Ceramic Matrix Composites for Rotorcraft Engines

Ceramic matrix composite (CMC) components are being developed for turbine engine applications. Compared to metallic components, the CMC components offer benefits of higher temperature capability and less cooling requirements which correlates to improved efficiency and reduced emissions. This presentation discusses a technology develop effort for overcoming challenges in fabricating a CMC vane for the high pressure turbine. The areas of technology development include small component fabrication, ceramic joining and integration, material and component testing and characterization, and design and analysis of concept components.

National Aeronautics and Space Administration

Fundamental Aeronautics Program

Subsonic Rotary Wing Project

Ceramic Matrix Composites for Rotorcraft Engines

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- The team for the CMC Vane task includes:
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Outline

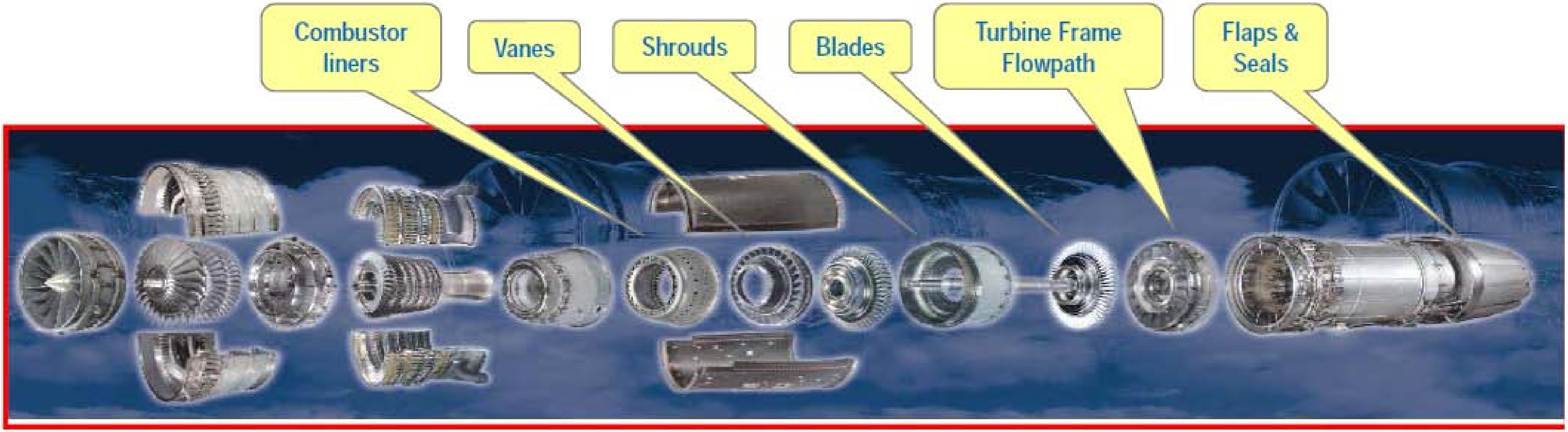
- Background Information on Ceramic Matrix Composites
  - Applications
  - Processing and properties

- Turbine Vane Application for Rotorcraft Engines

- Key Technology Development for Turbine Vanes in the SRW Project
  - Small component fabrication
  - Ceramic joining and integration
  - Material and component testing and characterization
  - Design and analysis of concept components

- Summary/Conclusions

Applications for CMCs in Gas Turbine Engines

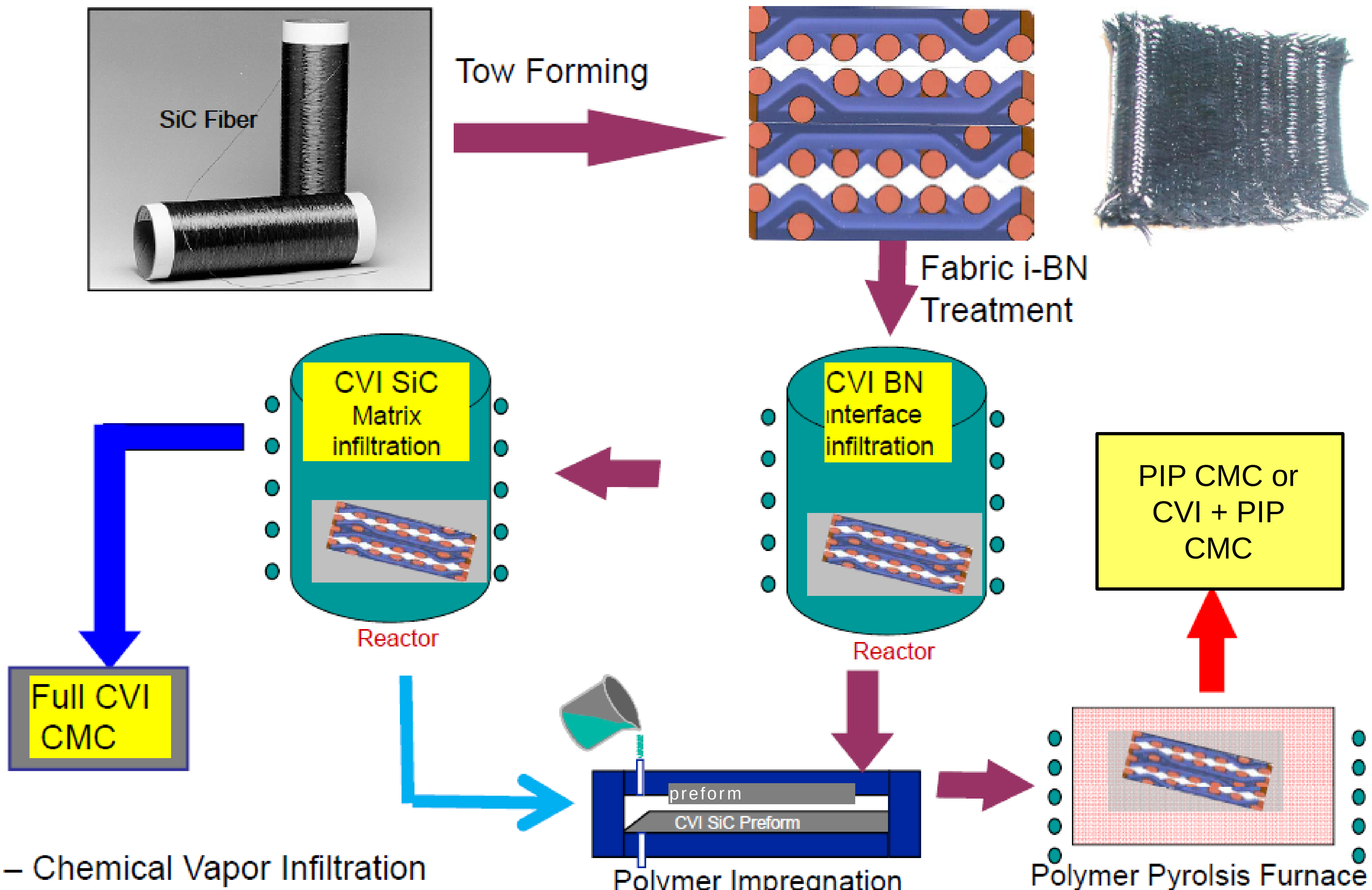


Courtesy of GE Aircraft Engines

Benefits:

- **Enabling for high OPR engines (higher turbine inlet temperatures) – reduce cooling air, reduce fuel burn and CO_2 emissions**
- **Weight = 1/3 of metals and 1/2 of titanium aluminides**
- **High OPR engines – higher combustor temperature – increased NOX, CMC combustor liner and first stage turbine vane reduce NOX**

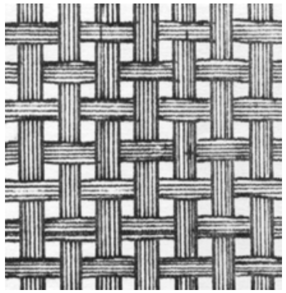
Fabrication Process for Gen III SiC/SiC CMCs (2700º F Capability for G.T. Engines)



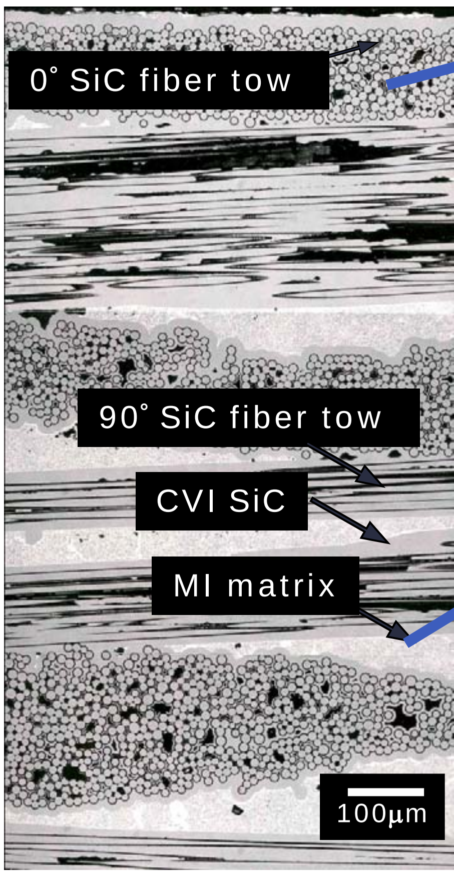
CVI – Chemical Vapor Infiltration
PIP – Polymer Impregnation Pyrolysis

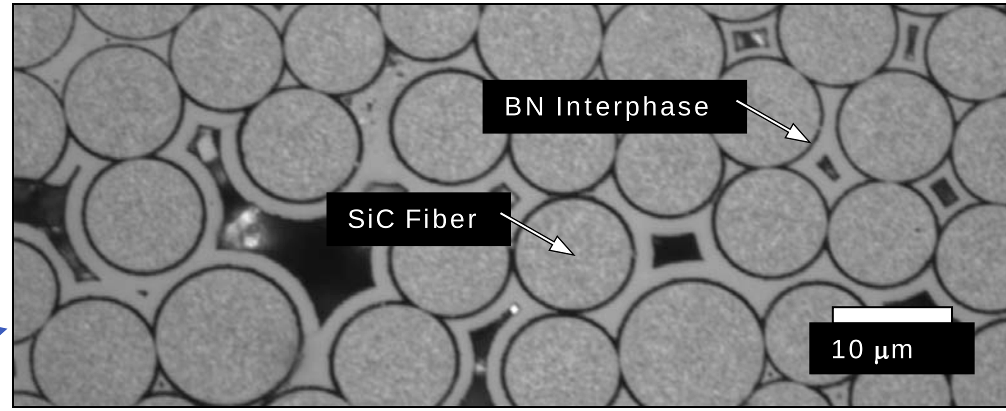
Ceramic Matrix Composite Materials
- Melt Infiltrated (MI) SiC/SiC

0-90 Plain Fiber Tow Weave

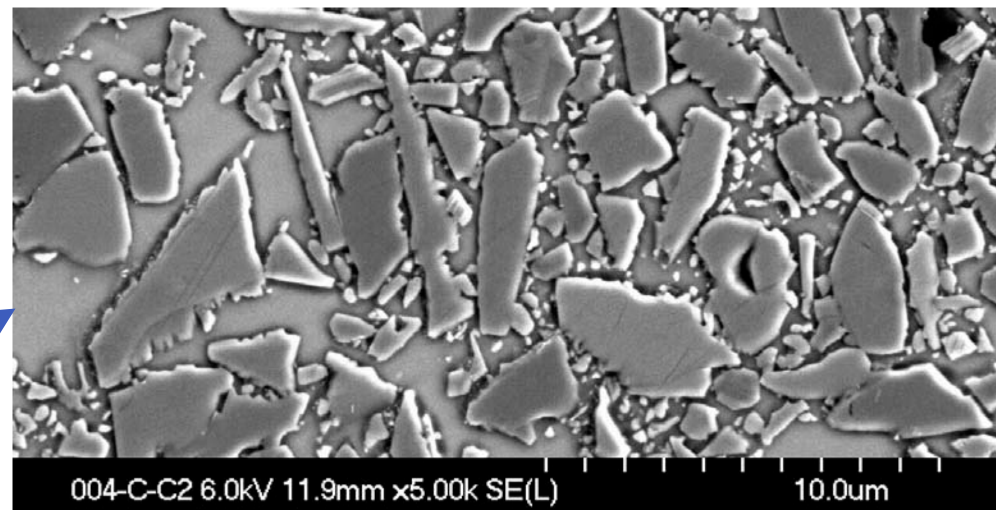


Composite Cross-Section





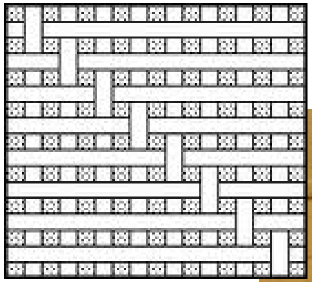
Sylramic™ SiC fibers within a tow



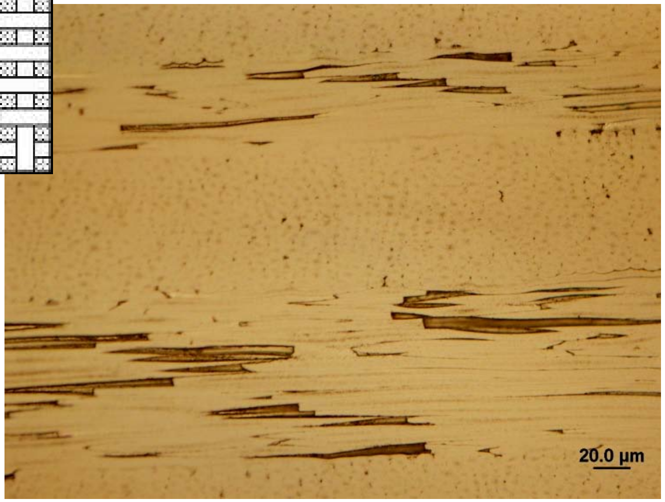
SiC grains and silicon within MI matrix

- **High thermal conductivity matrix**
- **Elimination of interlaminar porosity**
- **No matrix micro cracking**

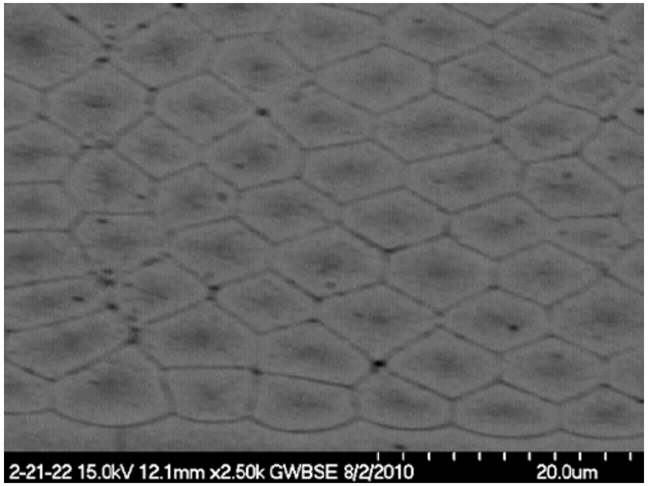
Commercial High Temperature Ceramic Material - SA-Tyrannohex (SiC Fiber Material)



8 Harness Satin Fiber Tow Weave



Optical Micrograph



SEM Micrograph

Features

- 8 Harness Satin Weave of SiC Tyranno fibers
- Layers hot pressed together
- Hexagonal sintered fibers
- Nano-layer of carbon on the fiber surface

Benefits of SiC SA-Tyrannohex

- High fracture toughness
- Fatigue resistance
- Low weight and high temperature capability
- Machinable and complex shape formation
- Candidate material for the vane endcap

SRW Large Civil Tilt Rotor Mission and Requirements

EIS = 2025 (2018 tech)

TOGW =108k lbm

Payload = 90 pass.

Engine = 4x7500HP

Fuel = 21,000 lbm

Range > 1,000nmi

Cruise > 300 knots

@Alt. ⇒ best range

Cruise L/D ≈ 12

Rotor tip speed

650 fps hover

350 fps cruise

LCTR Mission: 90 passengers, range: 1000 nmi., cruise speed 300 knots, cruise alt.: 28 k-ft.

LCTR Engine Characteristics:

7500-8000 HP, overall pressure ratio of 30, T4: 3000ºF hover and 2500ºF cruise, HPT turbine vane will have dimension of about 1” high and 1” long.

Comparison between the LCTR2 engine and other engines.

Engine	T4 (º F)	Overall Pressure Ratio
V22 (AE1107)	1740	16.7
T700	2600	17
LCTR2 (notional engine)	3000+	30+

SRW Vane Task Overview

Objective:

- Develop technologies for CMC turbine engine components that have higher temperature capability, higher fracture toughness, and require less cooling compared to current metallic turbine components.
- Targeted toward the first stage vane of the high pressure turbine (HPT).
- Provides higher efficiency, higher horsepower, and lower emissions.
- This is a technology development task rather than a component task

NASA GRC role vs. industry role:

NASA GRC is focused on a cooled HPT (lower TRL) whereas industry may be more focused on less cooled and lower temperature components (higher TRL) in the low pressure turbine (LPT).

GRC is focused on the engine requirements of the Large Civil Tilt Rotor Vehicle within the Subsonic Rotary Wing Project.

SRW's CMC effort compared to CMC efforts in other NASA projects (FA and ERA):

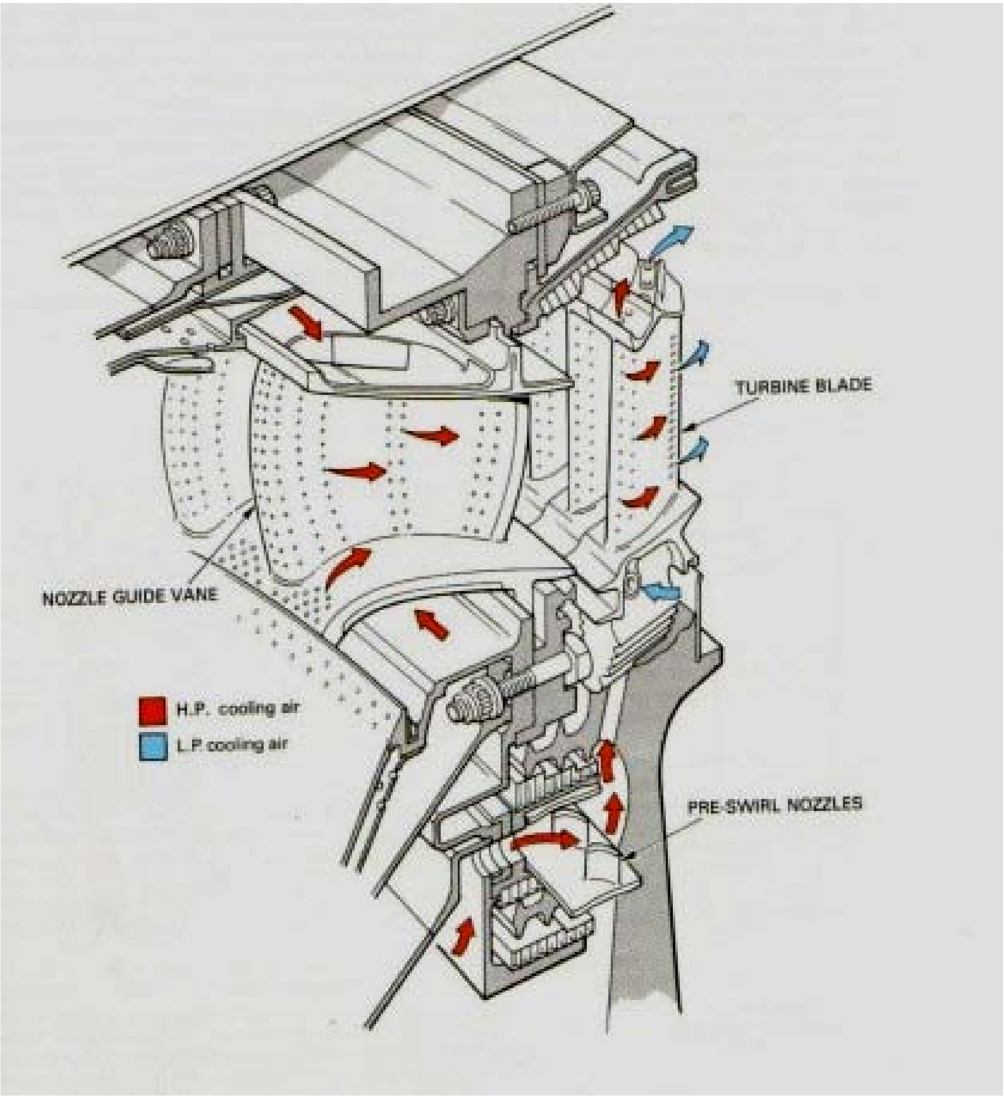
The SRW task is focused on small component fabrication and joining technology development.

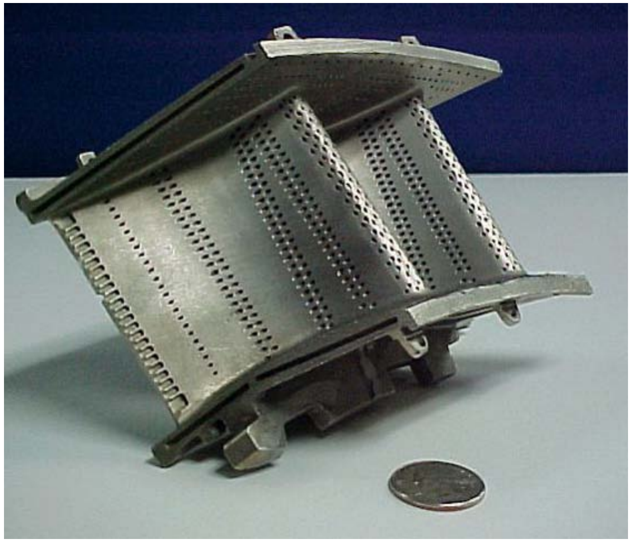
All CMC tasks within the projects communicate well with one another to ensure tasks are leveraged and there are no overlap in efforts.

Challenges:

Fabrication of a small airfoil (1"x1"), cooling schemes, engine operating conditions (i.e. T4 > 3000F, and OPR > 30), and joining to fabricate the component.

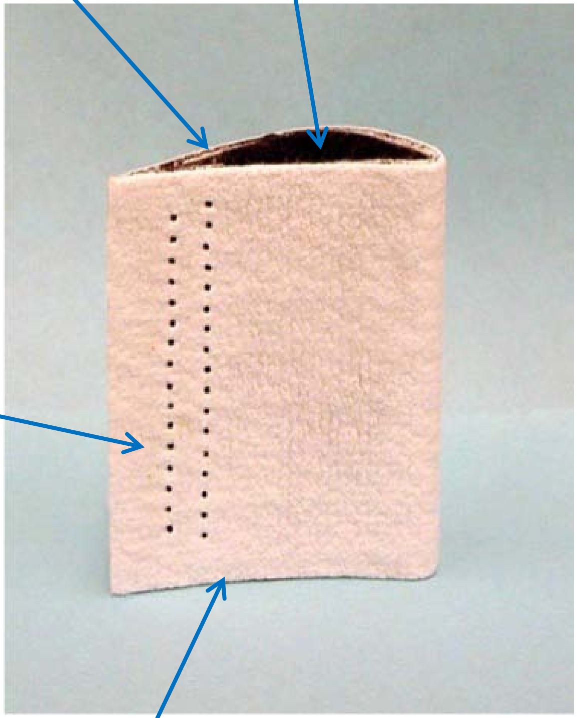
Current Metallic Vane Designs and Cooling Schemes





The preference in CMC turbine component development is to insert the CMC part in-place of the metallic one(s) rather than to drastically alter the outer geometry.

Challenges with CMC Vanes and Airfoils



- Production challenges are in fabricating the small radii, the tapered trailing edge, integrating the endcaps, and machining cooling holes.
- Design and material challenges are in meeting the high stress and high temperature requirements, providing sufficient cooling, and having a durable high temperature coating.

Areas Being Addressed by the SRW Vane Task

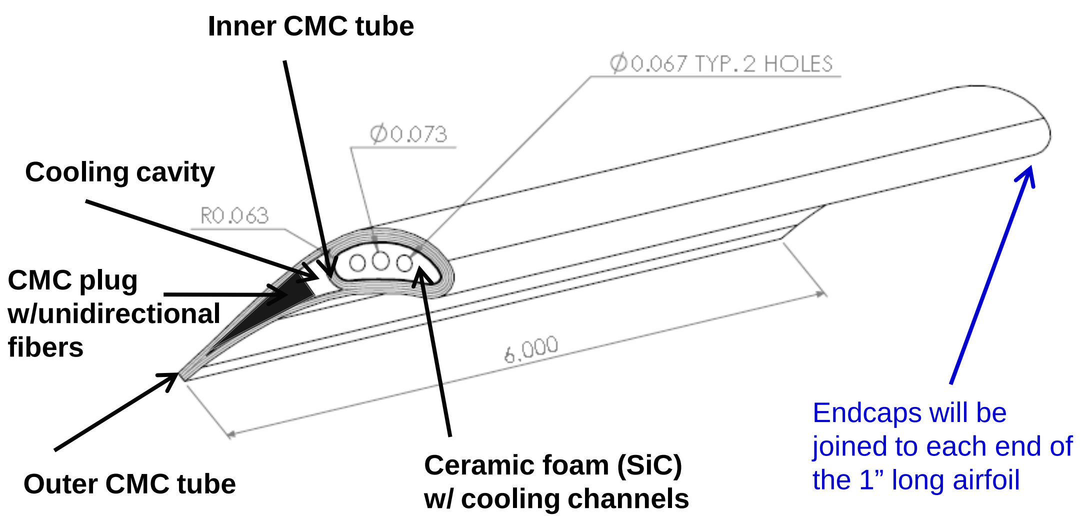
Key Technology Development for a Turbine Vane in the SRW Project

- Small component fabrication
- Ceramic joining and integration
- Material and component testing and characterization
- Design and analysis of concept components

Small Component Fabrication - Objective and Concept #1

Objective: Demonstrate fabrication ability of small 1”x1” airfoils (vane cord length x height)
Materials: SiC/SiC (w/Sylramic and Hi-Nicalon SiC fibers) in the form of braided CMCs, CMC/ceramic foam hybrid, SA-Tyrannohex hot pressed and machined into an airfoil shape
Issues: inter-laminar strength, leading edge, trailing edge, cooling channels, surface cooling holes

Airfoil Concept #1 - Internally Cooled Vane



Based on T-700 metallic vane contour and possible cooling hole choices.

Two types of silicon carbide fiber will be used for fabrication (Sylramic and Hi-Nicalon-S).

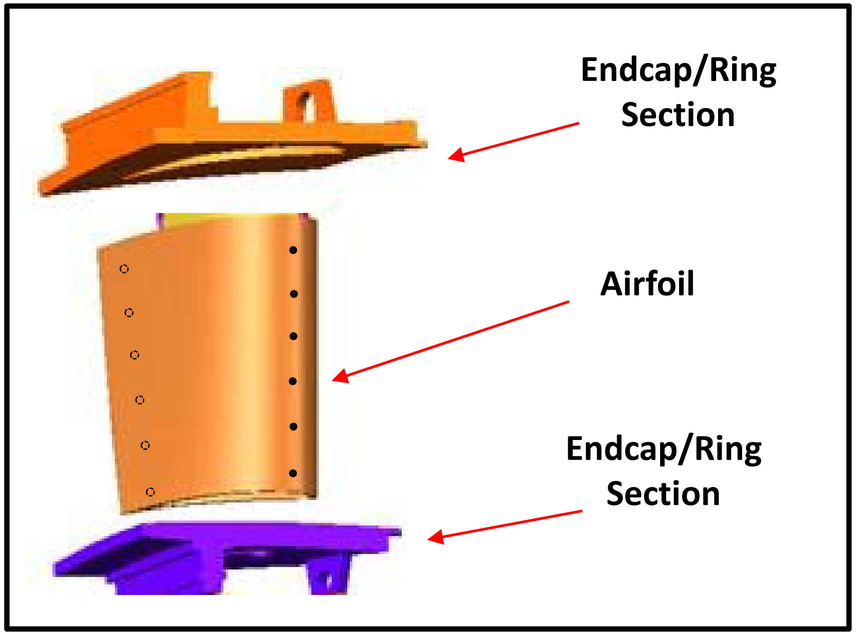
The airfoils should be delivered by April.

The 6” length will be cut down and allow for multiple tests and characterization.

Planned Sub-Element Testing
- Burner rig testing with and without internal cooling and EBC
- Heat flux test with and without internal cooling and EBC
- Testing of joined elements

Small Component Fabrication - Concept #2

Airfoil Concept #2 - Film Cooled Vane



The likely materials will be:
- SiC/SiC for the airfoil
- SA-Tyrannohex for the endcap

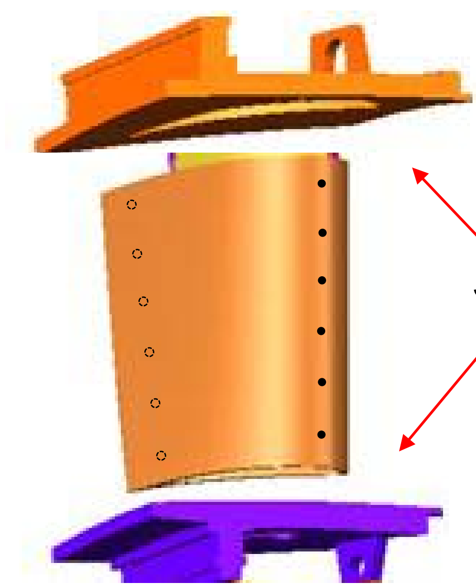
The airfoil will be fabricated this summer.

Planned Sub-Element Testing
- Burner rig testing with and without internal cooling and EBC
- Heat flux test with and without internal cooling and EBC
- Testing of joined elements

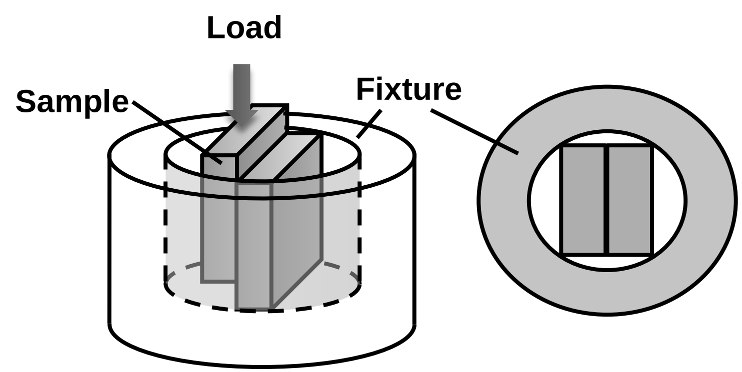
Ceramic Joining and Integration

Objective: Develop ceramic to ceramic (and ceramic to metal joining technology)
Materials: SiC/SiC, SA-Tyrannohex, (and superalloys)
Approach: - Develop processing details:
- interlayer
- conditions: time, temperature, and duration
- method: diffusion bonding, brazing, etc.

- Start with ceramic to ceramic joining of simple shapes
- Join more complex shapes
- Characterize and test (i.e. microstructural analysis, mechanical tests, thermal cycling, and burner rig)



Joining of airfoil and endcaps



Test configuration for single lap offset shear test.

Ceramic Joining and Integration
- Joining Processes

<u>Materials (dimensions 0.5” x 1”)</u>

- Substrate: SiC/SiC and SA-Tyrannohex

- Interlayers: Ti foil (10, 20 micron) and B-Mo alloy foil (25 micron)

- Ceramic substrates were ultrasonically cleaned in Acetone for 10 minutes
- Substrates were sandwiched around braze and foil layers

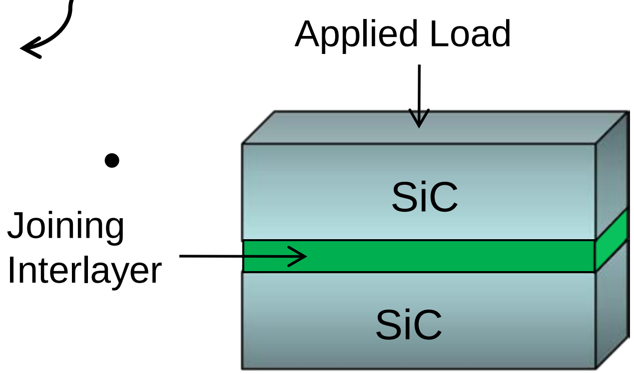
<u>Materials (dimensions 0.5” x 0.5”)</u>

- Substrate: SiC/SiC and SA-Tyrannohex

- Interlayer: pastes and tapes of Si-based eutectics

Diffusion Bonding

- Atmosphere: Vacuum
- Temperature: Ti 1200ºC,
  Mo 1400ºC
- **Pressure: 30MPa**
- Duration: Ti 4 hr
  B-Mo 4 hr
- Cool down: 2 ºC/min



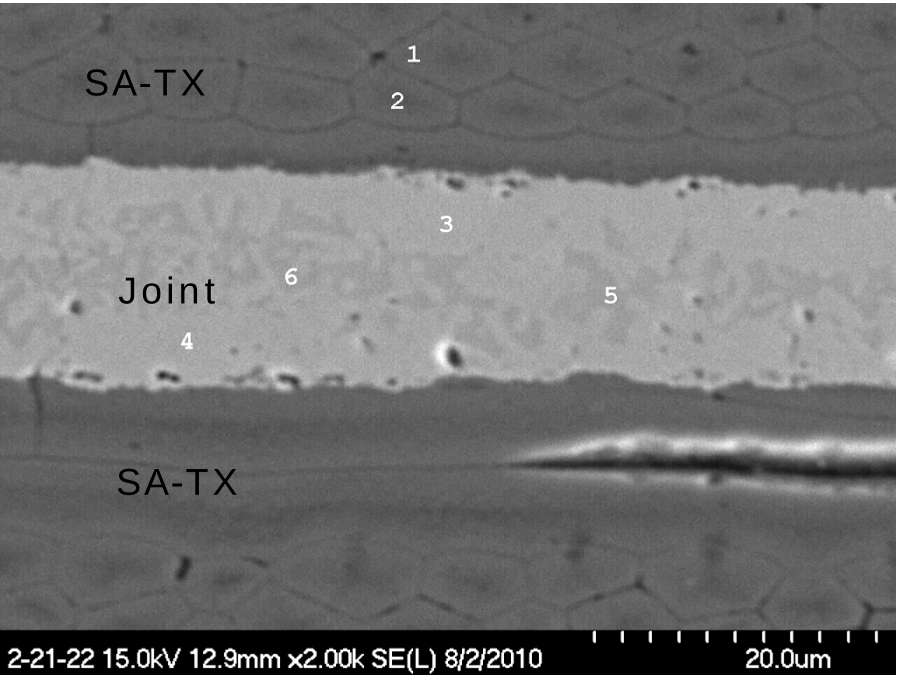
Brazing

- Atmosphere: Vacuum
- Temperature: 1340ºC (10ºC above the braze liquidus temperature)
- **Load: 100 g/sample**
- Duration: 10 minutes
- Cool down: 2 ºC/min

- Mounted in epoxy, polished, and joints characterized using optical microscopy and scanning electron microscopy with energy dispersion spectroscopy analysis

Ceramic Joining and Integration - Diffusion Bonding with 10 μm Ti Foil and 25 μm B-Mo Alloy Foil

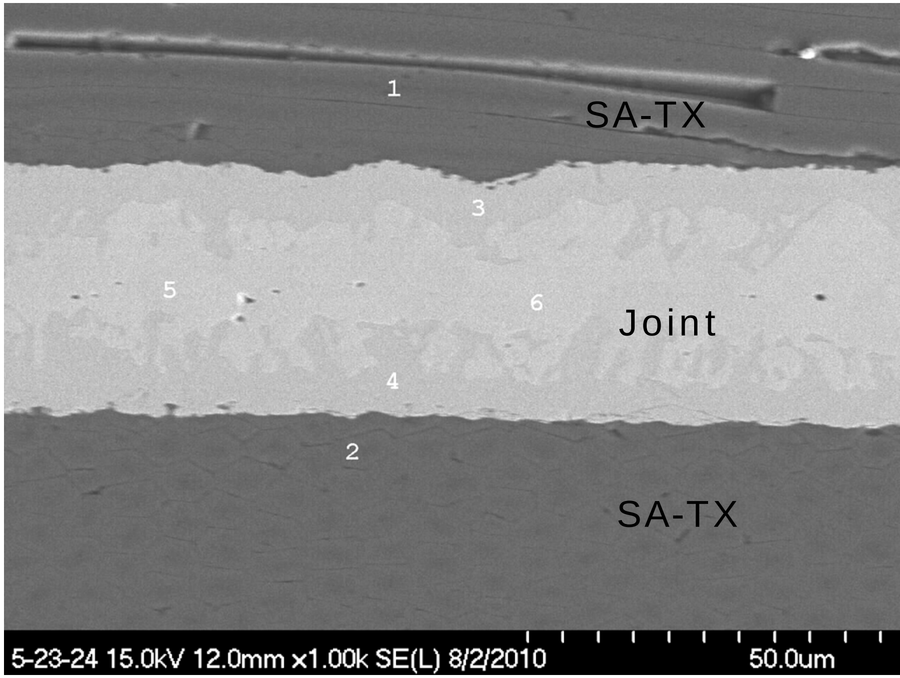
SA-Tyrannohex / **Ti** / SA-Tyrannohex



	C	Si	Ti
1	54.28%	45.72%	0%
3	44.89%	15.79%	39.33%
5	0%	69.39%	30.61%

Percents are atomic %

SA-Tyrannohex / **B-Mo alloy** / SA-Tyrannohex



	C	Si	B	Mo	O
1	58.34%	41.66%	0%	0%	0%
3	19.09%	5.51%	63.96%	8.25%	3.19%
5	0%	0%	89.18%	10.82%	0%

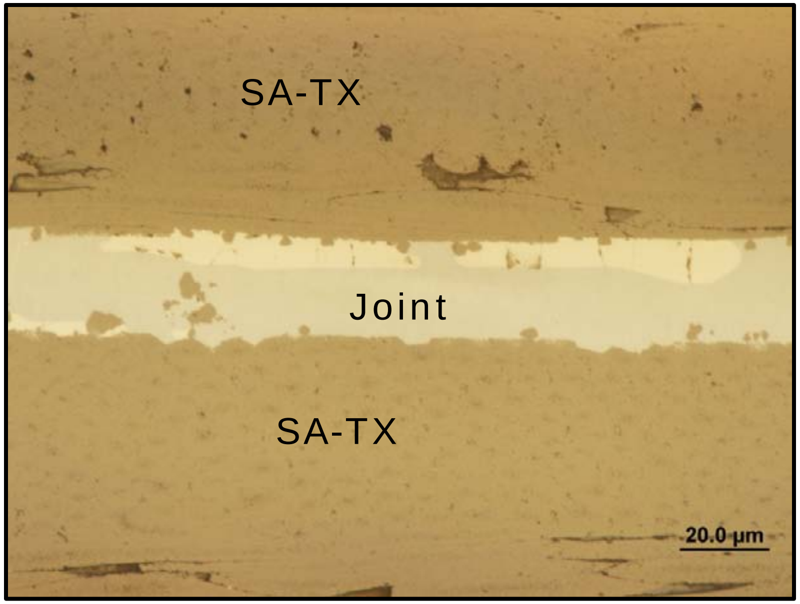
Percents are atomic %

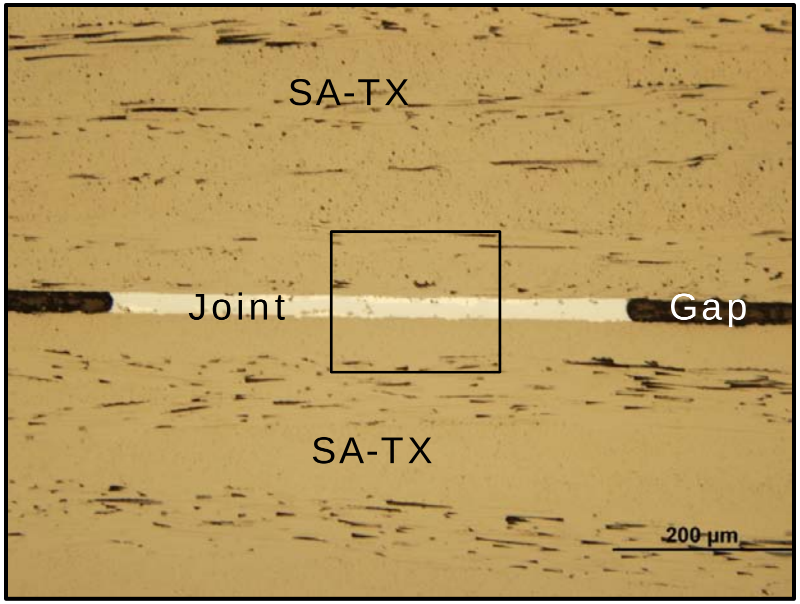
Very good quality bonds are obtained that are uniform and crack free.

However, the joining process requires high applied loads and flat sub-elements for joining.

Ceramic Joining and Integration
- Joining with Si-based Eutectic Phase Paste

Parallel SA-Tyrannohex / Si-Hf Eutectic paste / Parallel SA-Tyrannohex
- Magnifications at x10, and x100



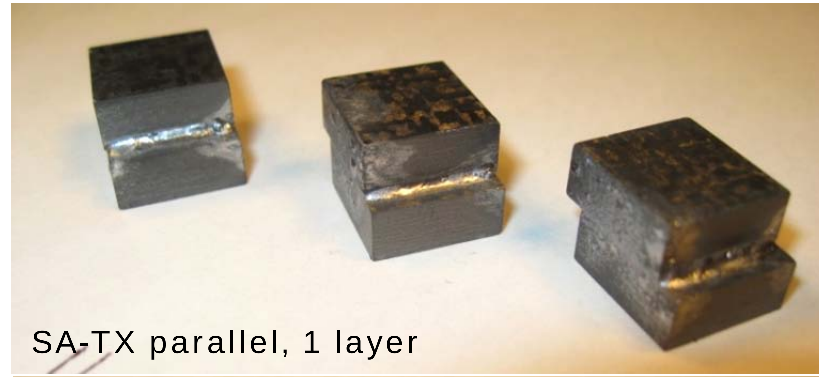


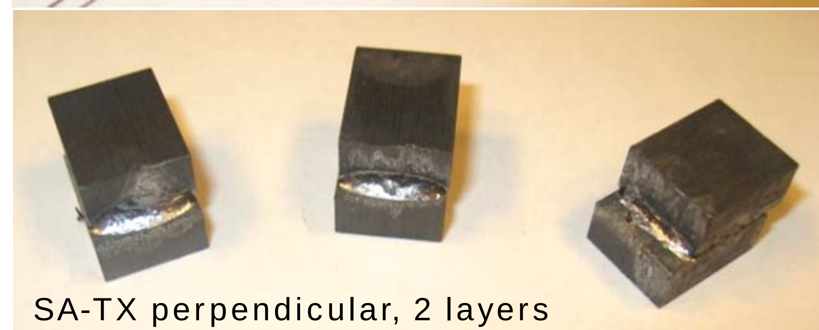
- Joints from Si-Hf eutectic phase paste are good quality showing adhesion to the ceramic substrates and no microcracking or fiber delaminations.
- However, joint formation is not uniform across the length and gaps are observed. Similar results were also obtained with Si-Ti and Si-Cr eutectic paste.
- Processing with Si-Hf eutectic tape interlayers rather than with pastes is being pursued to provide more uniformity across the joint.

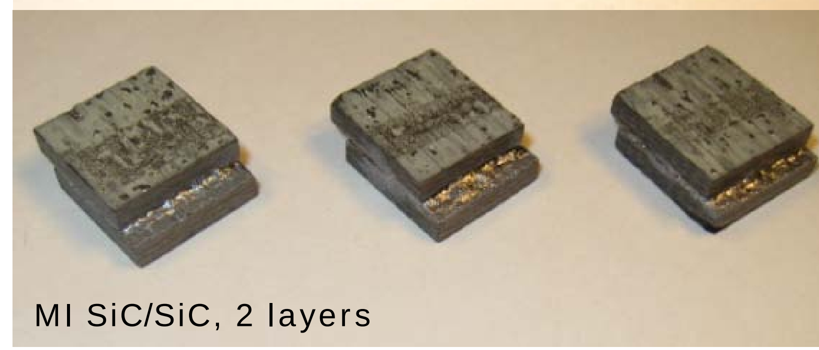
Ceramic Joining and Integration
- Joining with Si-Hf Eutectic Phase Tape

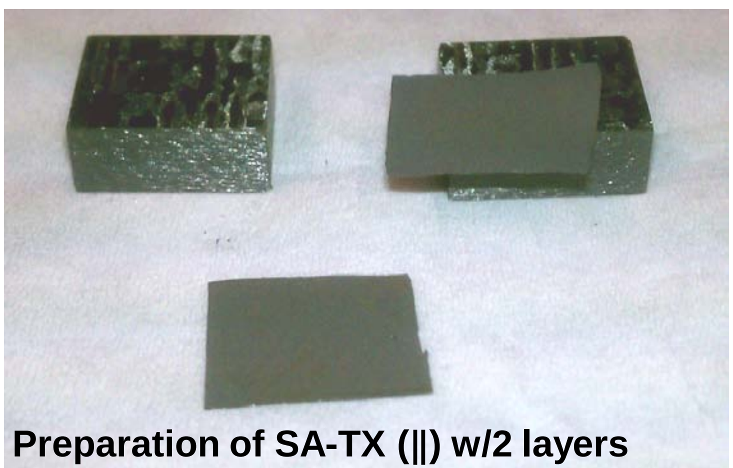
Joining with Eutectic Phase Tapes

- Three different substrates: SA-Tyrannohex (parallel), SA-Tyrannohex (perpendicular), and MI SiC/SiC.
- Joining interlayer: Si-Hf Eutectic tape - 1 layer and 2 layers.
- 8-14 pairs were joined from each of the six sets.
- Joined with 2 mm offset for mechanical tests.


SA-TX parallel, 1 layer


SA-TX perpendicular, 2 layers

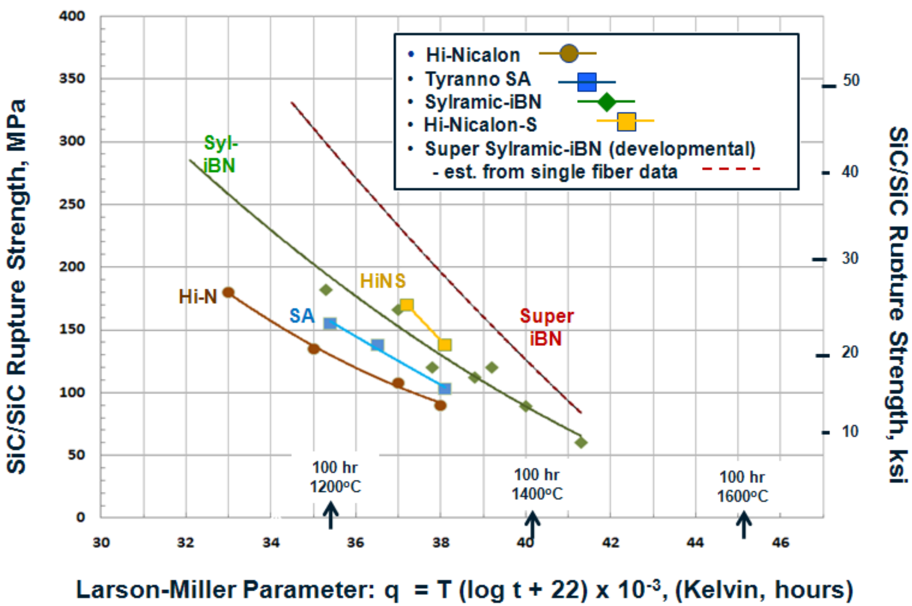

MI SiC/SiC, 2 layers


Preparation of SA-TX (||) w/2 layers

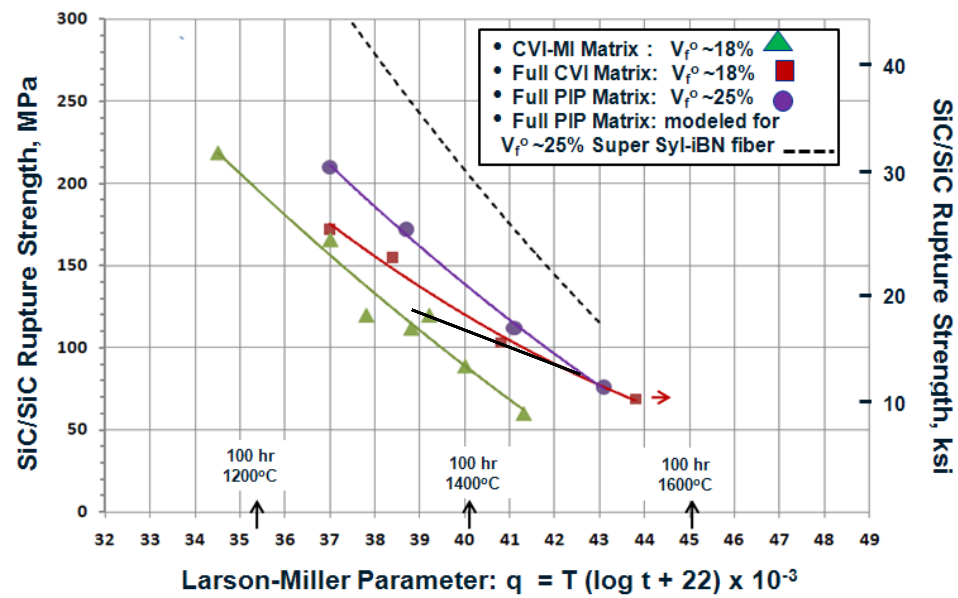
Joint characterization will include optical microscopy and scanning electron microscopy (SEM) with EDS, and mechanical testing (single lap offset).

Material and Component Characterization and Testing

Objective: model and conduct judicious selection of materials; test materials, coated materials, airfoils, and joined sub-elements to evaluate capabilities in more relevant conditions.



Effects on SiC/SiC Rupture Strength Data in Air by Reinforcement of a CVI-MI Matrix with various High-Performance SiC Fiber Types.

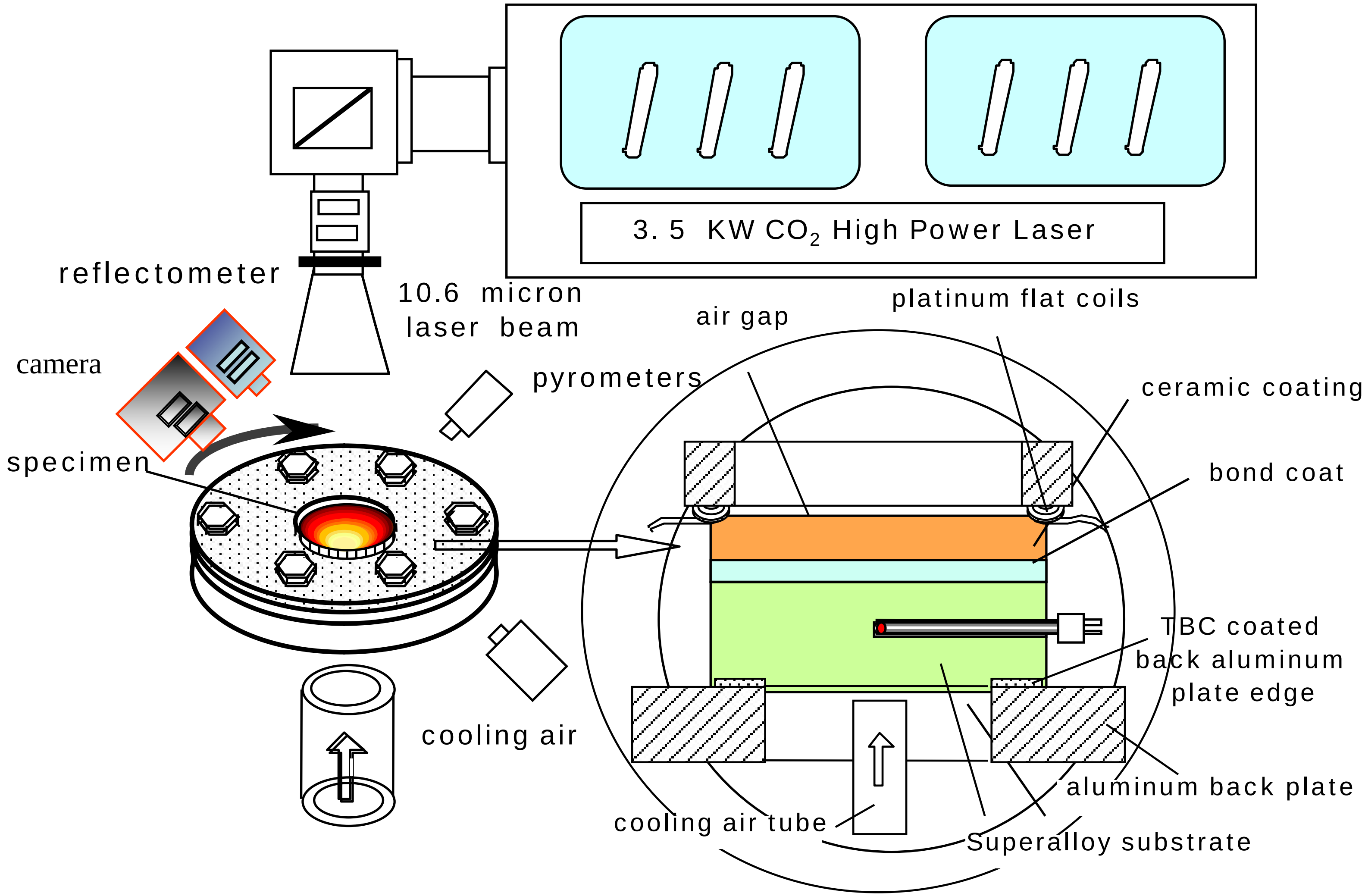


Rupture Strength in Air for SiC/SiC CMC with CVI-MI, Full-PIP, and Full-CVI Matrices reinforced by Sylramic-iBN Fibers. Also Tyrannohex SA (——).

An empirical model will be developed to act as the foundation of a more physics-based mechanistic model and predictive tool for down-selection of the optimum SiC/SiC processes, materials, and microstructures for a CMC HPT vane.

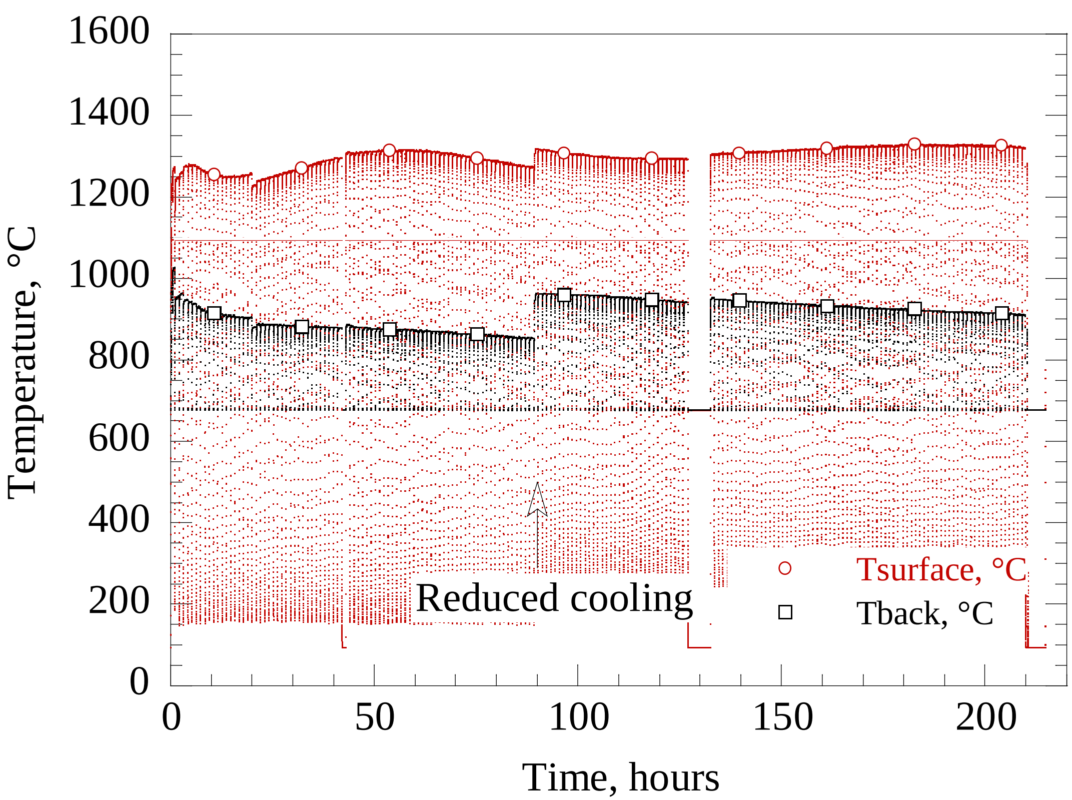
Material and Component Characterization and Testing - Laser High Heat Flux Thermal Gradient Tests

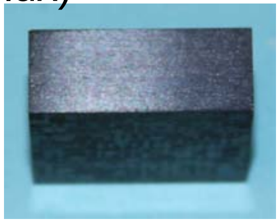
Laser High Heat Flux Thermal Gradient Rig



Material and Component Characterization and Testing – Ceramic Specimen Tested Under Cyclic Heat Flux Thermal Gradients

• SA Tyrannohex ceramic selected as a candidate material due to its excellent high temperature mechanical and thermal properties.
• The first 25x25x10 mm specimen was tested at under turbine thermal gradient cycling conditions: Tsurface 2300-2400ºF (1260-1316ºC), Tback 1700-1750ºF (927-954ºC), 1 hr cyclic in air, for total 195 cycles
• Late stage testing (after ~110 cycles) showed specimen delamination (increased surface temperature and reduced back temperature with cycling under heat flux)

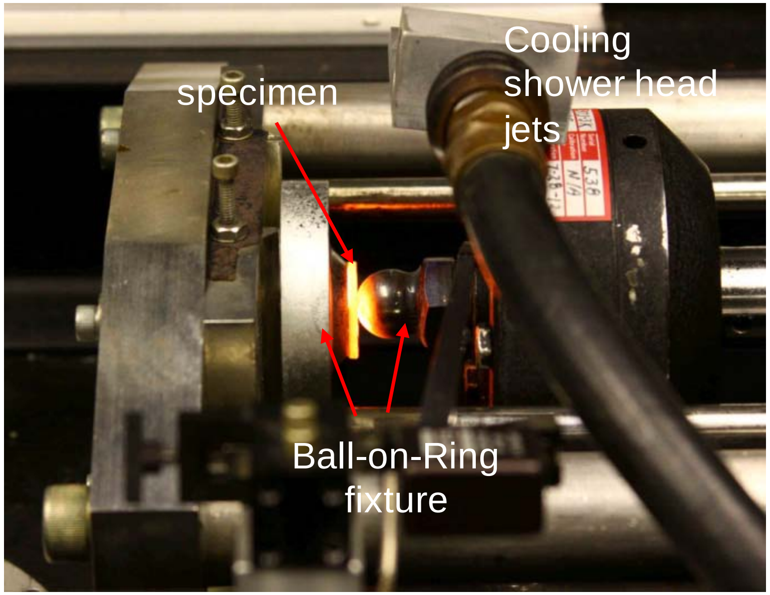




SA Tyrannohex initially selected for SRW project baseline airfoil material for evaluation: 1” square plate specimen

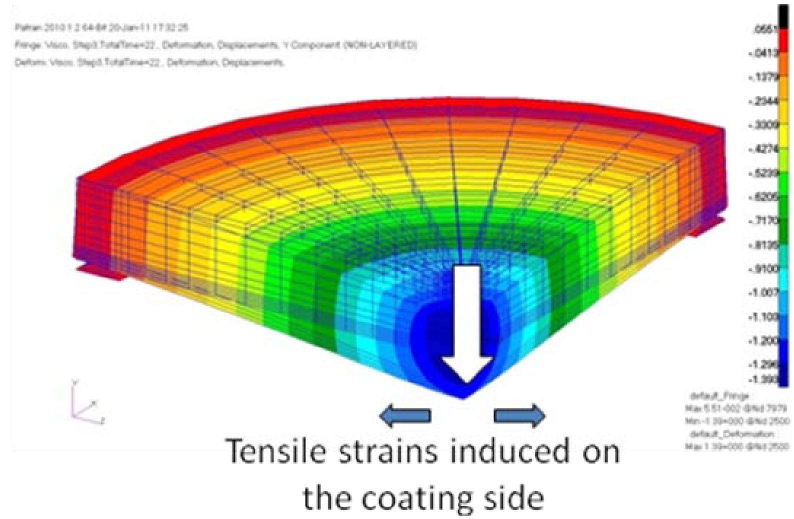
Specimen under testing

Material and Component Characterization and Testing - High Temperature Biaxial Creep Tests

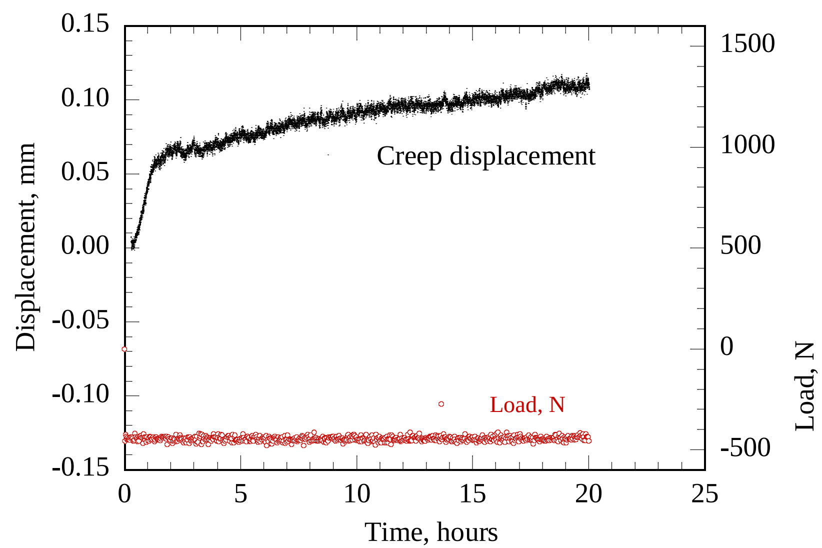


High temperature biaxial creep tests rig.

High temperature biaxial creep tests is an ideal testing capability for SRW coating and CMC airfoil development.



FEM analysis of a coated disk.

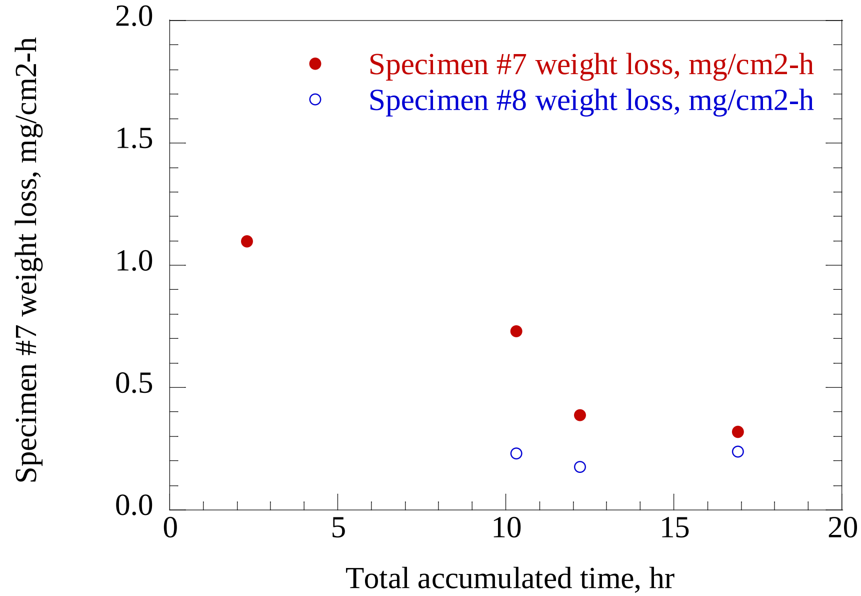


Creep response at 454 N constant loading

Material and Component Characterization and Testing - High Velocity High Pressure Burner Rig

High Velocity High Pressure Burner Rig Recession Tests
6 atm, tested at 2500ºF specimen surface, 200m/s gas velocity

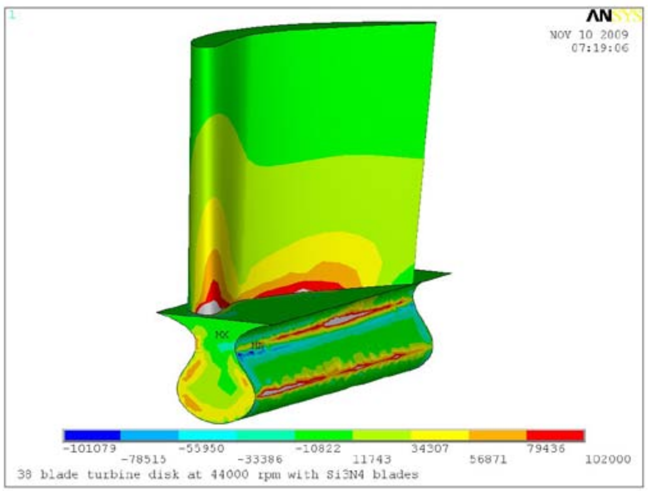
Uncoated SA Tyrannohex Ceramic Specimen High Pressure Burner Rig Recession Tests – 200 m/s



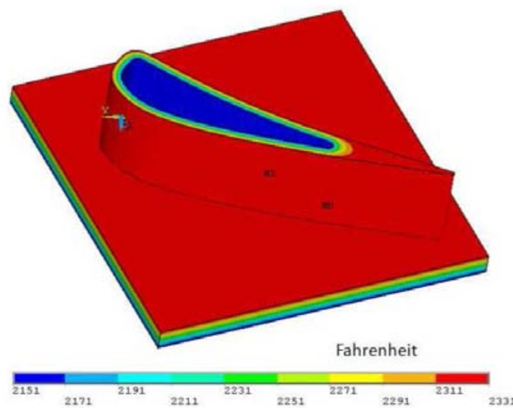
Design and Analysis of Concept Components

Objective: Investigate design issues for a vane component with emphasis on thermal and mechanical conditionals, material capabilities, and component cooling.

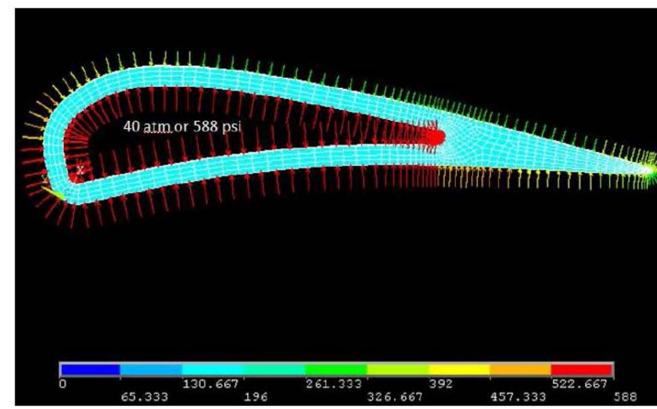
Approach: - In-house: stress analysis on first generation airfoils
- Out-of-house: N&R Engineering Phase 1 and Phase 2 SBIRs.



Blade Stress Analysis for Determination of a Blade versus Vane Task.



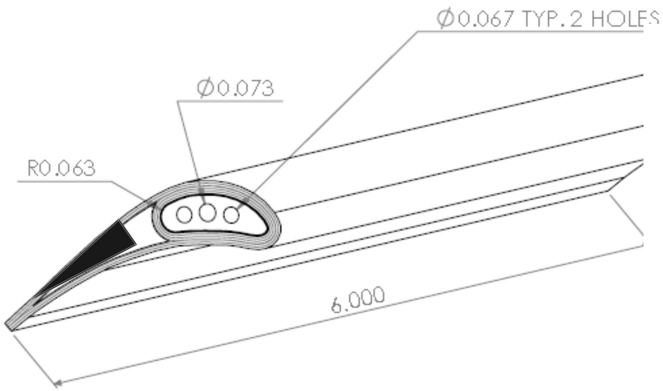
Vane Temperature Distribution (N&R).



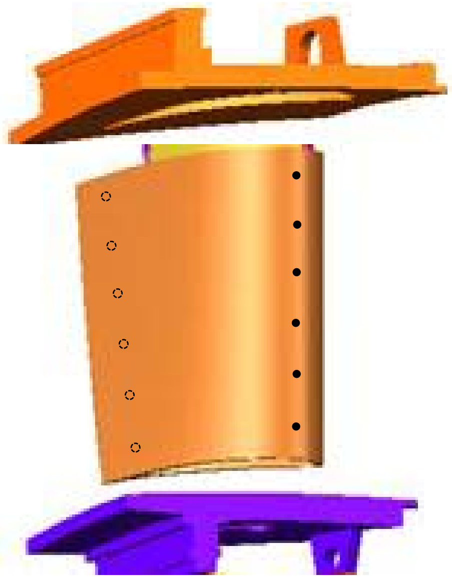
Vane Pressure Loads (N&R).

Design and Analysis of Concept Components - Thermal and Stress Analysis of Vane Designs

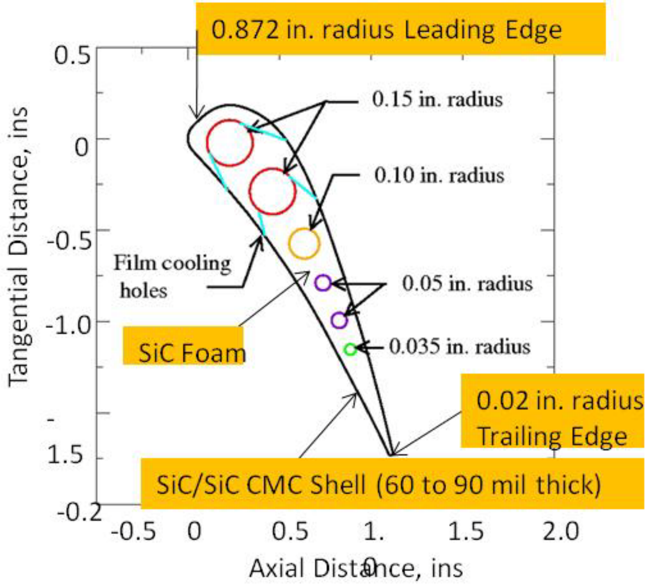
Airfoil Concept #1 - Internally Cooled Vane



Airfoil Concept #2 - Film Cooled Vane



Additional Design for Internally Cooled Vane



For the above designs, thermal profiles and loads due to thermal and mechanical stresses will be calculated.

Summary/Conclusions

- CMCs in turbine engine applications offer such benefits as:
  - Reduced fuel burn, reduced emissions, and lower weight
  - Higher temperature capability enables engine operation at higher power density (higher temperature and pressure)
  - Reduced cooling results in improved efficiency

- The SRW Vane task is addressing unique challenges the for the LCTR mission and engine class.

- Progress is being made in critical areas to include:
  - Small component fabrication
  - Ceramic joining and integration
  - Material and component testing and characterization
  - Design and analysis of concept components

- The concept sub-components and components with features for study will be demonstrated in challenging conditions that are relevant to the engine conditions.

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