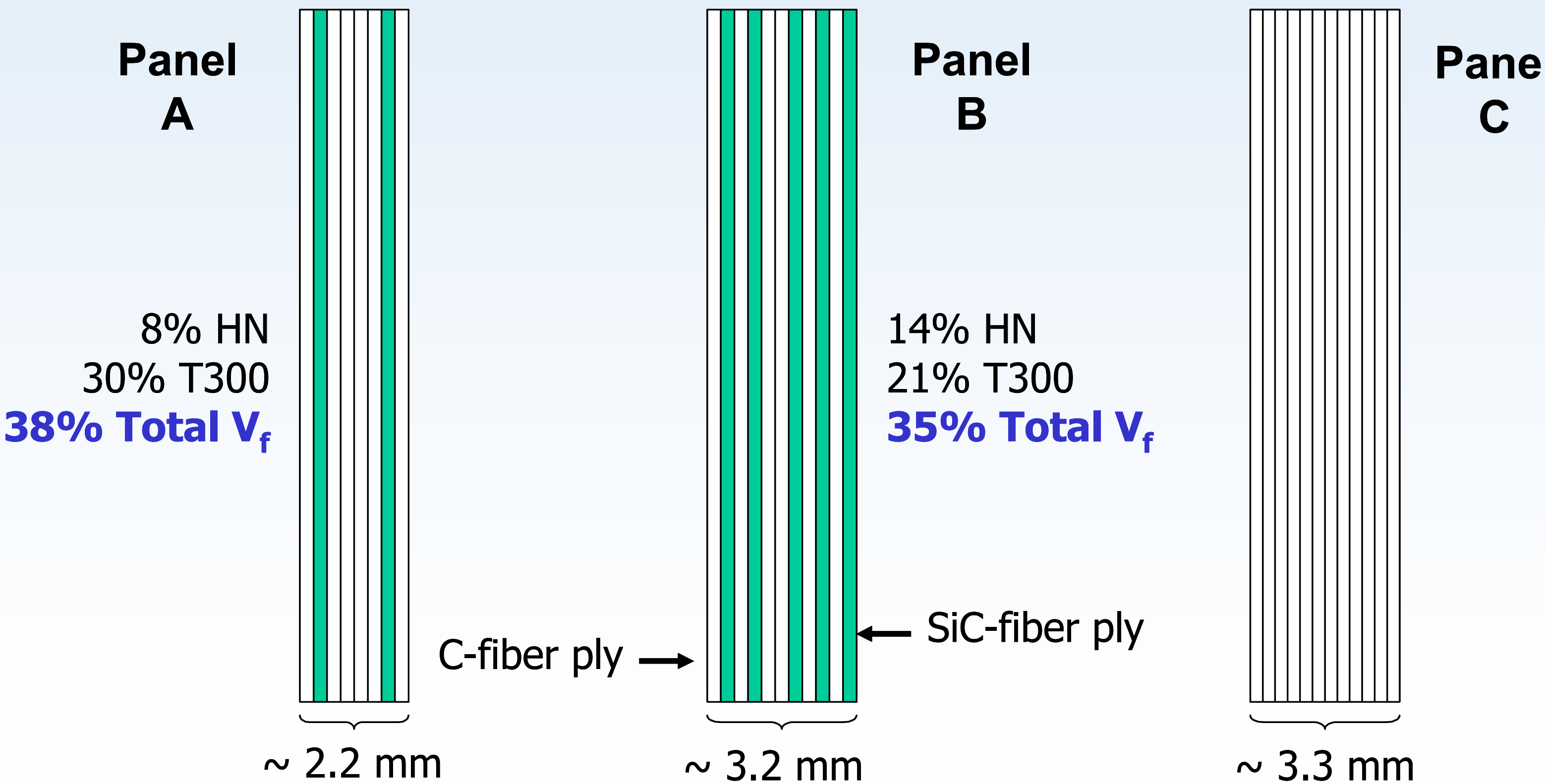
1, 2, and 3 ply Delaminated Panels

Potential Benefits of Hybrid Lay-Up in Ceramic Matrix Composites

- Vary plies (fiber-types) to manipulate residual stress and matrix cracking
- Create “oxidation fire-walls” to slow down oxidation of C-fibers
- Can manipulate ply sequence for thermal-degradation (e.g., > SiC fibers on cold side and > C fibers on hot side) or residual stress-management

Tested Panels of Hybrid C/SiC Fiber CVI SiC Composites

- 20 "EPM" dogbone specimens for each (12.6 mm in grip; 10 mm in gage)
- ½ the dogbone specimens seal-coated with SiC and the other ½ seal-coated with CBS coating
- RT tensile with acoustic emission and elevated temperature stress-rupture tests were performed in air



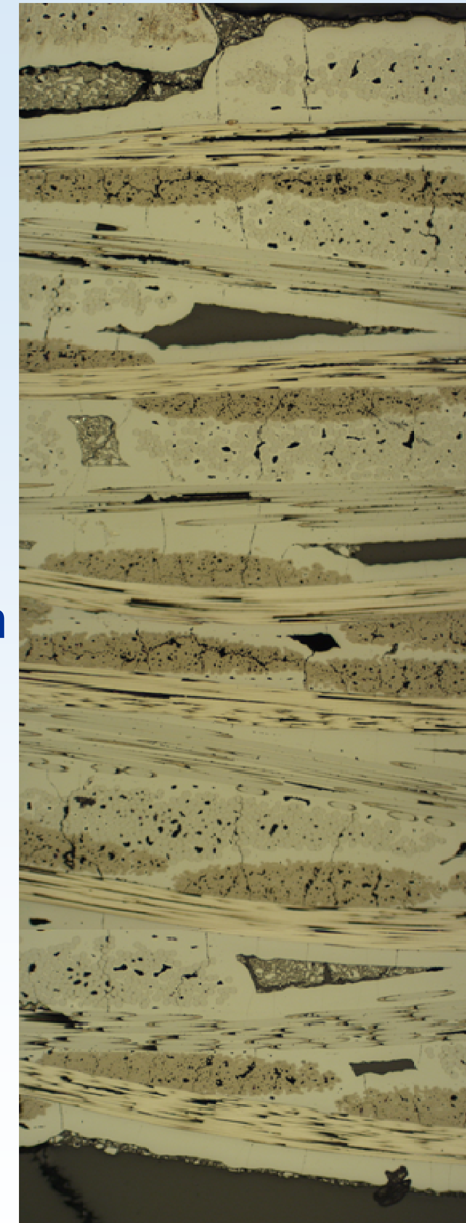
Panel A

2.2 mm

C HN C C C C HN C

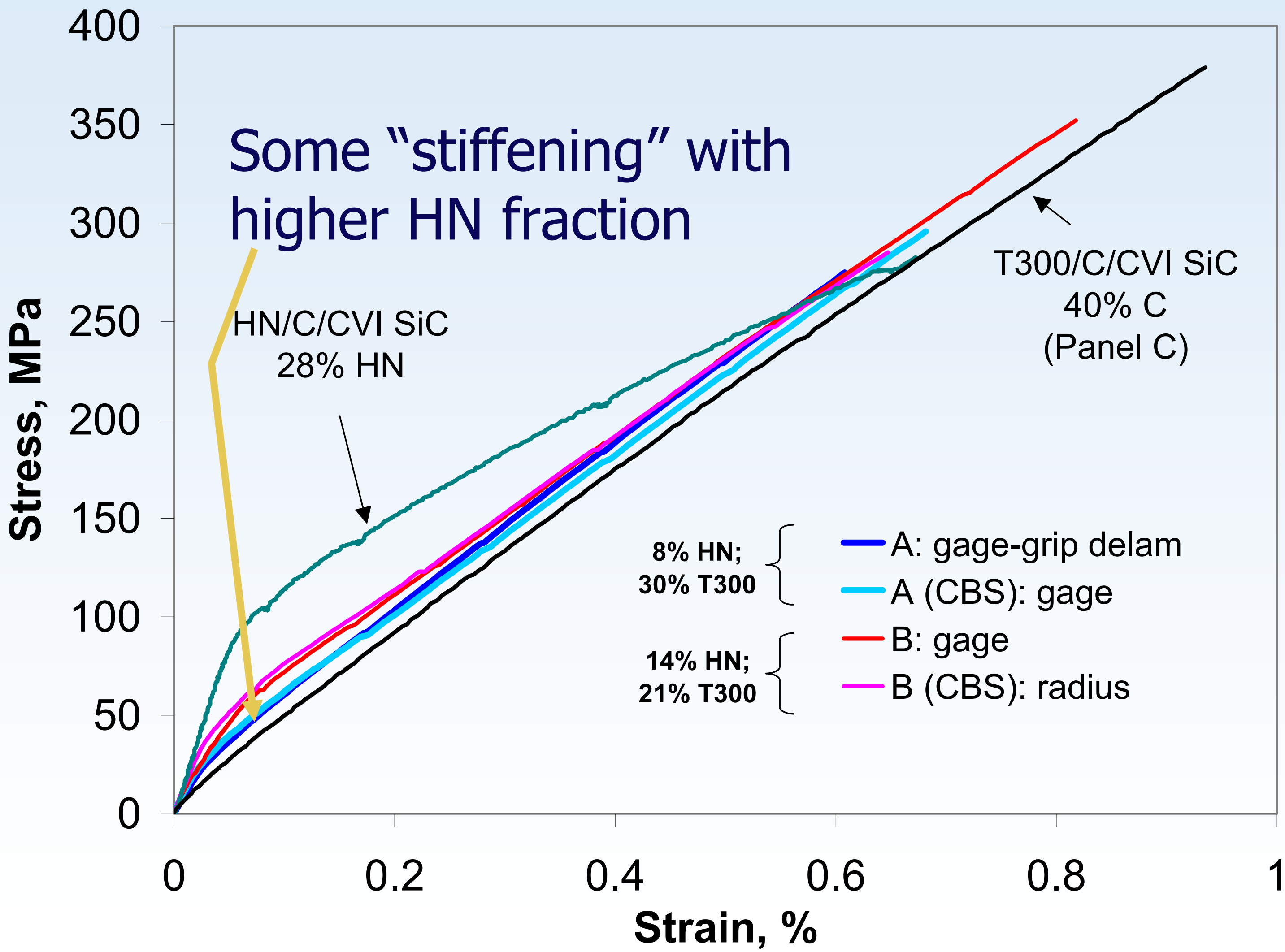
Panel B

3.2 mm

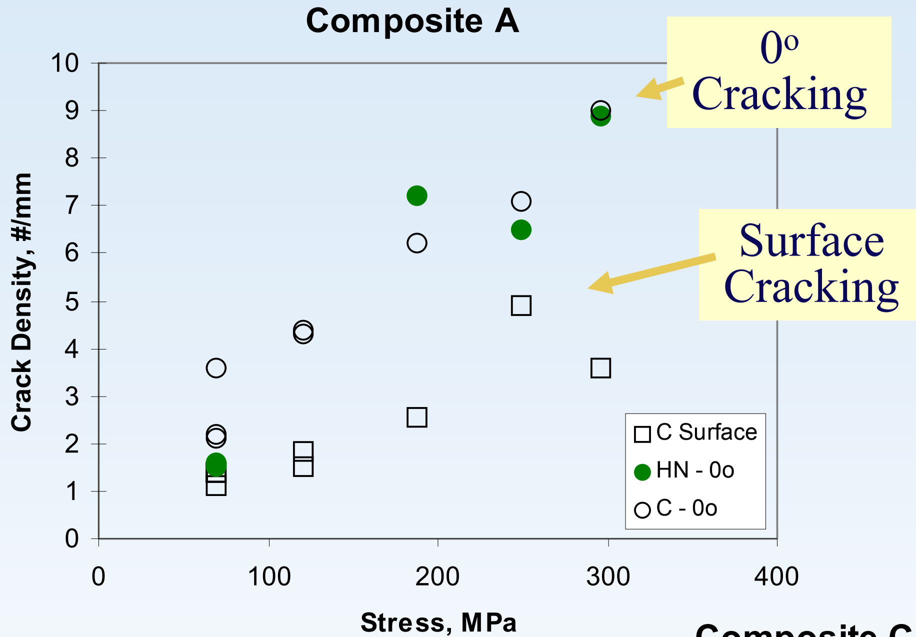


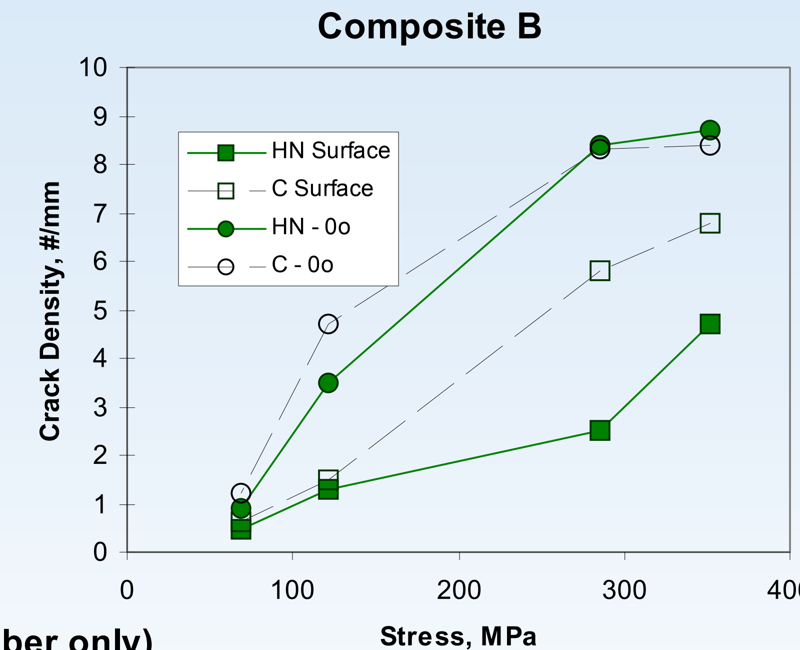
HN C HN C HN C C HN C HN C

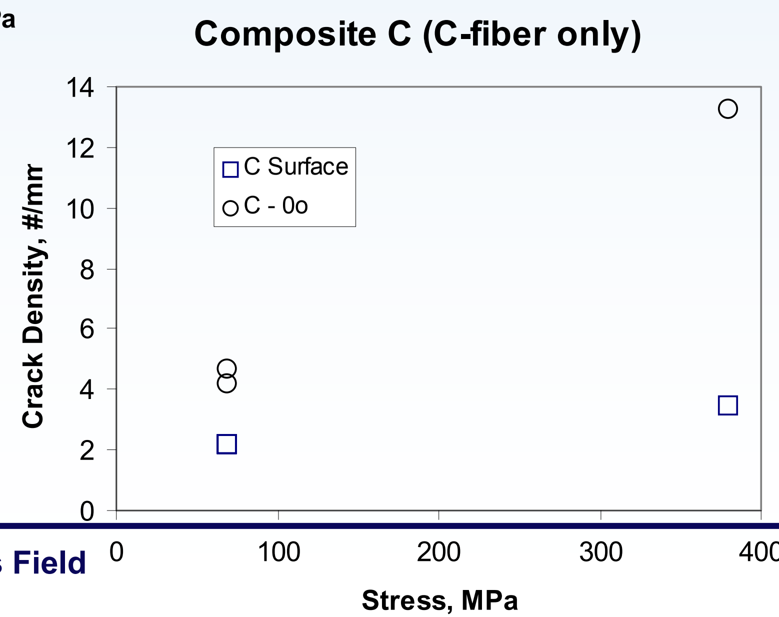
Room Temperature Tensile Behavior of Hybrid C/SiC Fiber CVI SiC Composites



Matrix Cracking in Hybrid C/SiC Fiber CVI SiC Composites





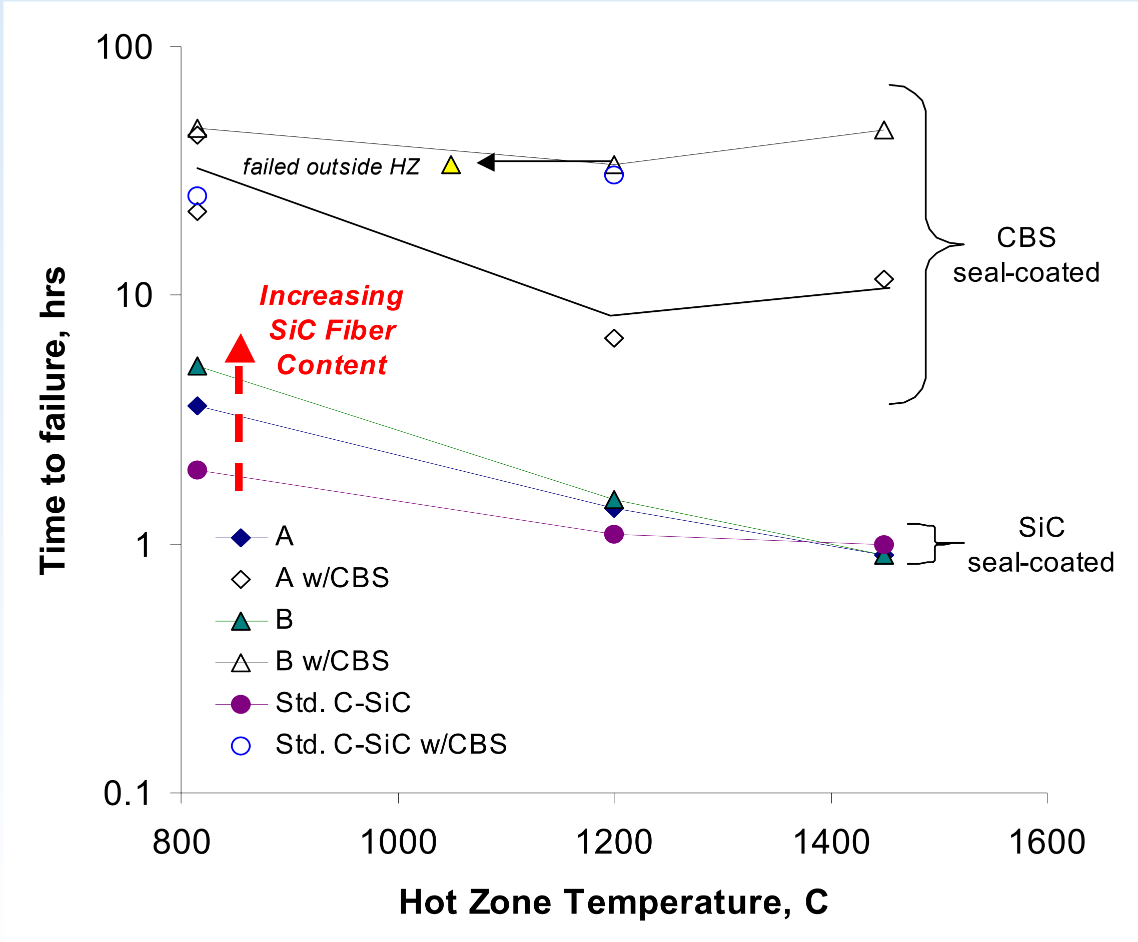


Matrix cracks counted over 10 mm length on surface and along 0° bundles on interior

Matrix cracking increases with stress similarly whether in C plies or HN plies

High Temperature Stress-Rupture Behavior in Air for Hybrid C/SiC Fiber CVI SiC Composites

Temperature Dependence for 69 MPa Rupture in Air

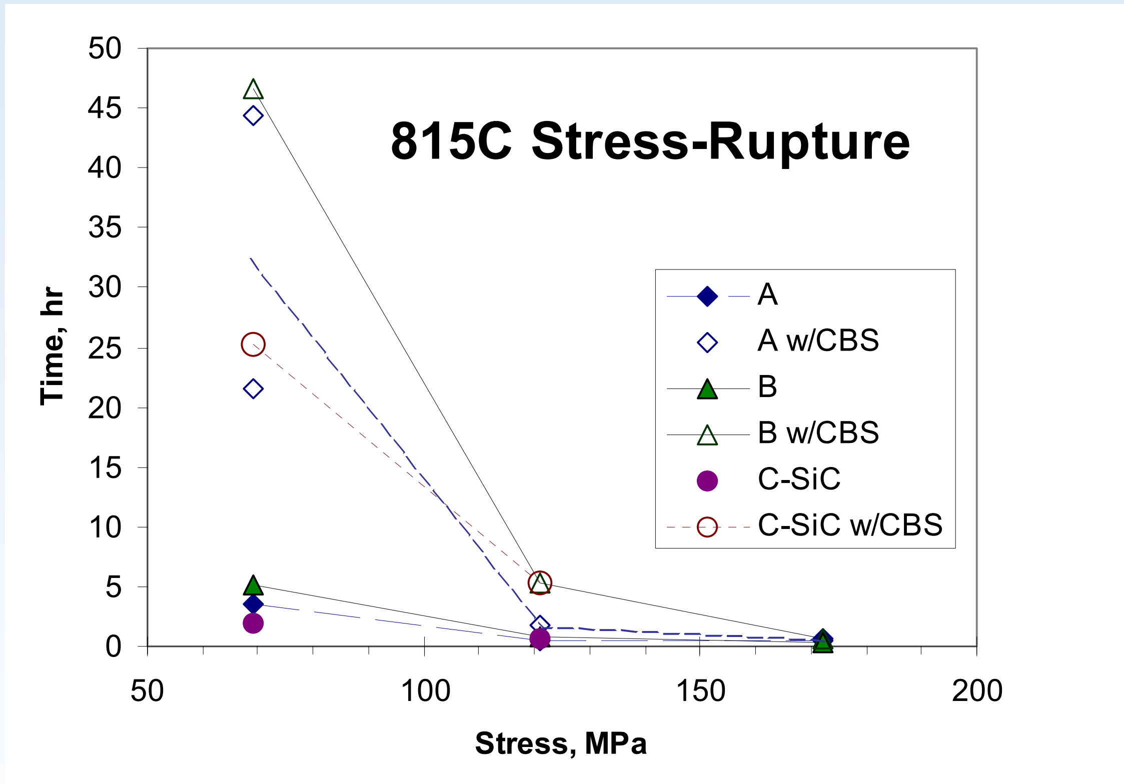


CBS coating provides best benefit at low stresses – no discernable difference for different fiber contents

Some benefit with more HN fibers for specimens not coated with CBS

High Temperature Stress-Rupture Behavior in Air for Hybrid C/SiC Fiber CVI SiC Composites

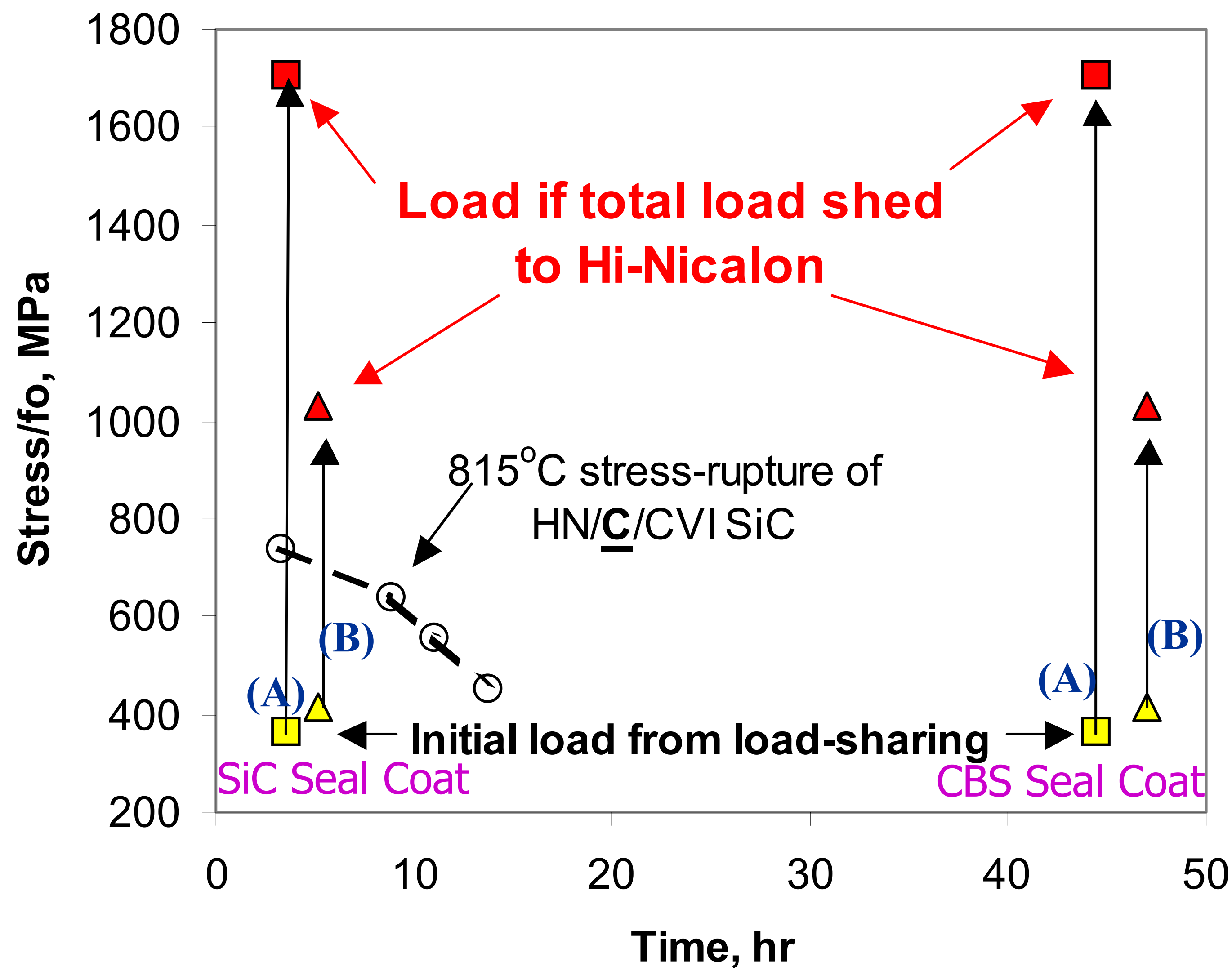
Stress Dependence for 815°C Rupture in Air



CBS coating provides best benefit at low stresses – no discernable difference for different fiber contents

Some benefit with more HN fibers for specimens not coated with CBS

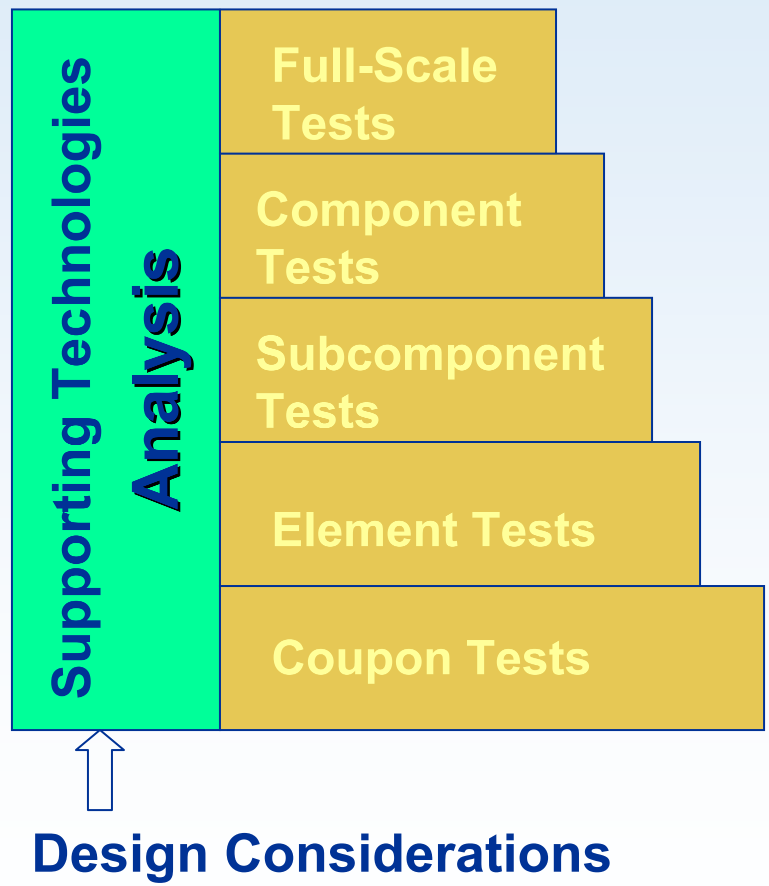
Increased loading of HN in C+HN/SiC due to oxidation of C fibers will be too great to significantly prolong rupture life in air



Composites with Hybrid Lay-up

- **Composite plates with alternating C and HiNicalon fiber plies could be fabricated with some delamination – probably better suited for tube-shaped structures**
- **HN plies do increase stiffness; however, this is mostly due to higher modulus of HiNicalon**
  - ***Matrix cracking occurred at low stresses for all of the C fiber-containing composites***
- **Minor intermediate temperature stress-rupture improvement observed for HiNicalon containing composites**
- **CBS coating significantly improves stress-rupture life at low stresses, regardless of C and HiNicalon content**

Joining and Assembly Technologies for Manufacturing of Ceramic Composite Structures



Affordable, Robust Ceramic Joining Technology (ARCJoinT)

Apply Carbonaceous Mixture to Joint Areas

Cure at 110-120°C for 10 to 20 minutes

↓

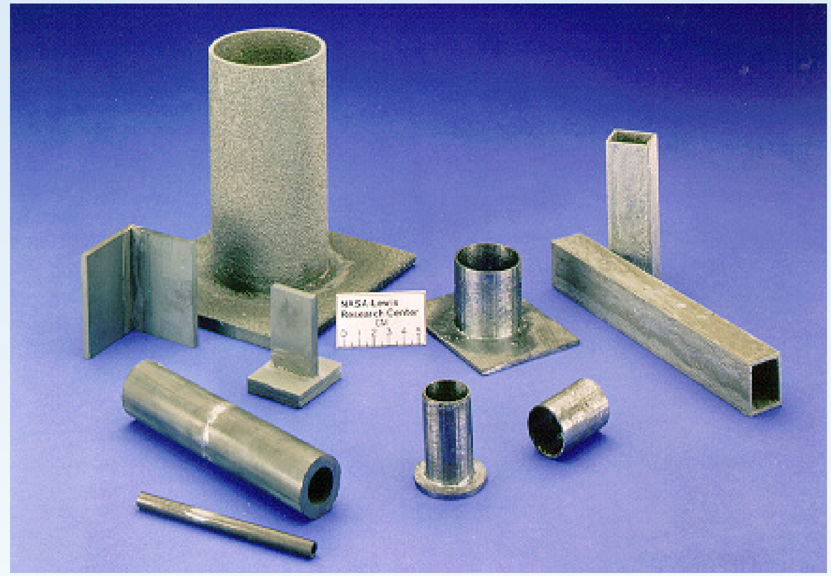
Apply Silicon or Silicon-Alloy (paste, tape, or slurry)

Heat at 1250-1425°C for 10 to 15 minutes

↓

Affordable and Robust Ceramic Joints with Tailorable Properties

1999 R&D 100 Award
2000 NorTech Innovation Award



Advantages

- Joint interlayer properties are compatible with parent materials.
- Processing temperature around 1200-1450°C.
- No external pressure or high temperature tooling is required.
- Localized heating sources can be utilized.
- Adaptable to in-field installation, service, and repair.

ARCJoinT is Used to Join and Repair a Wide Variety of Ceramic Composite Materials

ARCJoinT

SiC-Based Ceramics
- Reaction Bonded SiC
- Sintered SiC
- CVD SiC, Porous SiC

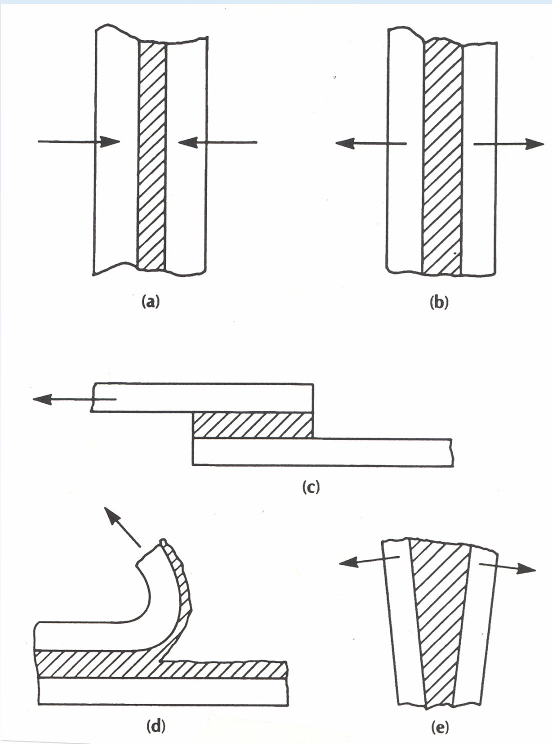
SiC/SiC Composites
Melt Infiltrated SiC/SiC
CVI SiC/SiC Composites
PIP SiC/SiC Composites

C/SiC Composites
- Melt Infiltrated C/SiC
- CVI C/SiC Composites
- PIP C/SiC Composites

C/C Composites
- CVI C/C Composites
- Resin Derived C/C
- C-C/SiC with MI

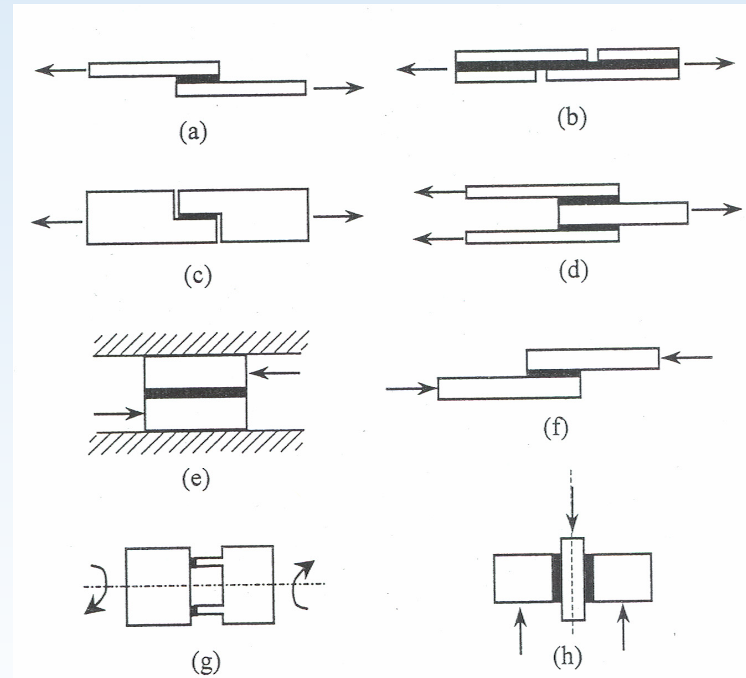
- ***Composites with Different Fiber Architectures and Shapes***
- ***Ceramics with Different Shapes and Sizes***

Technical Challenges in Design and Selection of Joints in Advanced Ceramic Composites



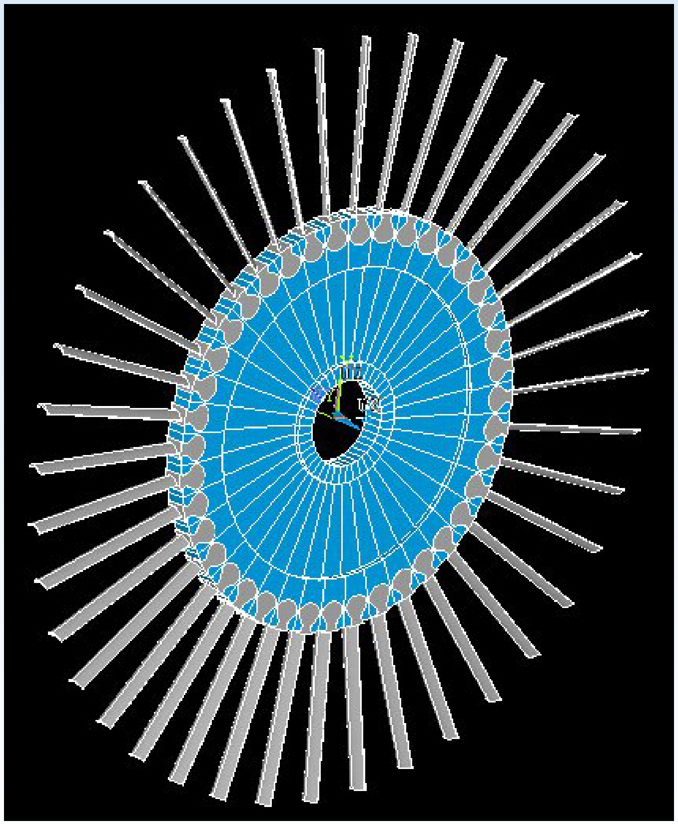
(a) Compression; (b) Tension; (c) Shear; (d) Peel; (e) Cleavage

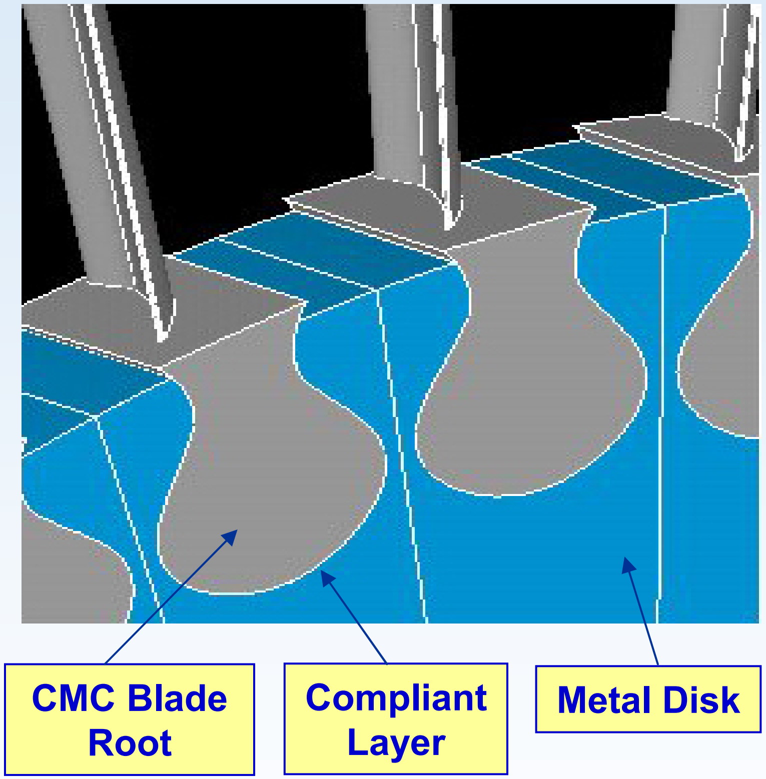
Typical Ceramic Joints will have Combination of Stresses Under Operating Conditions



Different Types of Shear Tests

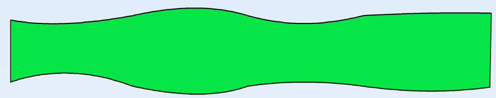
Fabrication of Thick C/SiC and SiC/SiC CMC Subelements



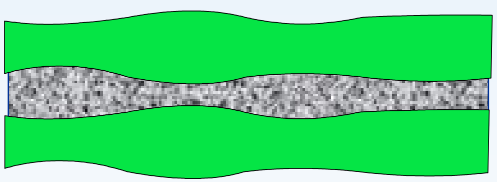


Need for a joining and attachment technology that both accommodates the material differences between the CMC blade and the metallic disk and matches the operational thermal-mechanical loads to the CMC material capabilities.

Effect of Surface Roughness on the Shear Strength of Joined CVI C/SiC Composites

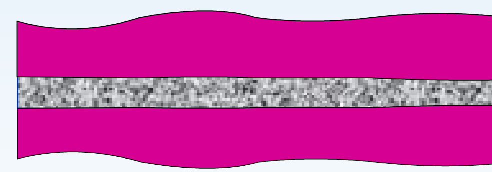


CVI C/SiC Composites



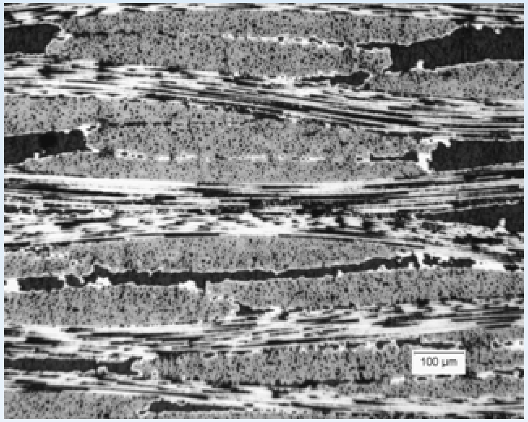
Joints with As-Fabricated Surfaces

Joints with As-Fabricated/ Machined Surfaces

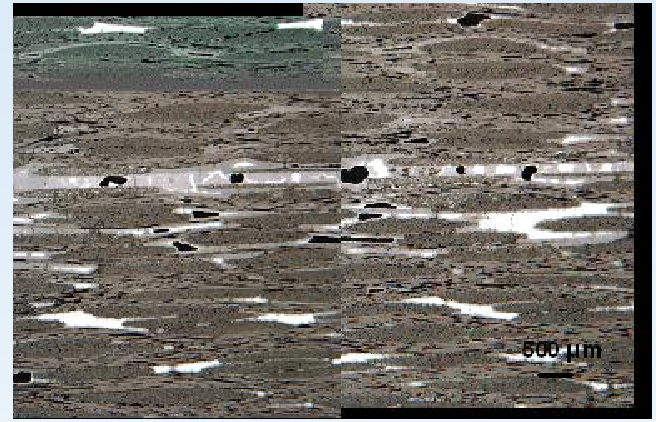


Joints with Machined Surfaces

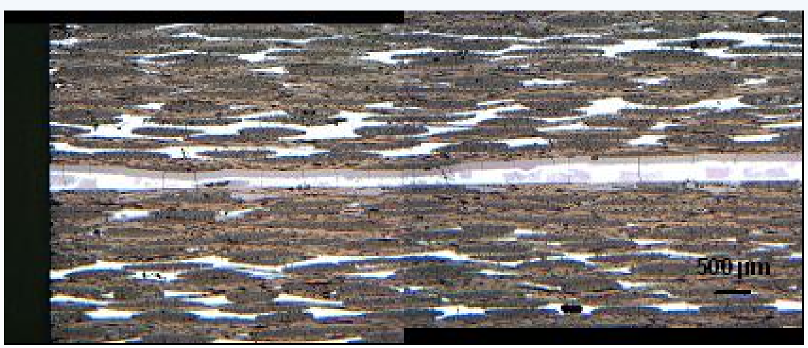
Microstructure of As-Fabricated and Joined CVI C/SiC Composites



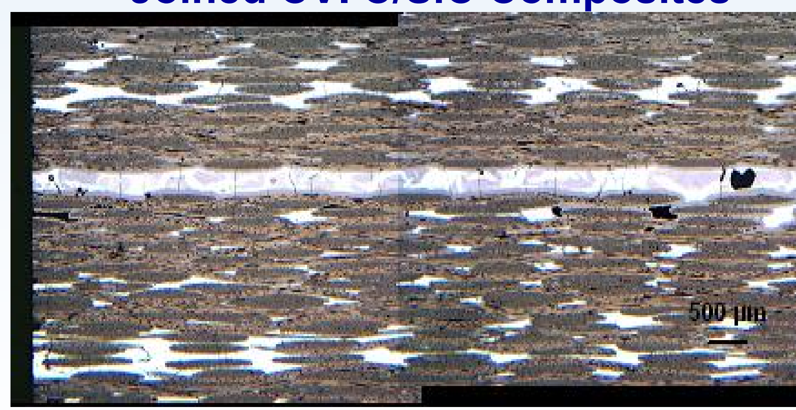
CVI C/SiC Composites
(as fabricated)



Joined CVI C/SiC Composites

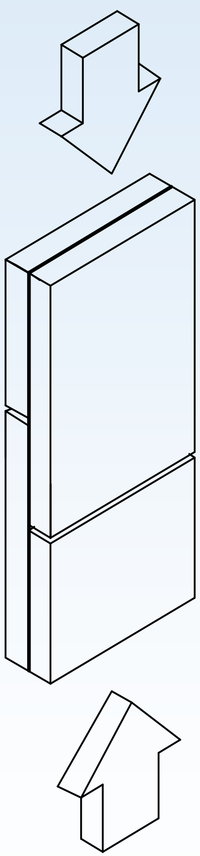


Joined CVI C/SiC Composites
(one surface machined and
one surfaces as received)



Joined CVI C/SiC Composites
(both surfaces as received)

Specimen Geometry and Test Fixture Used for Compression Double-Notched Shear Tests



ASTM C 1292-95a (RT) and ASTM C 1425-99 (HT)

Specimen Dimensions

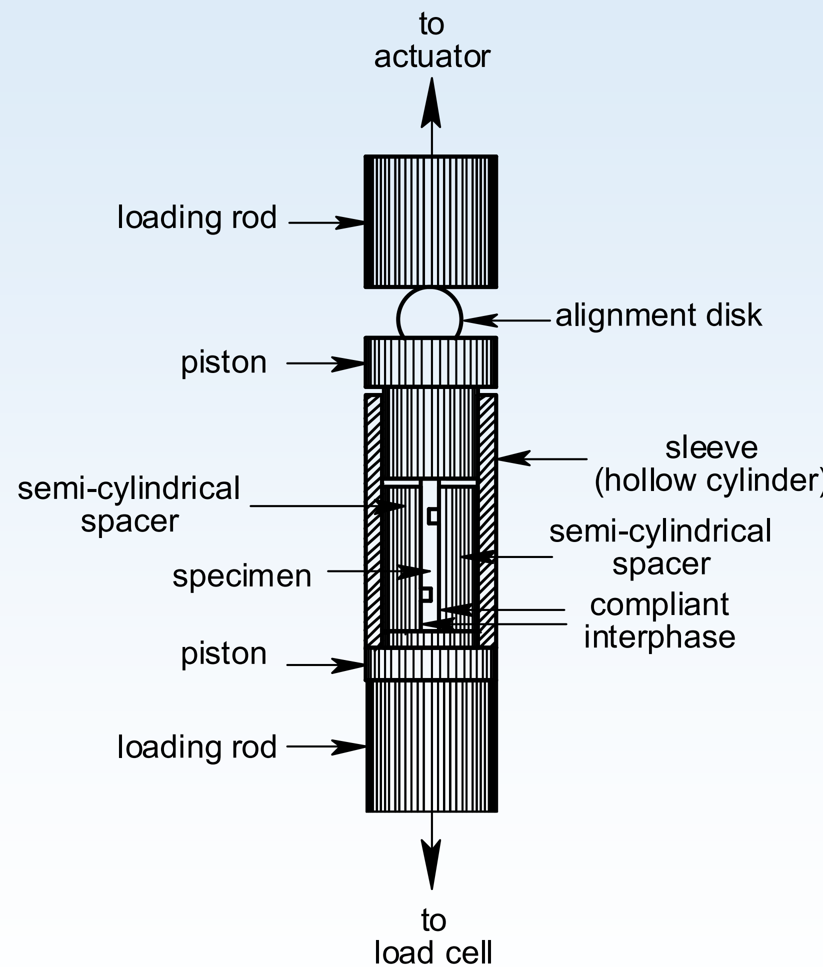
Specimen length (L) : 30 mm *(±0.10 mm)*

Distance between notches (h) : 6 mm *(±0.10 mm)*

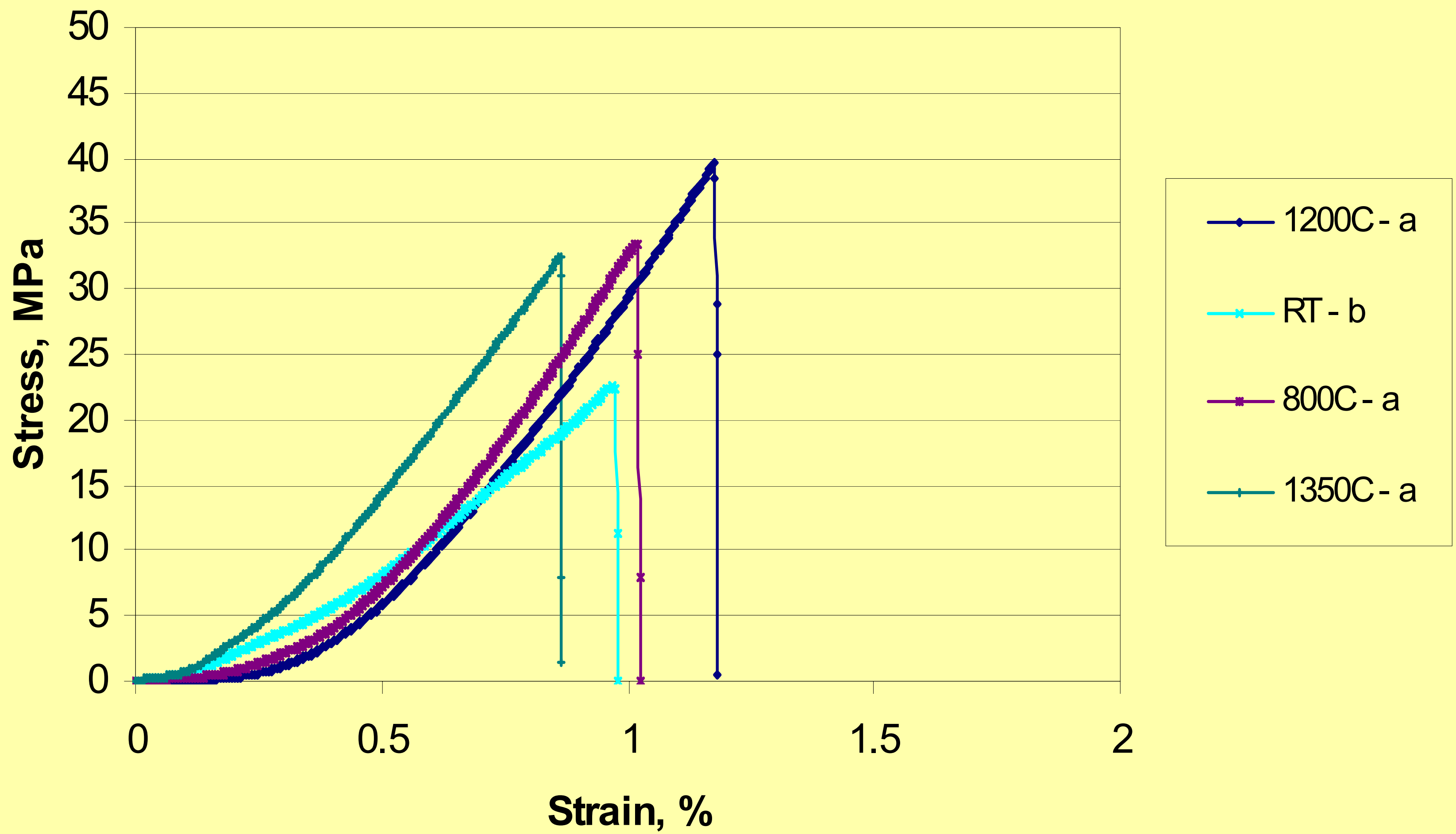
Specimen width (W) : 15 mm *(±0.10 mm)*

Notch width (d) : 0.50 mm *(±0.05 mm)*

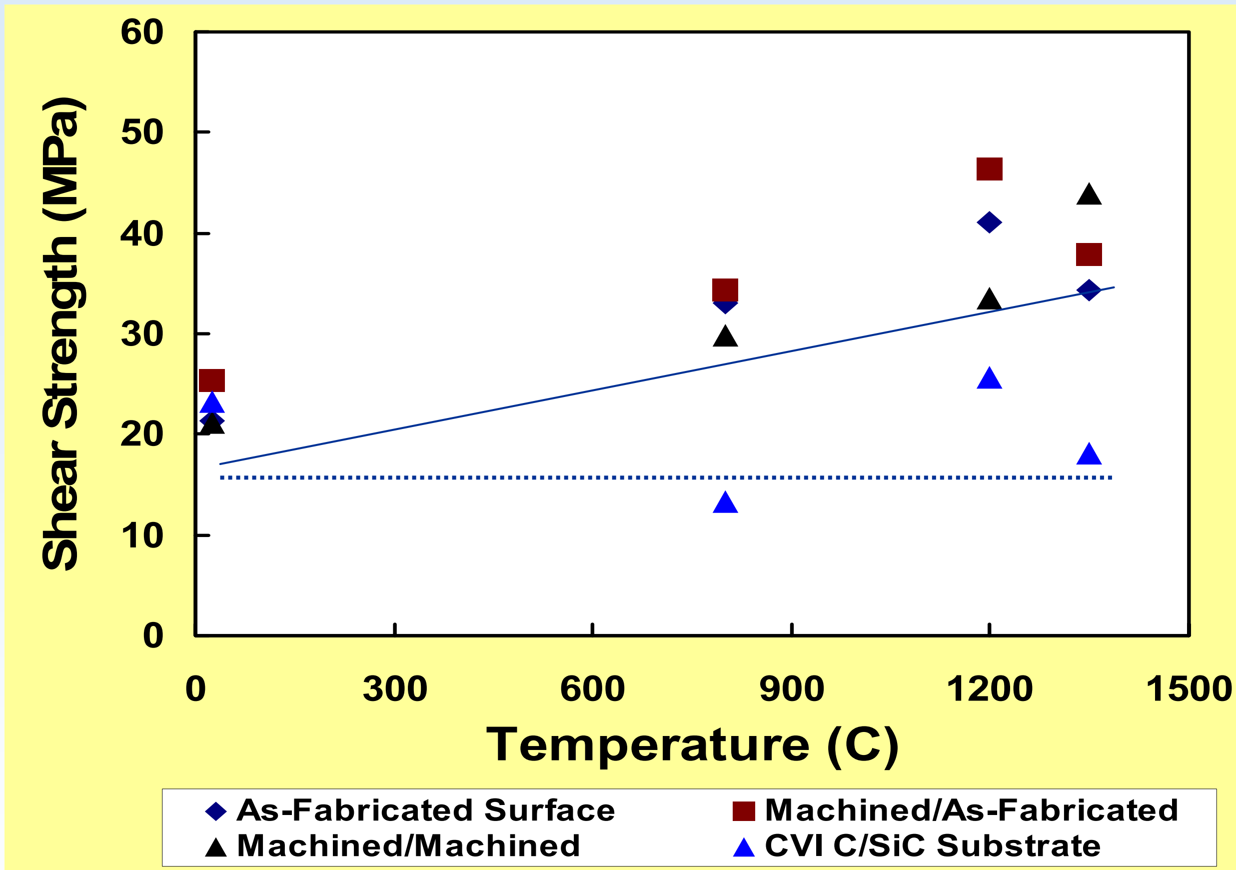
Specimen thickness (t) : *(adjustable)*



Typical Behavior of Joints During Shear Tests



Compression Double Notch Shear Strength of Joined CVI SiC Composites at Different Temperatures



- Shear strength of joints increases with temperature and is higher than the CVI SiC composite substrate.
- No apparent influence of surface condition on the shear strength of joints.

Summary and Conclusions

- In the early 1960's, CMCs seen as answer to problems posed by high temperature applications but *trial and error* efforts were not successful.
- In the 1970's and 80's predictive modeling provided the critical directions for the producers and users of CMCs.
- In the 1990's, standardized test methods, design codes and data bases began to *"Legitimize"* CMCs as viable engineering materials just as the materials systems began to be implemented in target design applications.
- In the 21st century, intelligent design of materials and systems, low cost manufacturing, and ceramics education will help propel CMCs into common usage.

Acknowledgments

- Dr. Andy Eckel, Martha Jaskowiak, Dr. Jim DiCarlo, NASA GRC and Dr. Greg Morscher, OAI
- Dr. R.T. Bhatt, US Army, Vehicles Directorate, NASA Glenn Research Center
- Professor Michael Jenkins, University of Detroit-Mercy
- Ron Phillips and other technical staff, QSS Group, Inc.