High Temp. CMC Nozzles for 65% Efficiency
DE-FE0024006

2018 UTSR Conference Presentation

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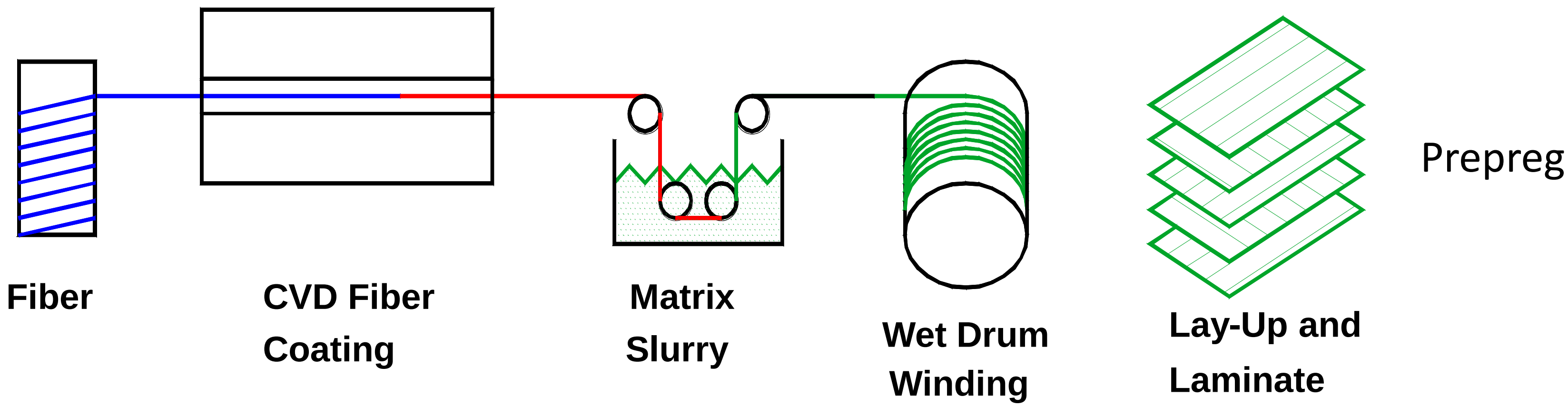
Agenda

- What is GE's CMC Material
- What is a Turbine Nozzle
- Pivot Overview
- Nozzle Design Evolution
- Fabrication Trials
- Clemson Surface Treatment
- High Temperature Seal Materials
- EBC Durability Evaluation

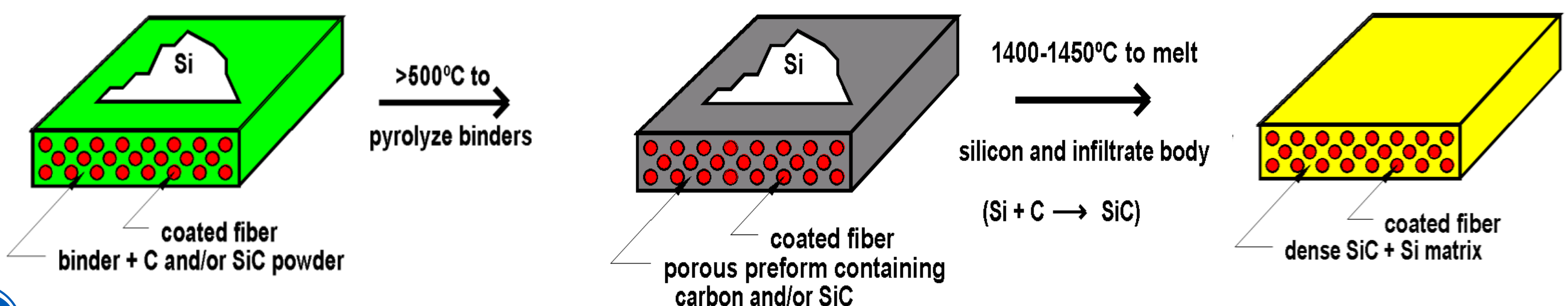
What is GE's CMC Material

GE Ceramic Matrix Composite (CMC) Processing

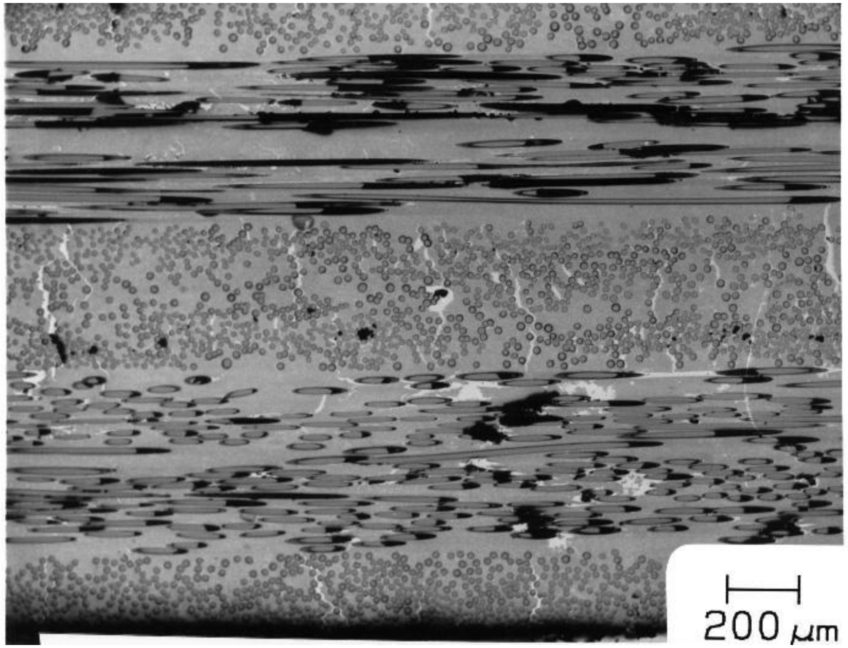
Preform Fabrication

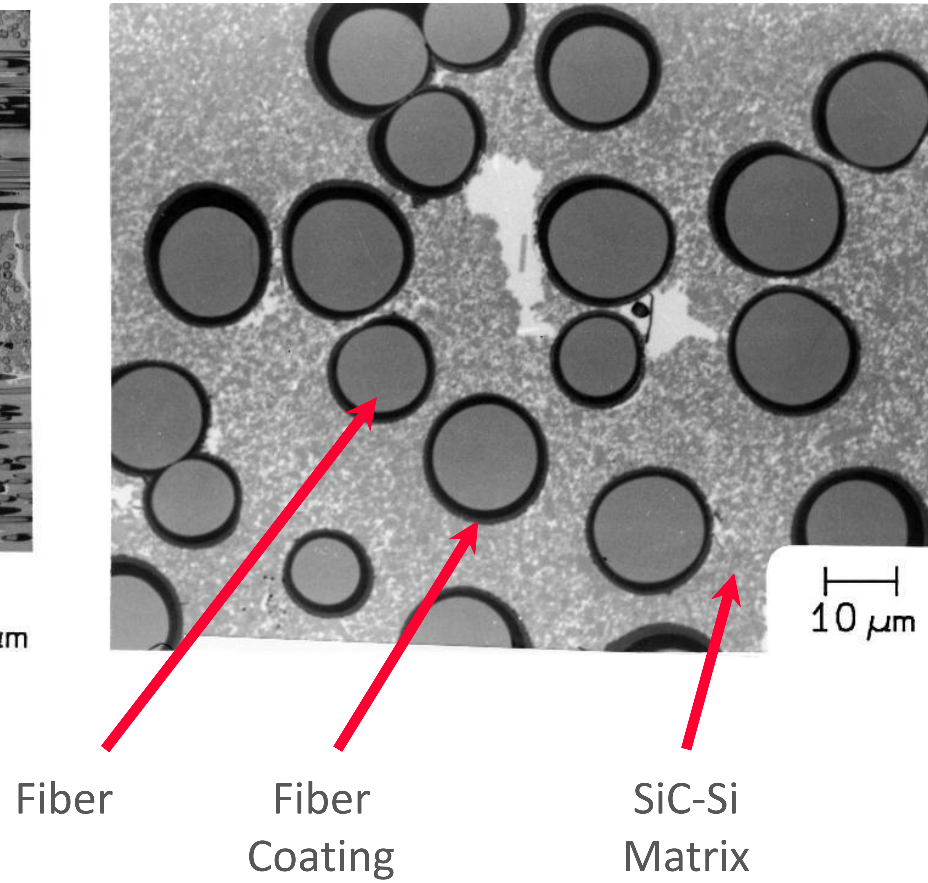


Melt Infiltration



Microstructure of Prepreg MI Composites





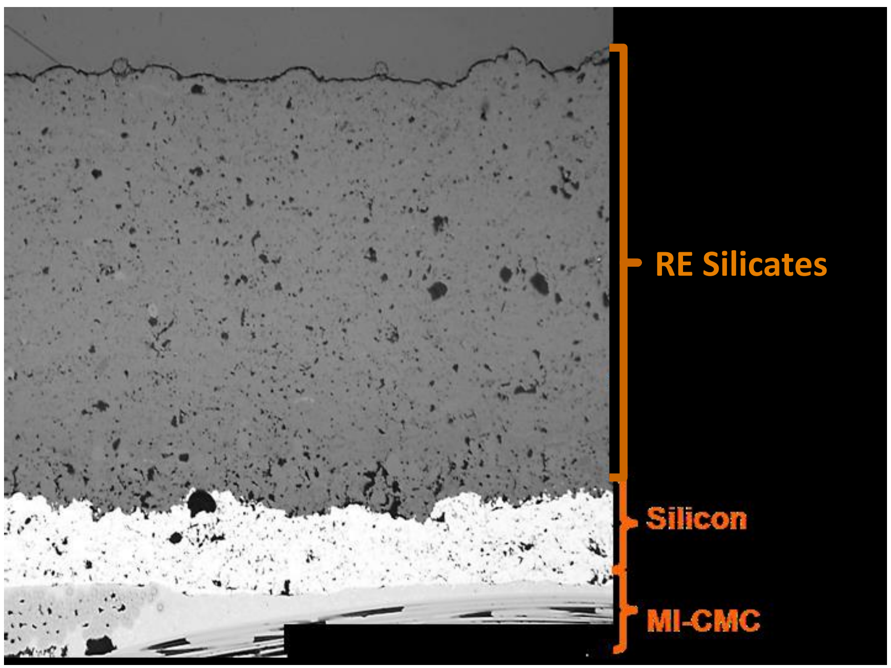
- Fibers Homogeneously Distributed; Vf = ~25%
- Separated Fibers and Fiber Coatings
- ~2-3% Matrix Porosity

Environmental Barrier Coating (EBC)

EBC needed for turbine applications to prevent silica volatilization and surface recession from water vapor in combustion gas

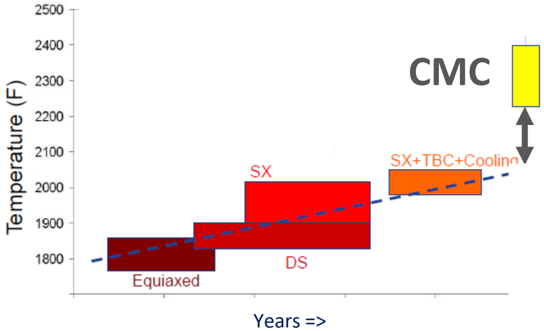
$SiO2 + H2O \rightarrow Si(OH)_x$ (gas)

Baseline System

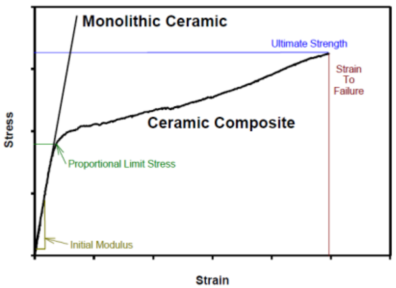


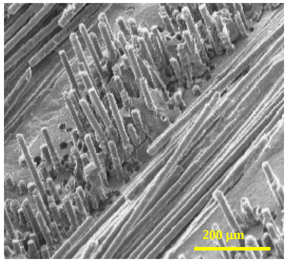
Advanced system
- Retain Si bond coat
- Rare earth silicate layers
  - ✓ CTE match
  - ✓ recession resistance

GE & DOE Advancing Development of CMC Material for Power Generation

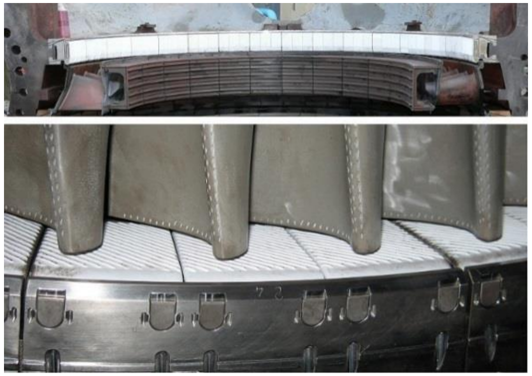


Increased material temperature capability …
… efficiency, output, reduced COE

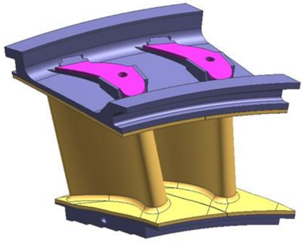




100,000 hrs High-temp testing…
… & toughness demonstrations



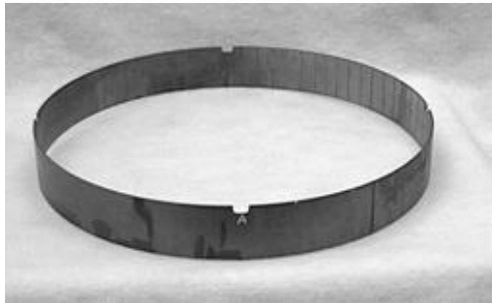
Field service demonstration …
… >20,000 hrs on 7FA shroud set



DOE 2016 phase 2 award …
… High Temp CMC Nozzles

Nearly 44000 hrs of CMC Field Experience

Stage Shroud Ring
47cm dia
1000 hrs
2 MW Machine
2000



Combustion Liner
~30 cm dia x 27 cm length
12,855 hrs, 45 cycles
Solar 5 MW gas turbine
2005 - 2006

First Shroud Demo 160 MW machine
5366 hrs, 14 cycles
2002-2003

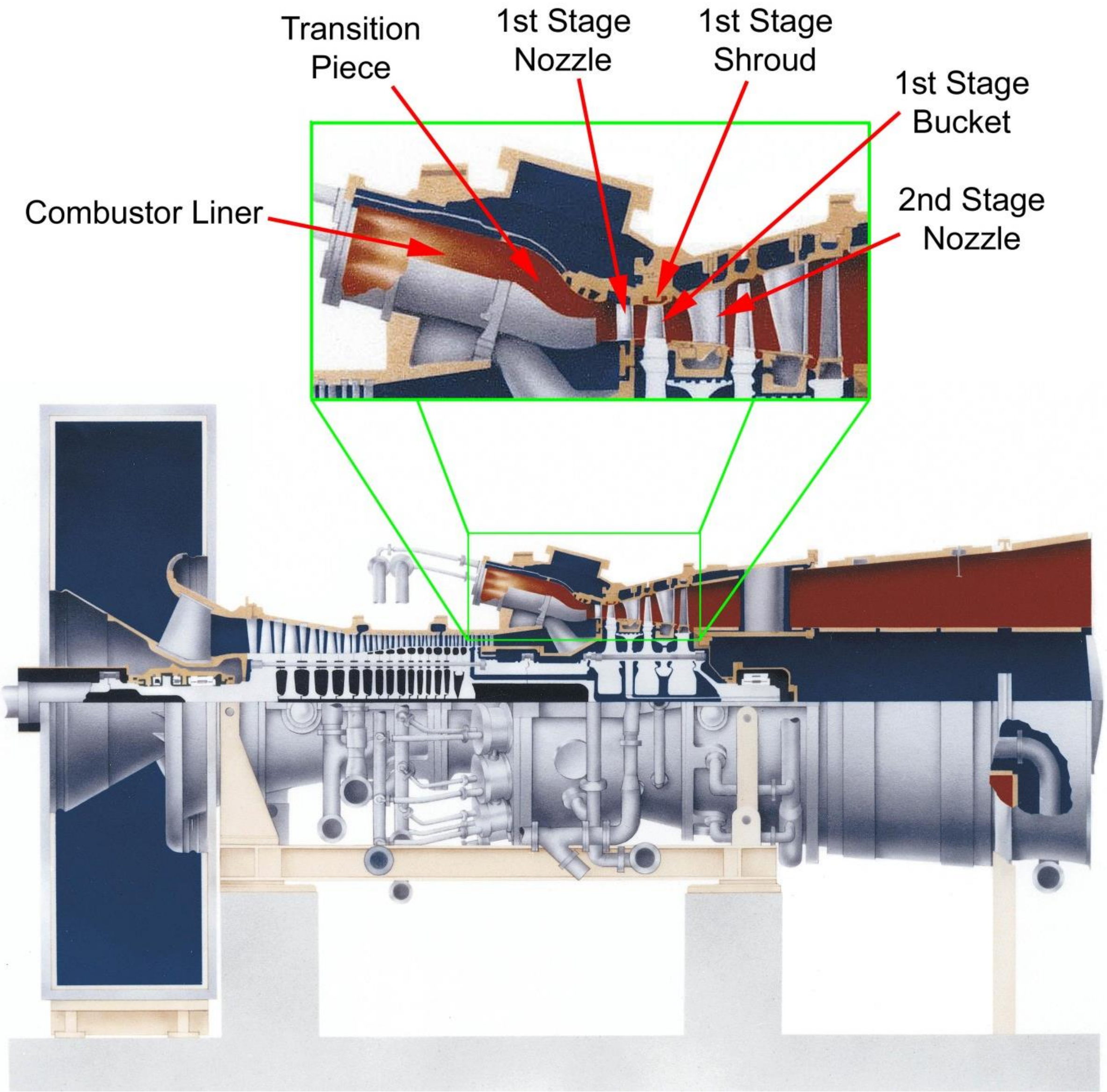
Shroud Durability Test 1
2930 hrs, 552 cycles
2006 - Continuing

Shroud Durability Test 2
21740 hrs, 126 cycles
2011 - 2014

Shroud
~8 cm x 15 cm first stage shroud
96 per full set – 160 MW machine

What’s a Turbine Nozzle

Industrial Turbine Applications



Basic Design Attributes

Flow Acceleration

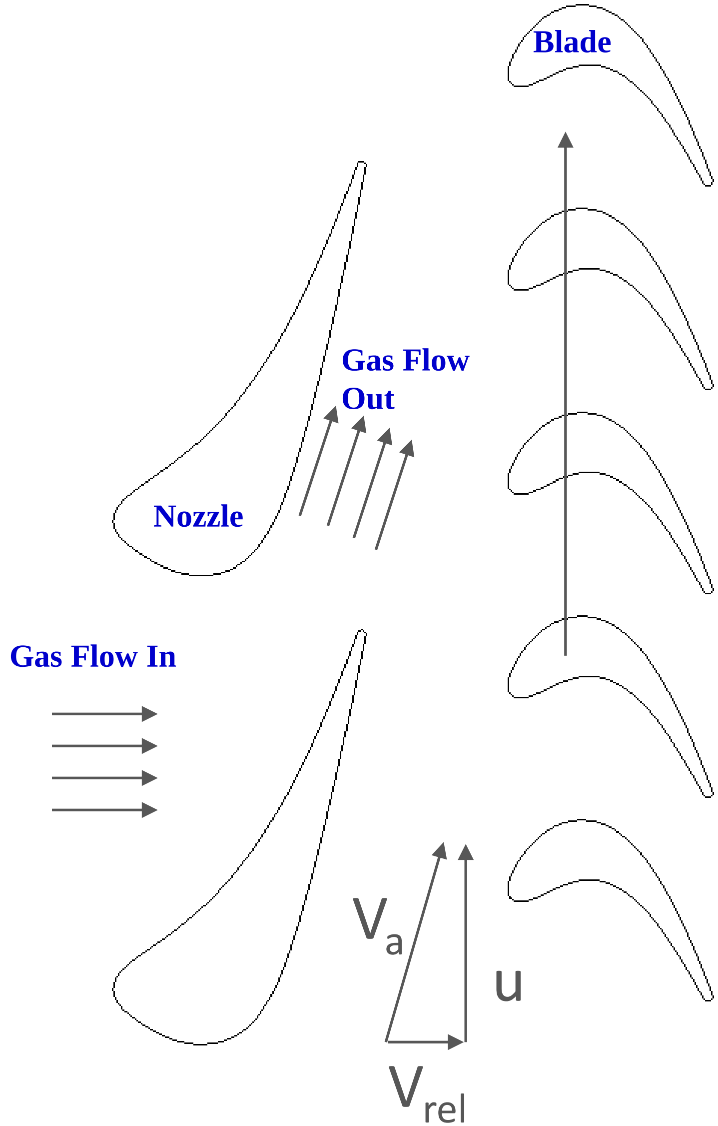
Turn and accelerate the high temperature and pressure, low velocity combustion flow into the downstream turbine blade row.

Mounting

Latter stage nozzles are typically cantilevered from outer structures

Cooling

- Cooling the nozzle structure to acceptable bulk temperatures
- More cooling directly reduces engine performance.



Program Overview - Pivot

Pivot Overview…

New

- Nozzle design and fab for engine test, Task 2.11 and 2.13
- Expanded sealing effectiveness test, Task 2.14
- Cold flow bench test, Task 2.15
- Nozzle instrumentation and assembly for engine test, Task 2.16
- One year extension 3/20 to 3/21… for machine flowpath definition

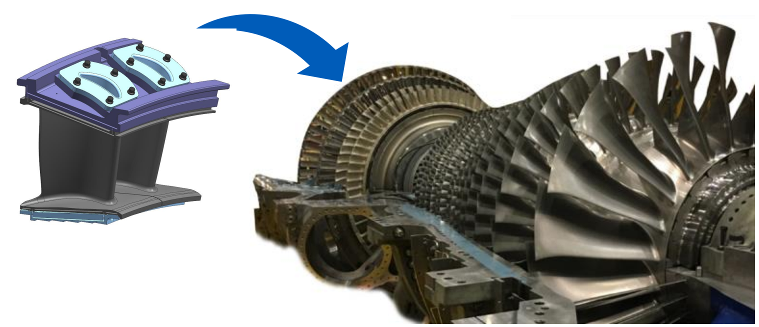
Enabling an effective "real world" test of the CMC technology

Unchanged

- High temp seal test for durability, Subtask 2.2.5
- EBC Durability Test, Task 2.7
- Feature Test for Strength, Task 2.8
- Clemson Seal surface improvement, Subtask 2.4.2

Application to GE's most advance HA class turbine

2018	2019	2020
Design	Fab	Prep



GE Solution

Cooled high-temperature CMC nozzles

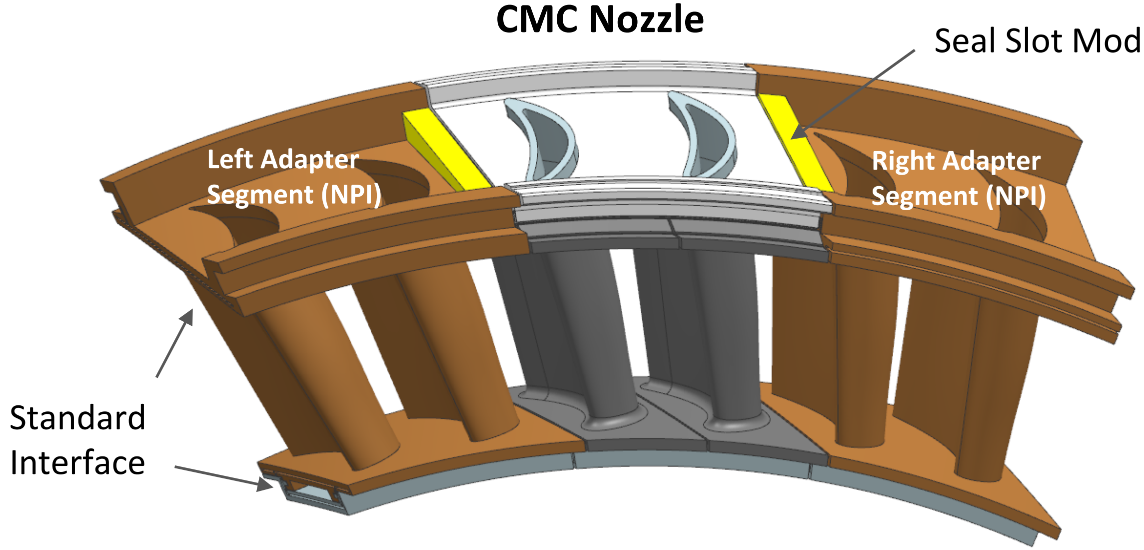
- Support load following capabilities of modern grid
- Allow higher turbine inlet temperatures (~3,100°F)
- Applicable to IGCC with pre-combustion carbon capture
- Means of improvement – improved cooling designs, better sealing, reduced leakage
- Leverage advanced manufacturing processes

Nozzle Design Evolution

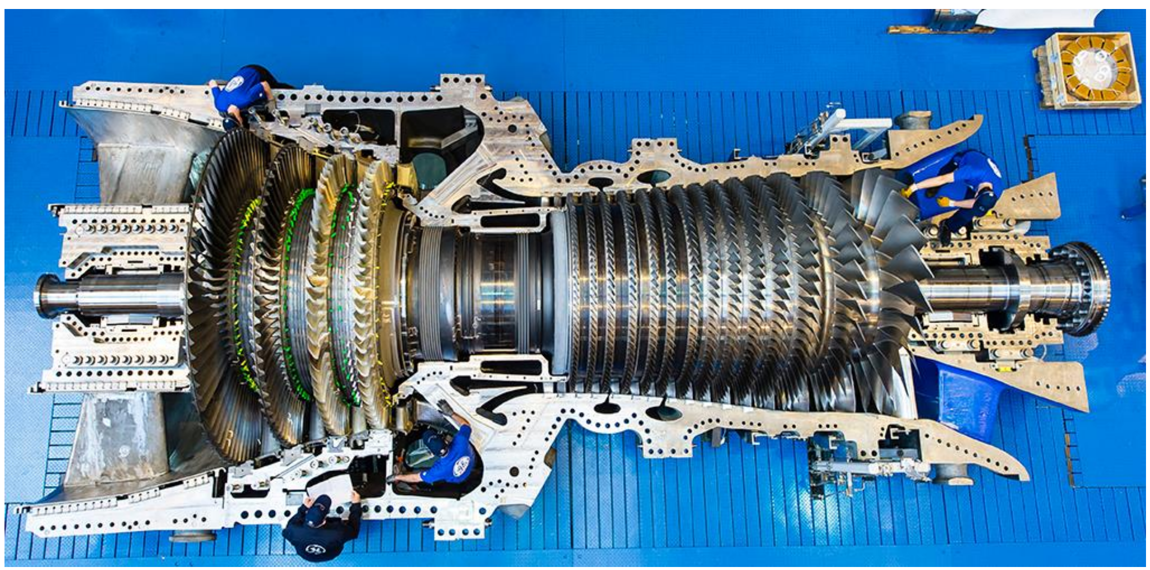
CMC Nozzle Maturation

- Actual engine test hardware
- Same HGP geometry as metal nozzles
- Unique slash face seal slot geometry
- Requires adapter nozzle segments
- Can fit future HA class GTs

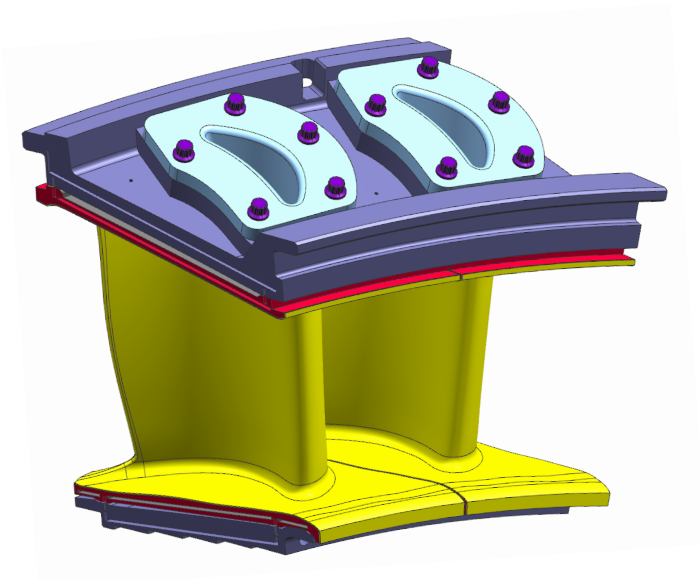
Test Assembly - Pivot (2018)



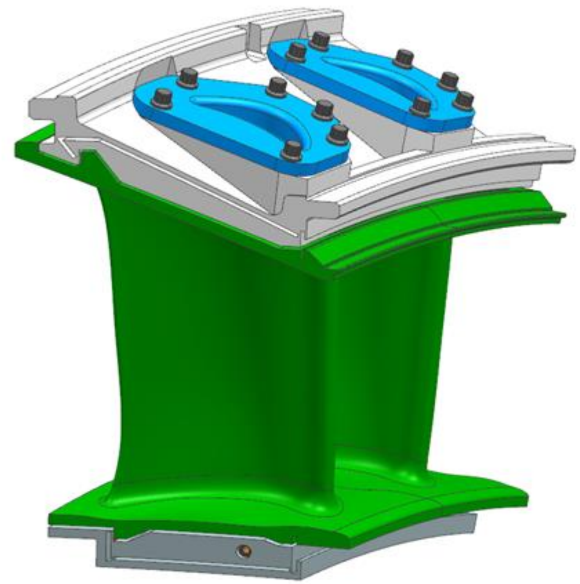
(conceptual model shown)



CMC Nozzle Evolution



2017

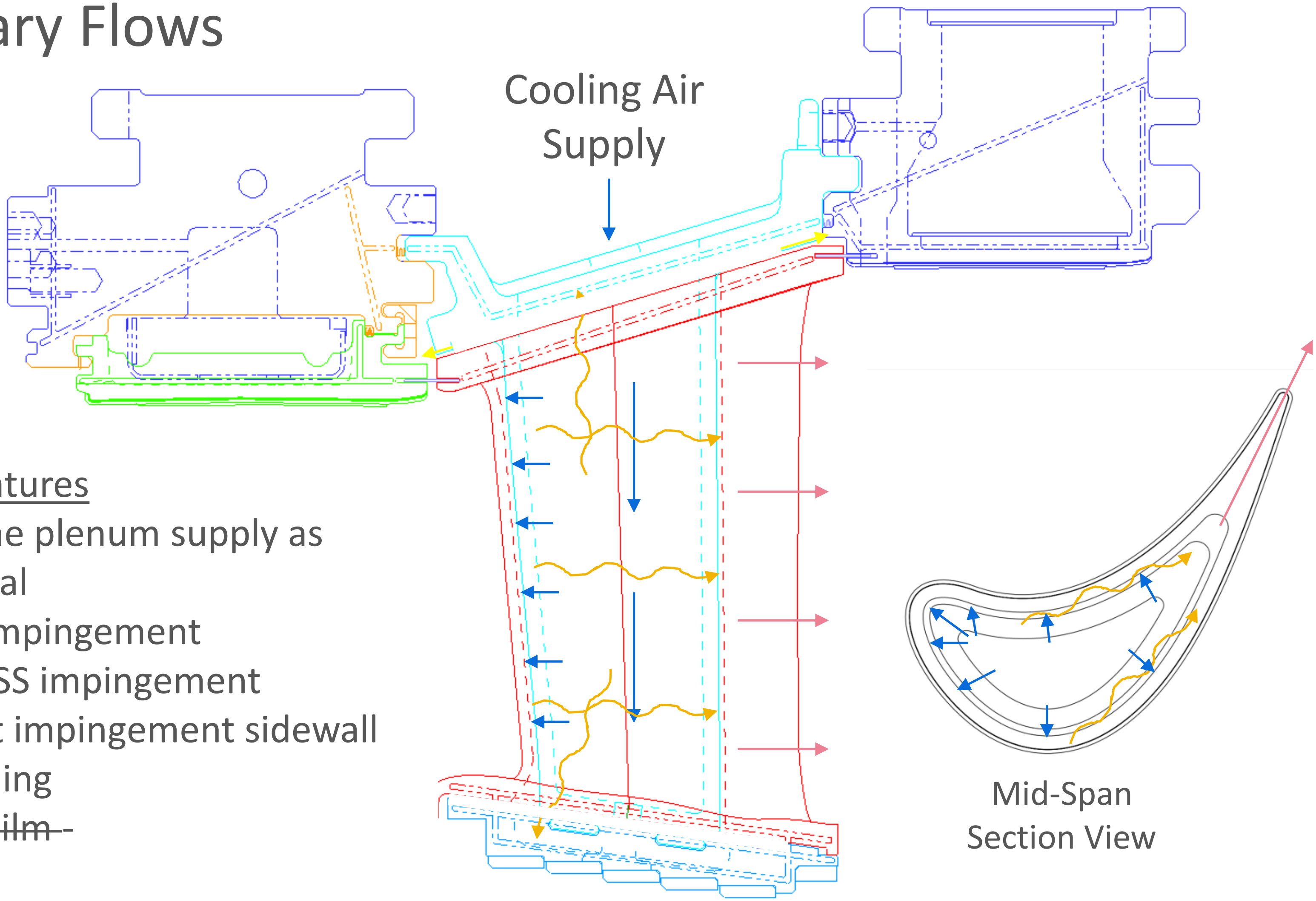


2018

- Rig test only
- Non-rotating interfaces
- No swirl effects
- Bolted Spar-to-diaphragm

- Larger engine size
- GT rotating interfaces
- Swirl effects
- Pinned diaphragm attachment

Secondary Flows



Mid-Span
Section View

Main Features

1. Same plenum supply as metal
2. LE impingement
3. PS, SS impingement
4. Post impingement sidewall cooling
5. ~~PS Film -~~

Bulk Temp	Metal to CMC Delta
Vane	400F

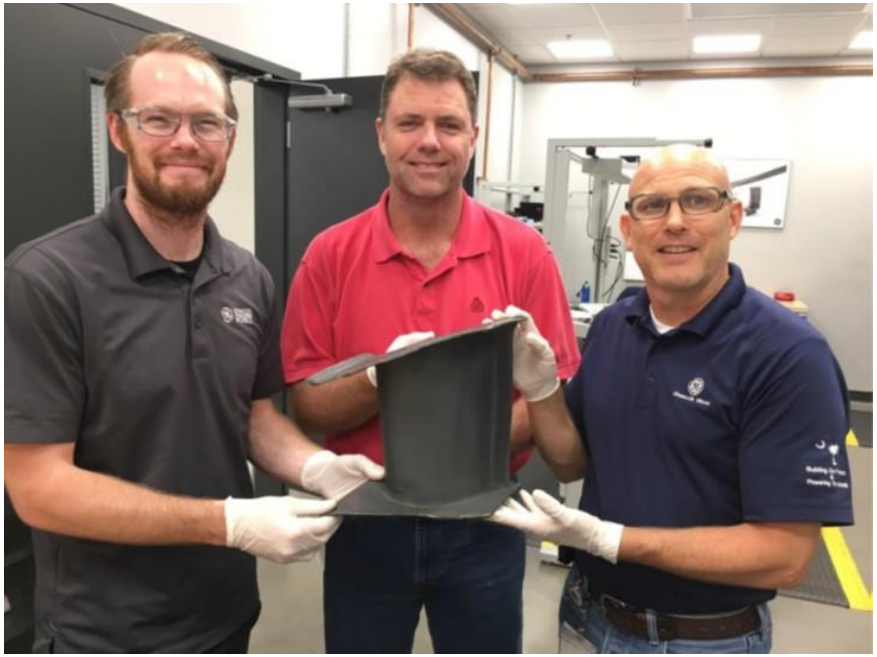
Higher allowable operating temperatures reduces cooling flow

Fabrication Trials

Fabrication of nozzles

Initial fab trials

This task will identify design considerations needed to facilitate successful nozzle manufacturing. Since the nozzle has many surfaces, airfoil, end wall, cooling passages, etc., several manufacturing iterations will be required to define a process that will deliver a finished part. Strategic design changes can often aid the manufacturing of CMCs.



Identify the design changes and manufacturing processes needed to make a successful CMC nozzle

Thermal Processing

Thermal Processing CTQs

- Creating porosity at each step
- Dimensional stability through heat cycles

Preform assembled and ready for Thermal Processing → Autoclave: Heat, Pressure, Vacuum → Pyrolysis: Heat, Inert Atmosphere → Melt Infiltration: Heat, Vacuum, Silicon Source

Distortion Reduced

Revisions in thermal cycles greatly reduces distortion

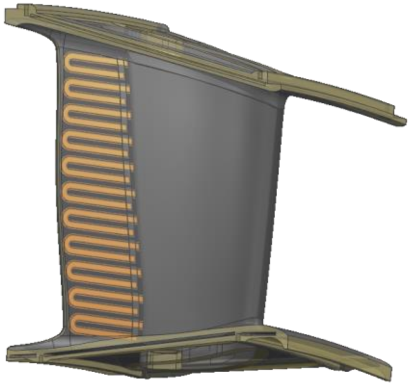
TE Cooling

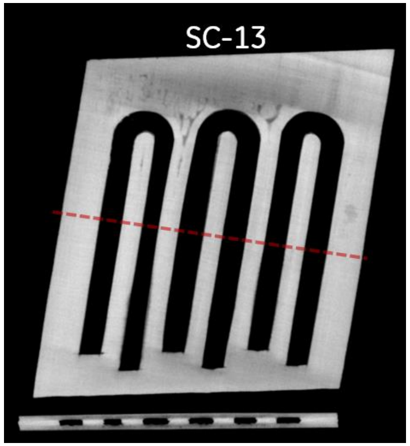
Electric Discharge Machining (EDM)

- Straight holes from TE to inner cavity
- Numerous small diameter holes

Internal Cooling Passages

- Performed trials to develop the process on flat coupons
- Final process worked with an open ended passage or fully closed



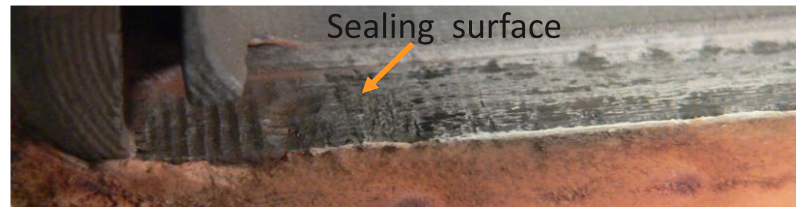


Clemson Surface Treatment

Seal Surface Improvement for CMC

Background

- A smoother sealing surface leaks less
- Current manufacturing method may not produce required surface finish.
- Surface finish may deteriorate during operation.



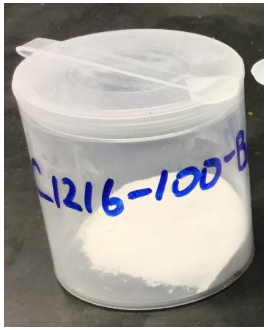
Goals

- Create a durable smooth sealing surface
- Easy application with no CMC material property degradation

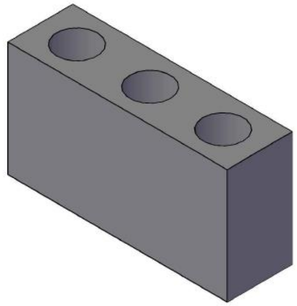
Proposed Solution

- Coat sealing surface with vitreous material
- Maximize use temperature while staying below Si melting temperature (2570F) during processing
- Application techniques: brush on, tape/mold, air spray
- Application thickness: 0.02 to 0.05 inch

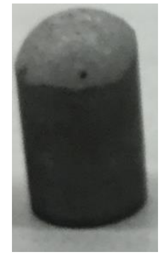
Experimental work



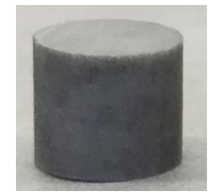
Mixed Compound



Graphite Crucible



Ceramic Rod

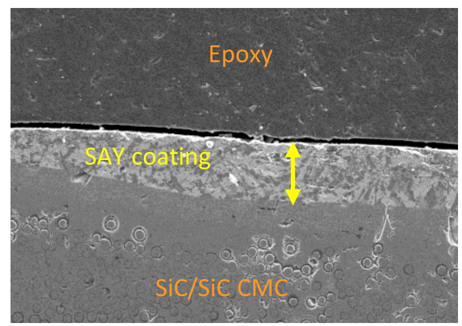


Machined Rod

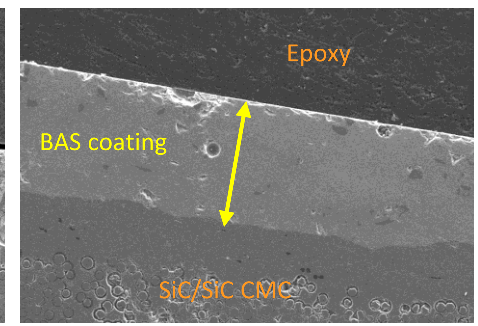
Application, Thickness, Wettability, Reactivity

Raw powder on SiC/SiC Coupon

Processed coated coupon



SAY coating

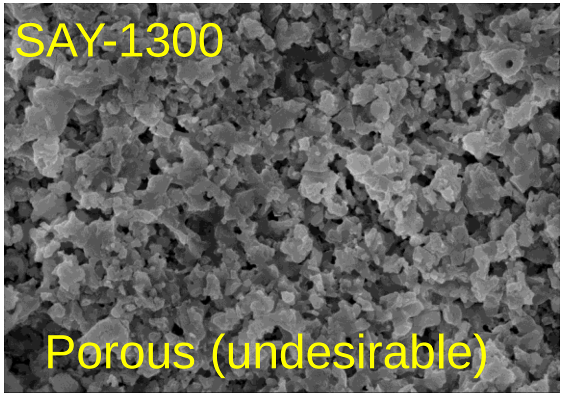


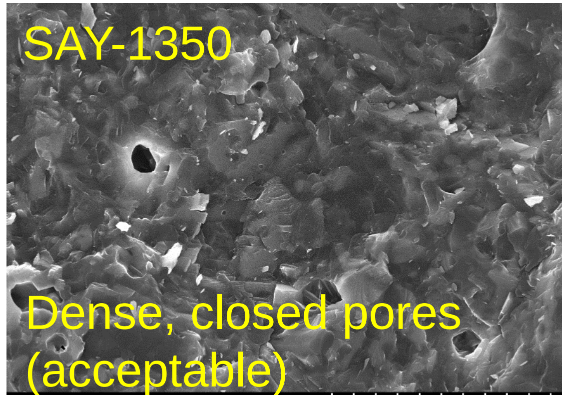
BAS coating

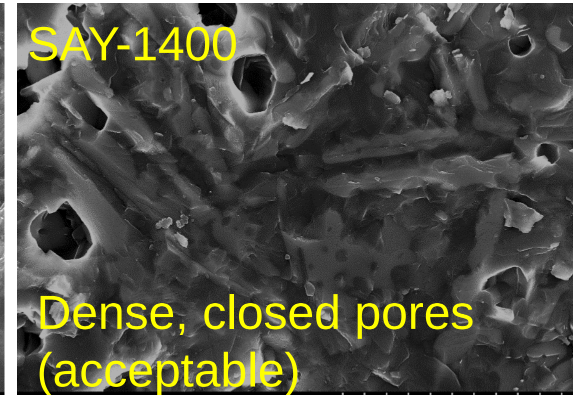
Processing steps defined, application to CMC coupons demonstrated

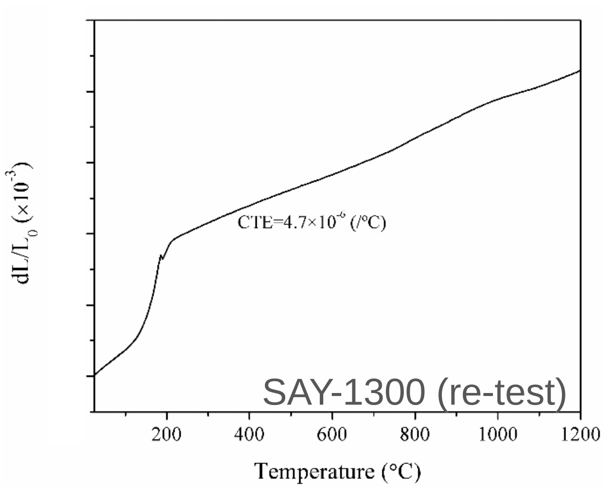
Results

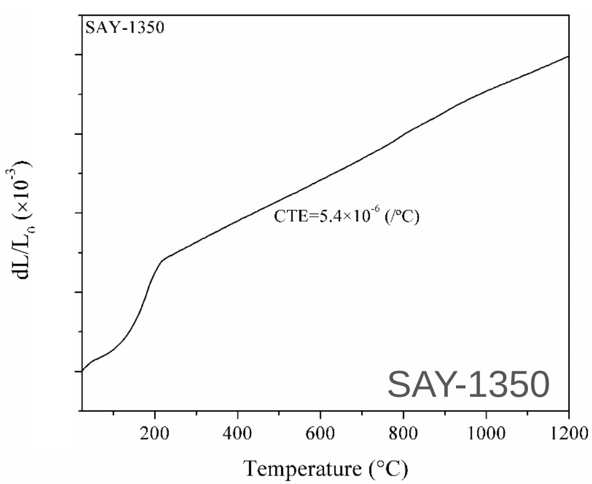
Microstructure – Dense or low porosity microstructure assumed to proved better sealing surface

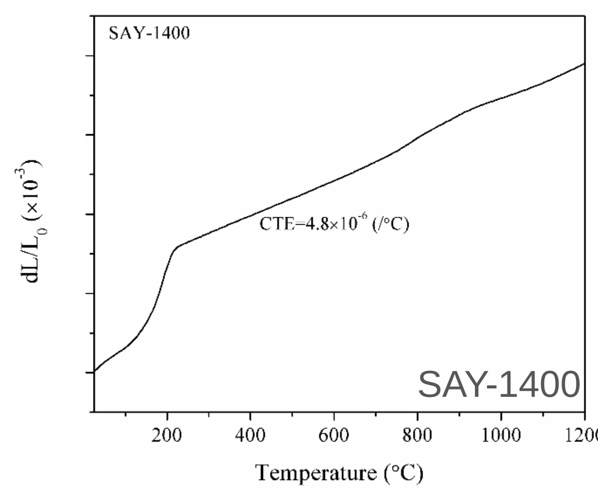






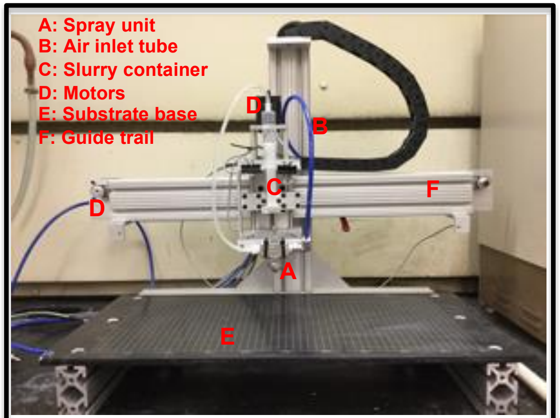






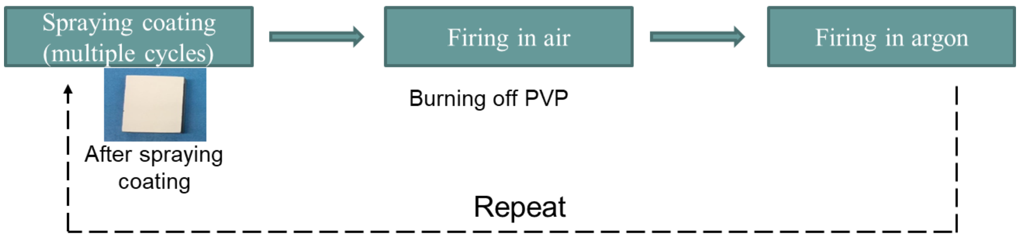
Microstructure and CTE of coatings are being quantified to determine optimal processing temperatures and compositions

Coating Application



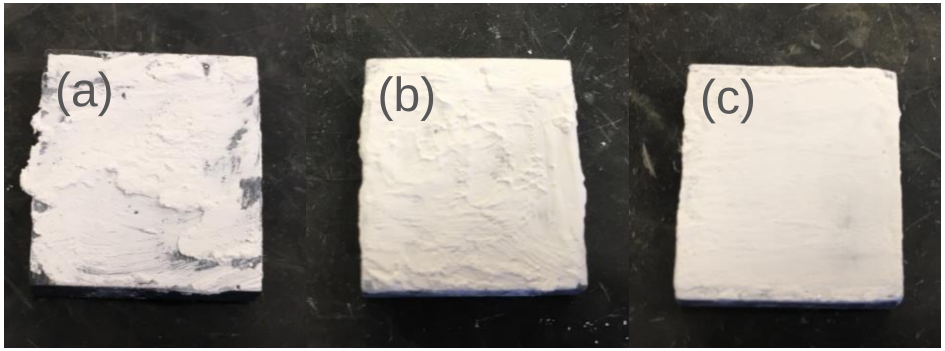
A controlled spray system to make coatings from liquid precursors or slurries

Spray



Consistent application achieved using controlled spray system

Brush-on

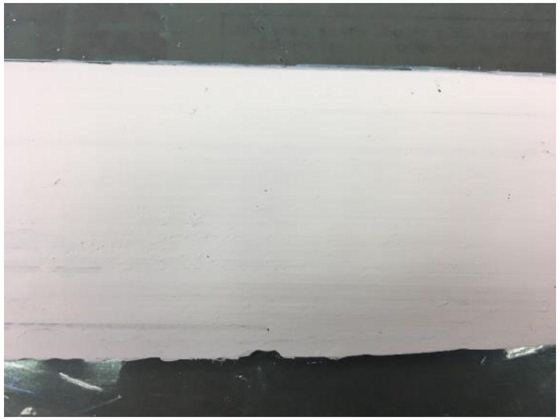


(a) Ceramic powders (high wt.%)/Isopropanol

(b) Ceramic powders (low wt.%)/Isopropanol

(c) Ceramic powders (low wt.%)/Isopropanol/Polyvinyl Butyral (binder, 1 wt.%)

Tape



Various application methods required for production applications

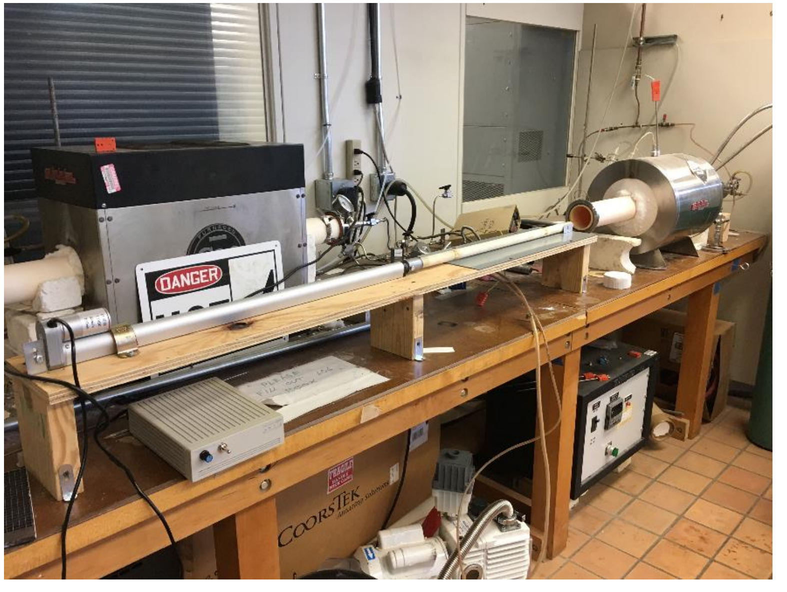
Next Steps

Characterize coated samples (roughness, thickness, porosity)

Complete Furnace Cyclic Testing (FCT) (does thermal cycling degrade coating)

Summarize application methods

Final report



FCT Equipment Setup

High Temperature Seal Materials

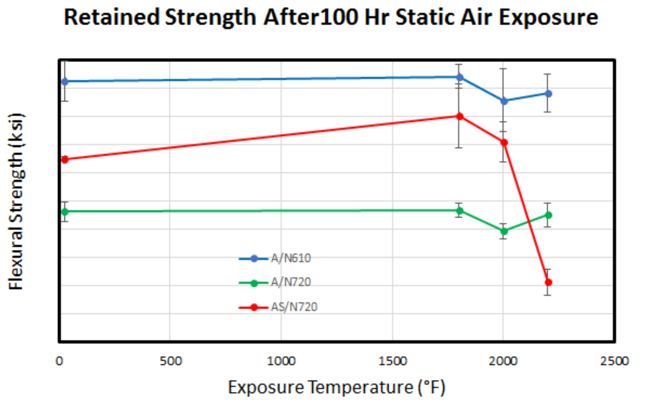
Intersegment Seal Material Candidates

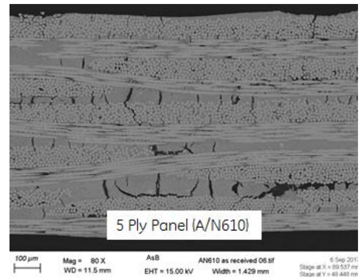
- Oxide-Oxide CMC

Material	Composition
AN610	Al_2O_3 Fiber/Al_2O_3 Matrix
AN720	Al_2O_3 Fiber/Al_2O_3-SiO_2 Matrix
ASN720	Al_2O_3-SiO_2 Fiber/Al_2O_3-SiO_2 Matrix

- FeCrAl alloy (w/Mo & Y)
  - Kanthal sheet stock

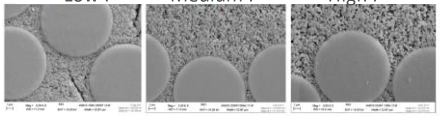
Oxide-Oxide CMC Evaluations





AN610 Ox-Ox (all-Al_2O_3) Microstructures

100 Hrs Oxidation



Steam Exposure of Ox-Ox CMC Materials

Material	Composition
AN610	Al2O3 Fiber/Al2O3 Matrix
AN720	Al2O3 Fiber/Al2O3-SiO2 Matrix
ASN720	Al2O3-SiO2 Fiber/Al2O3-SiO2 Matrix

- Weight loss is consistent with SiO_2 content of material

Fracture Toughness Retention

Exposure Condition	MATERIAL AN610	AN720	ASN720
As-received	0.25 mm	2.20 mm	1.85 mm
°F-100hrs	2.10 mm	2.69 mm	Failure
°F-100hrs	2.60 mm	2.80 mm	Failure

AN610 AN720 ASN720

As-received

°F-100 hrs

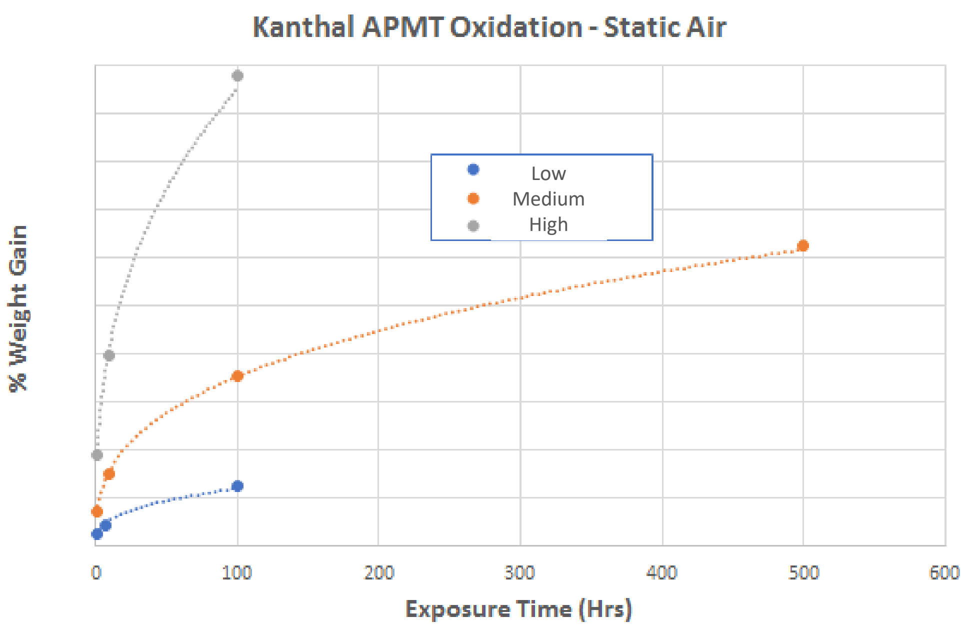
°F-100 hrs

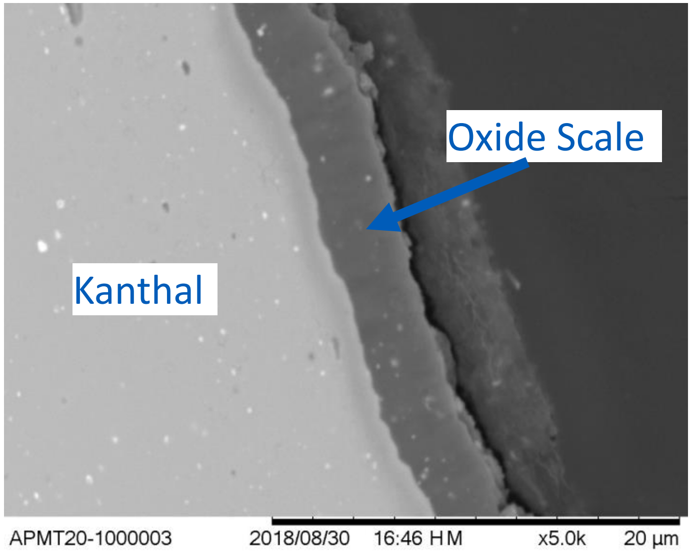
Next tests for AN610 – Hi-temp wear resistance against SiC CMC & EBC at Aviation, creep & chemical compatibility

Kanthal Characterization

Kanthal (FeCrAl Alloy with Mo & Y)

- Oxidation testing in progress - static oxidative exposures at >1500F characterization includes oxide scale microstructure wgt change, dimensional changes



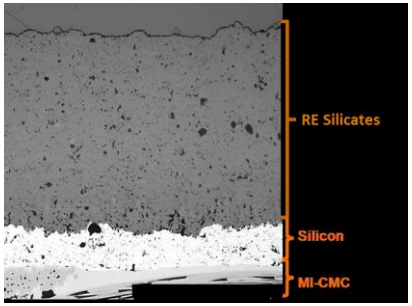


100 hrs oxide scale only ~5μm thick

- Next tests: flexural creep, chemical compatibility

EBC Durability Evaluation

EBC Durability Evaluation



EBC is required to prevent recession

Task deliverable

- prepare EBC samples
- subject to thermal gradient conditions consistent with nozzle in turbine
- quantify degradation over time to predict EBC life

For the nozzle application

- Design requested thick EBC for added thermal barrier effect
- 2-4X the thickness of previous Power field experience

Test conditions

- Daily thermal cycling
- Evaluate at 1/2/4/up to 8k hr. for bond-coat oxidation and EBC micro-voiding rate

EBC Durability Test Matrix

	Exposure Duration (hours)	Produce Samples	Rig Exposure	Met + eval	Target Date
Thin Coating 1	1000				✓
	2000			in process	3Q18
	4000				2Q19
	8000				3Q19
Thick Coating 1	1000				✓
	2000		running		3Q18
	4000		running		4Q18
	8000		running		3Q19
Thin Coating 2	1000		running		3Q18
	2000				1Q19
	4000				2Q19
	8000	in process			3Q19
Thick Coating 2	1000	in process			4Q18
	2000	in process			1Q19
	4000	in process			3Q19
	8000	in process			3Q19

Observations

- Thicker coating show propensity for crack
- Added a thinner coating to the test matrix
- Thinner show less propensity for cracks

Next Steps

- Complete nozzle design… CMC and metal
- Fabriate full scale and full featured nozzles
- Flow test fabricated nozzles

Key Risk

- Design stresses are too high… *feature test risk areas to determine strength or perform a life assessment*
- CMC fab process yields poor quality… *many build trials used to determine the optimum process*
- Sealing or cooling is insufficient... *bench flow the seals and sub-assembly, verify/modify flow circuit and seal geometry as necessary*

Q&A
Discussion