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

2019 UTSR Conference Presentation

John Delvaux

This material is based upon work supported by the Department of Energy under Award Number **DE-FE0024006**.

November 6, 2019

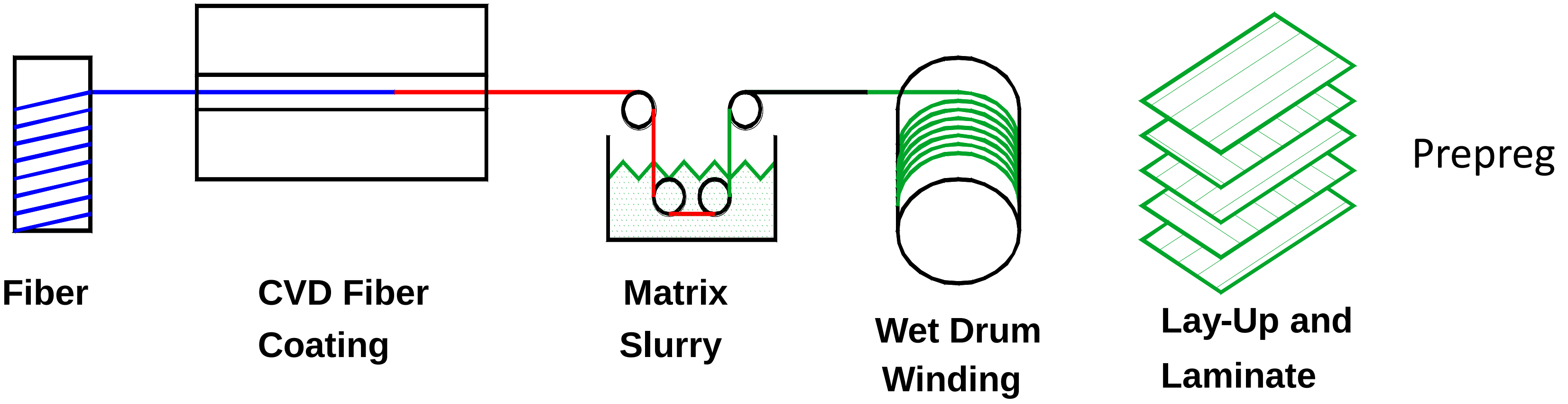
Agenda

- What is GE's CMC Material
- What is a Turbine Nozzle
- Program Overview
- CMC Material Advancement
- Nozzle Design Evolution
- Fabrication Trials
- Clemson Surface Treatment
- EBC Durability Evaluation
- Next Steps

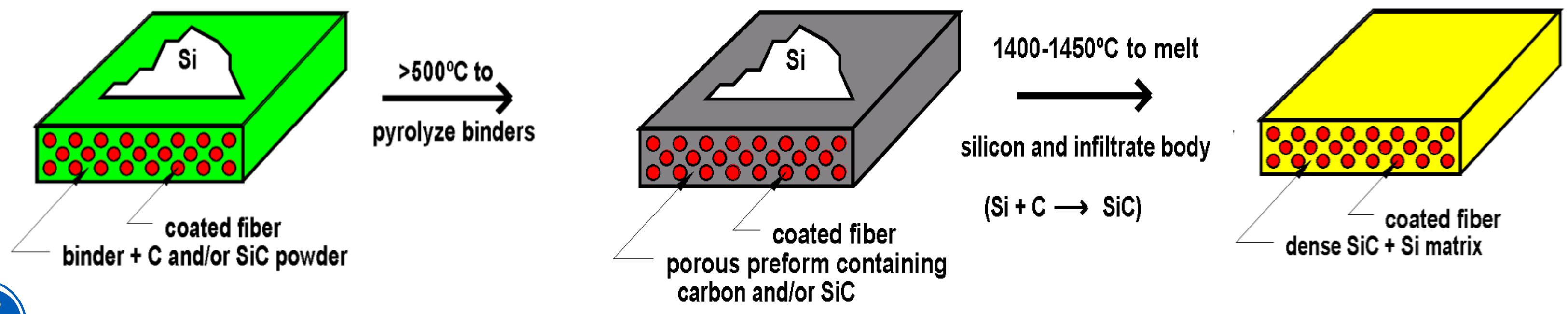
What is GE’s CMC Material

GE Ceramic Matrix Composite (CMC) Processing

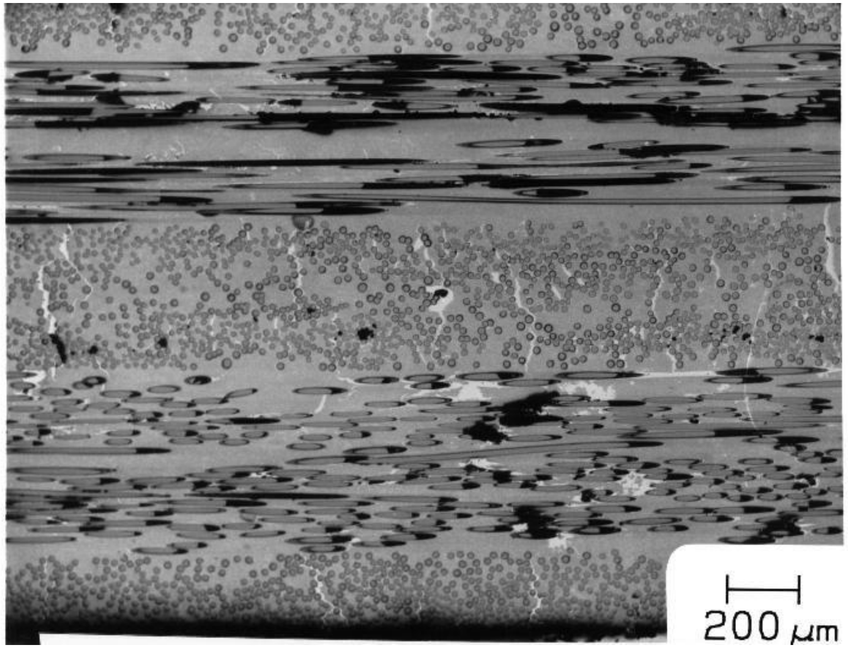
Preform Fabrication

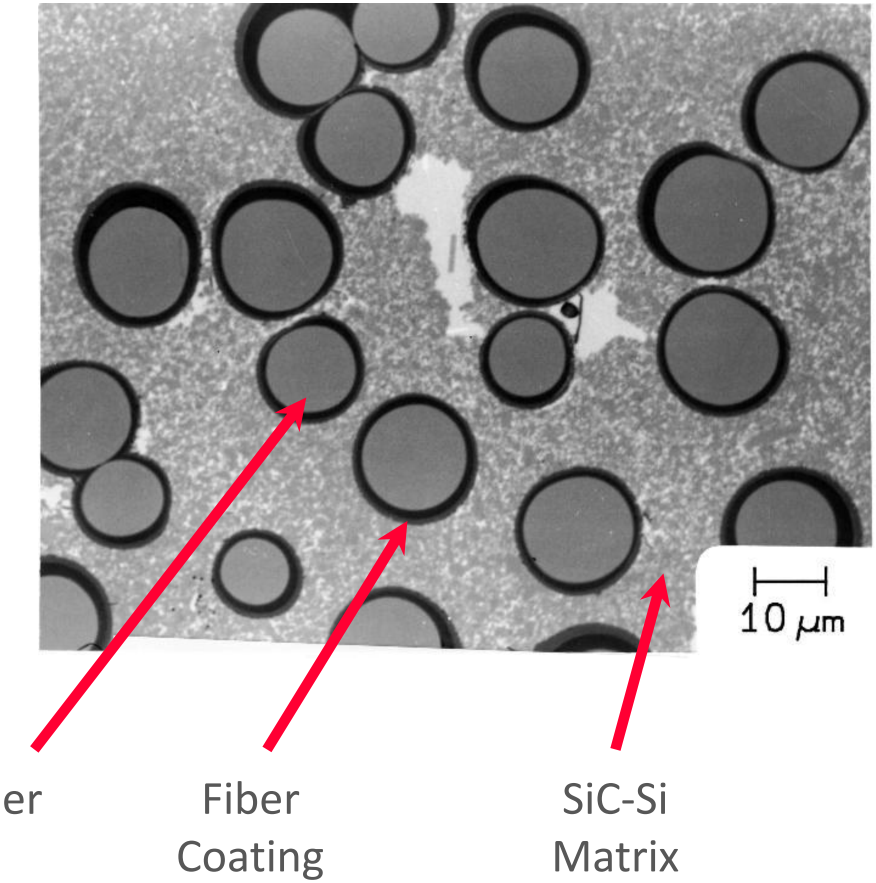


Melt Infiltration



Microstructure of Prepreg MI Composites





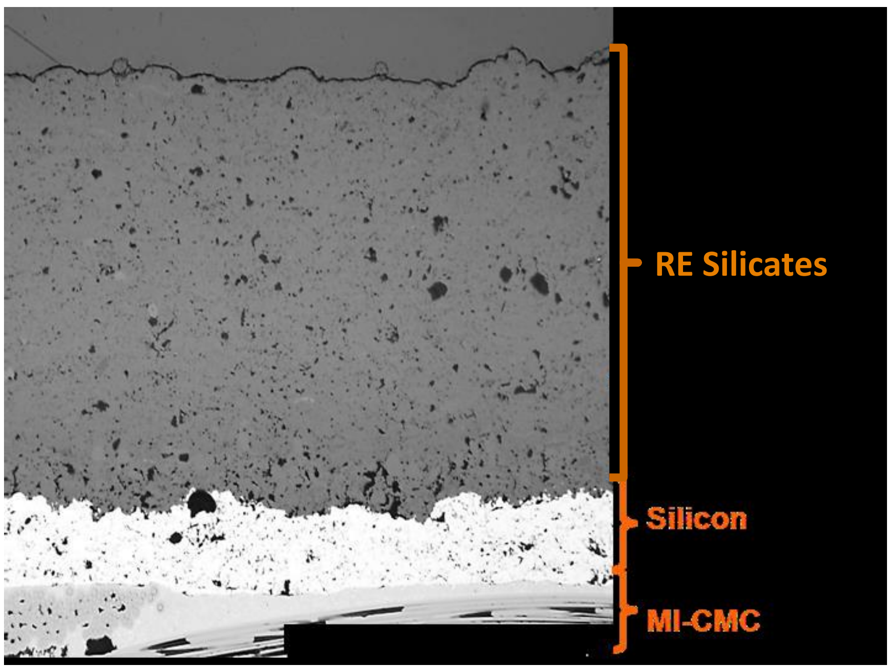
- Fibers Homogeneously Distributed; Vf = ~25%
- Separated Fibers and Fiber Coatings
- ~2-3% Matrix Porosity

Environmental Barrier Coating (EBC)

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

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

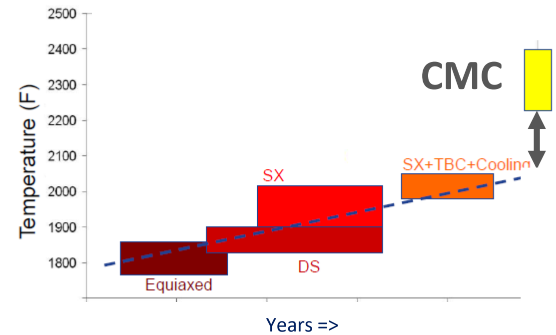
Baseline System



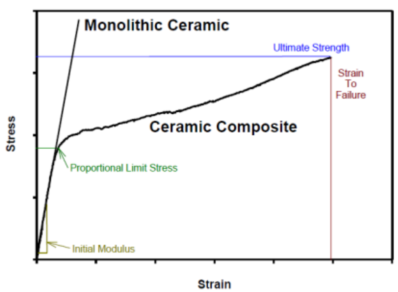
Advanced system

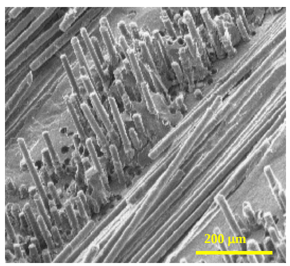
- Retain Si bond coat
- Rare earth silicate layers
  - ✓ CTE match
  - ✓ recession resistance

GE & DOE Advancing Development of CMC Material for Power Generation



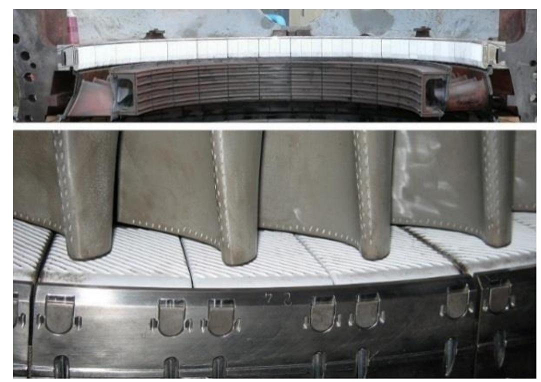
Increased material temperature capability …
… efficiency, output, reduced COE

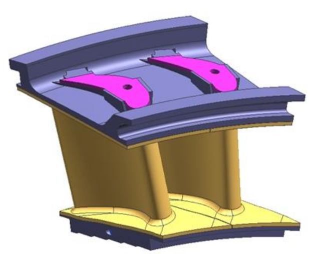




100,000 hrs High-temp testing…
… & toughness demonstrations

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

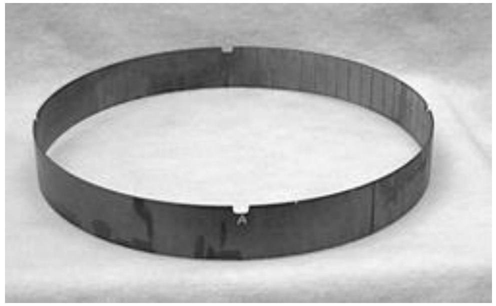




DOE 2016 phase 2 award …
… High Temp CMC Nozzles

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

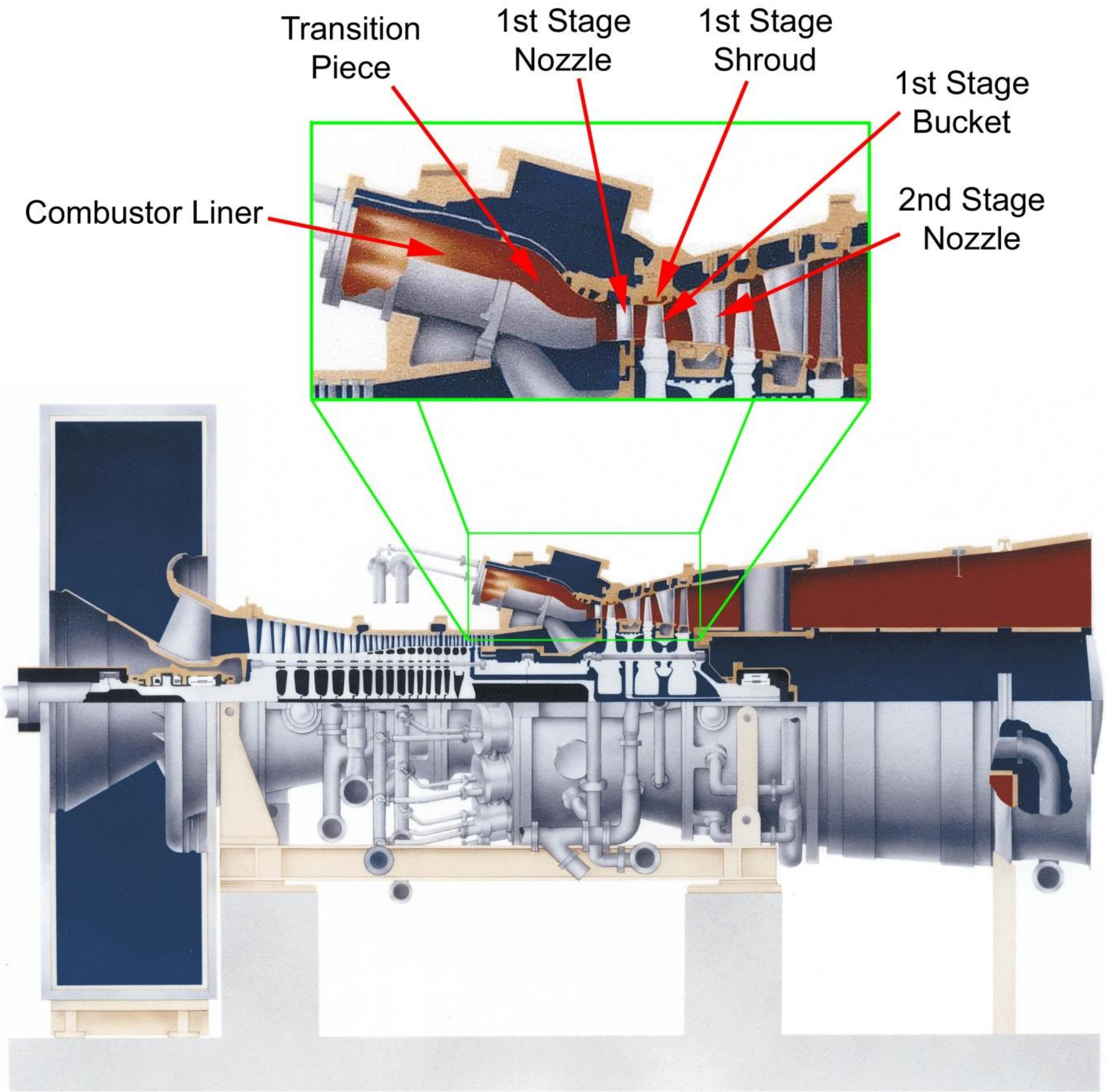
Shroud Durability Test 1
2930 hrs, 552 cycles
2006 - Continuing

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

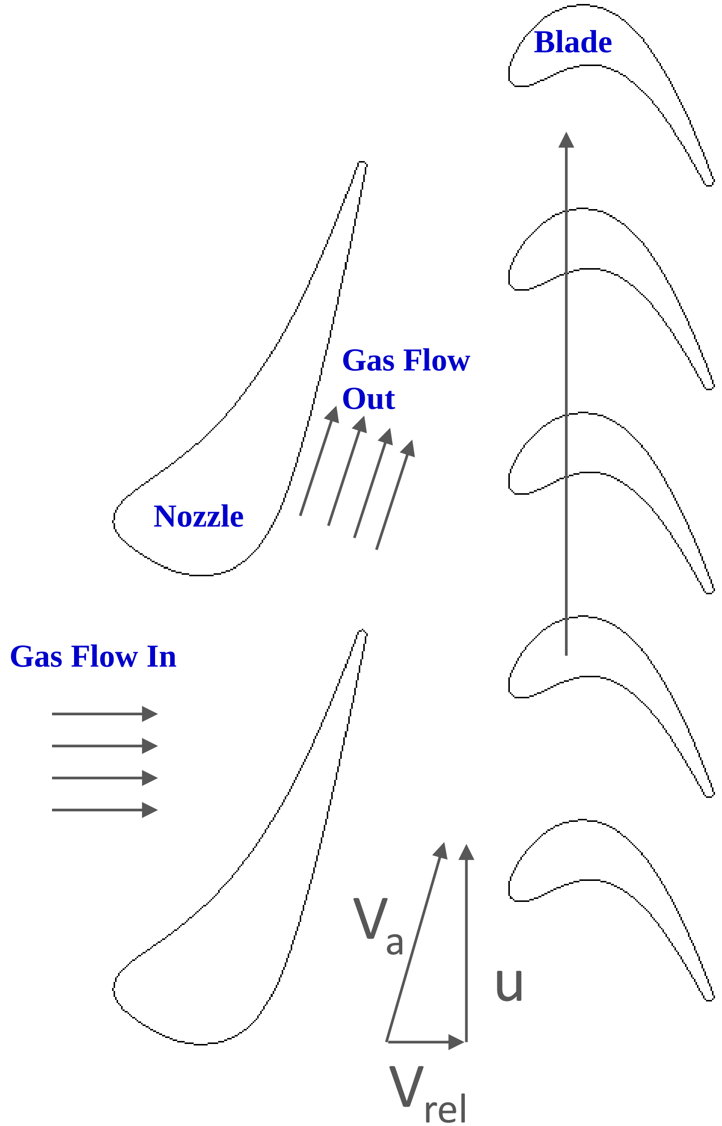
Turn and accelerate the high temperature and pressure, low velocity combustion flow into the downstream turbine blade row.

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

CMC S2N DoE Program Summary

2019 Project Objectives
- Design a CMC S2N with reduced cooling flow that supports 65% CC efficiency
- Build the nozzle using the current CMC material system provided by GE Aviation
- Test the nozzle in HA machine in TS7
- Identify design challenges and limitations for a future production product

CTQs

	Target	Status		
Design & Build	*100%*	*100%*	●	*Demonstrated*
Flow Savings	*100%*	*100%*	●	*W-Seal perimeter seals*
Performance Goal	*100%*	*100%*	●	*Supports 65% eff goal*
Test Demo Strength and Life	*100%*	*100%*	●	*EBC spall & recession*

Key Milestones

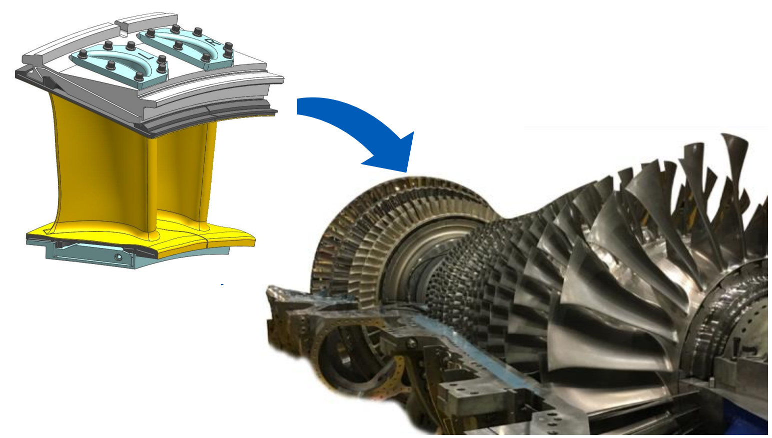
	Finish	Status		
Preform Definition	*Jun-19*	*May-19*	✓	*Complete 1m early*
EBC Durability	*May-19*	*May-19*	✓	*Best results to-date*
DDR	*Mar-19*	*Aug-19*	✓	*Pivot & HGP Freeze*
CMC vane layup and build	*Q2-20*	*not started*	●	*Tapes not available*

● Per Plan ● Risk with recovery plan ● Risk, expect schedule/ budget overrun

Delta to Metal	**Value**
Cooling Flow	2/3 Less
Output	7 MW
Efficiency	0.15 pts

Application to GE's most advance HA class turbine

2019	2020	2021
Design	Fab	Prep



TRL Transitions

3 — **Scaled Lab** — 4 — **Full Scale Lab** — 5 — **Full Scale Engine** — 7

Program Start

Scaled Lab

Component testing in lab

- Scaled design and fab with cooling and sealing features
- Scaled feature test for strength and life at room temp
- Preliminary seal flow test demonstrate capability
- Capable seal material identified
- Seal surface finish improvement

Current State

Full Scale Lab

Component testing in lab

- 100% prototype scale, design, fab and feature test for strength and life at room temp
- 8000hr EBC test at 100% thermal temp and loads
- Seal flow test at prototype pressures ratios, offsets and flows
- Seal material test at prototype temp and loads
- Cooling flow test at prototype scale and P-ratio at room temp

Anticipated Program Completion State

Full Scale Engine

Instrumented nozzle in advance HA-class turbine

- 100% Prototype Scale
- 100% Mass Flow
- 100% Gas Constituents
- 100% Mechanical Load
- 100% Thermal Load

Operational System Prototype Tests Complete

Phase II Program

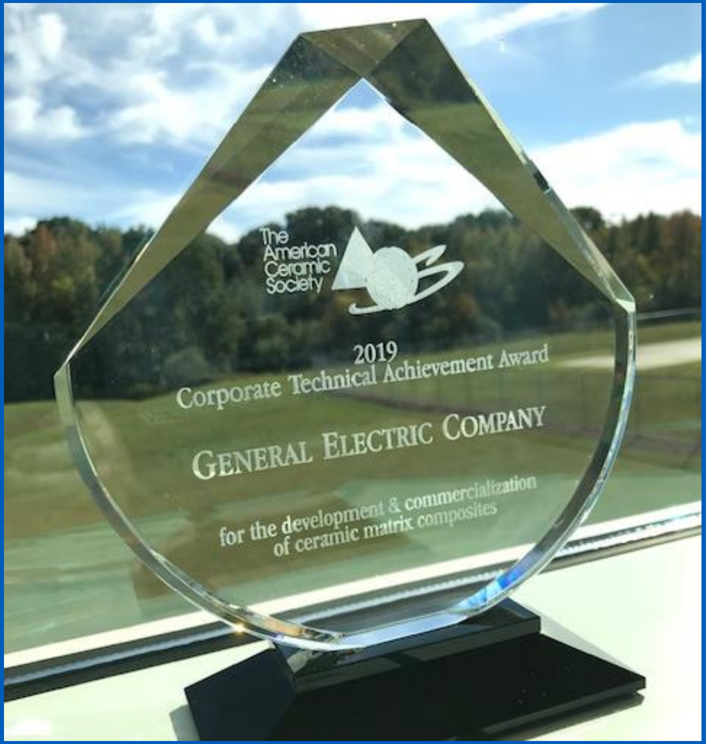
Within 12 Months

GE Solution

Cooled high-temperature CMC nozzles

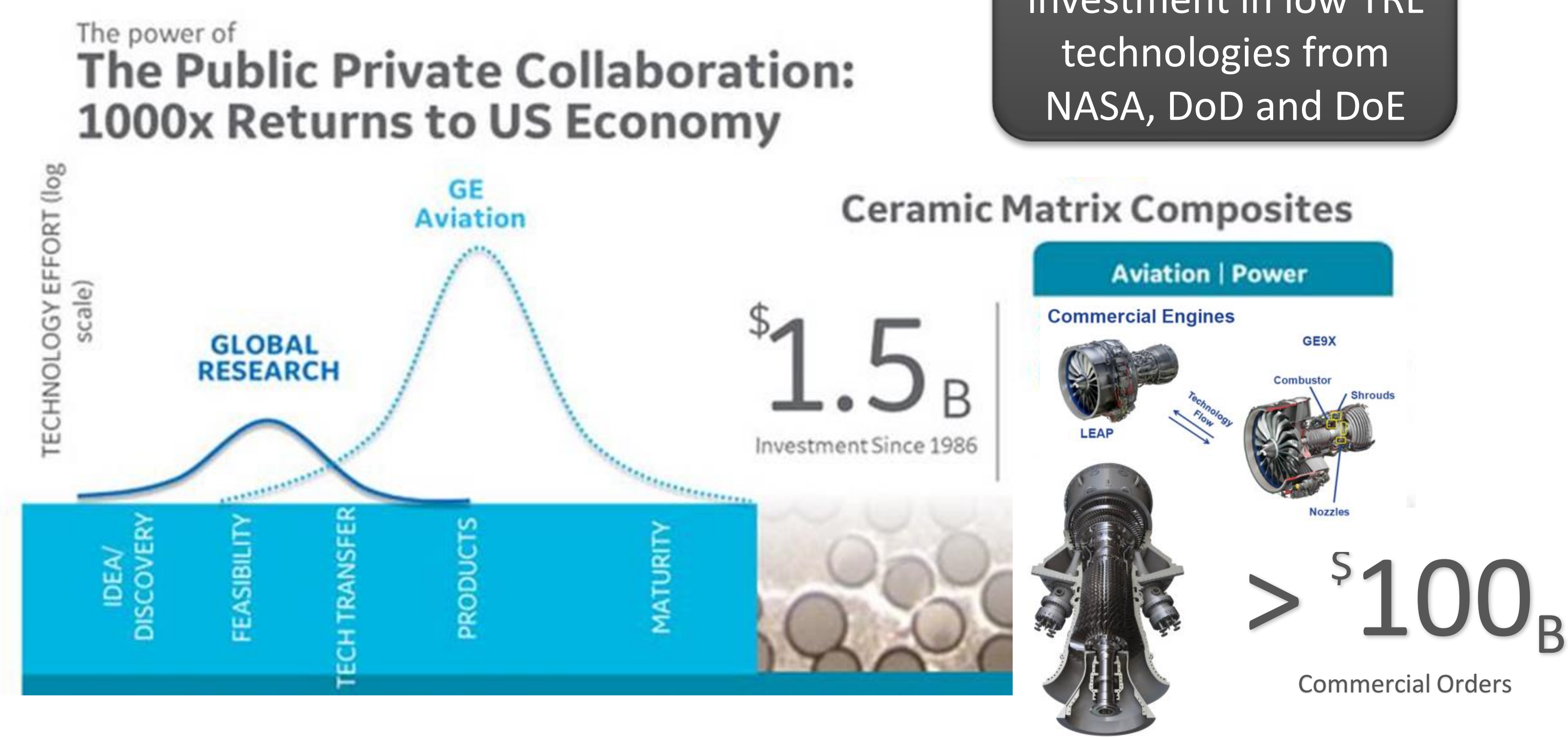
- Support load following capabilities of modern grid
- Allow higher turbine inlet temperatures (~3,100°F)
- Applicable to IGCC with pre-combustion carbon capture
- Means of improvement – improved cooling designs, better sealing, reduced leakage
- Leverage advanced manufacturing processes

SiC Material Advancement



Success Required Investment and Time

Enabled by ~ $100M investment in low TRL technologies from NASA, DoD and DoE



Next Gen HA Class Turbines

Collaborative CMC technology investment has paid off… thank you DoE

GE SiC Material Production Coming Online….

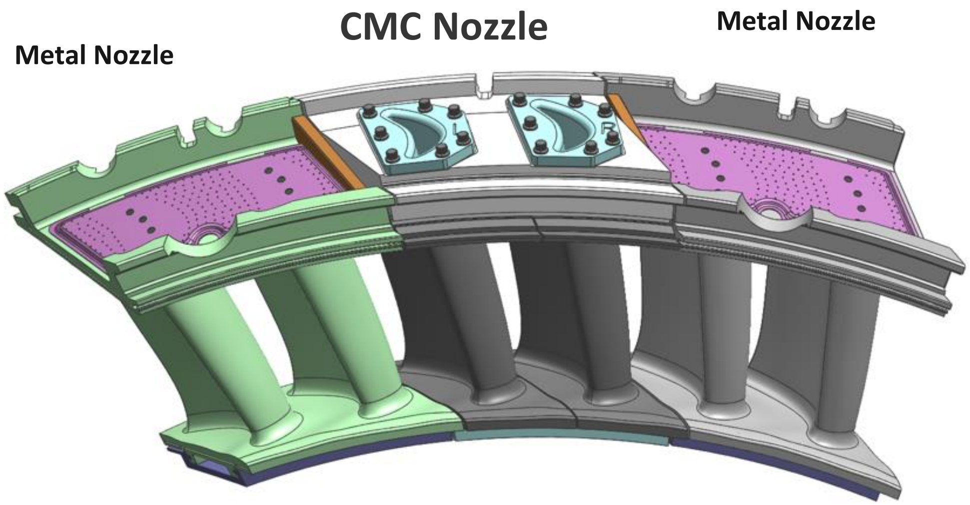
Significant enhancement to tape production

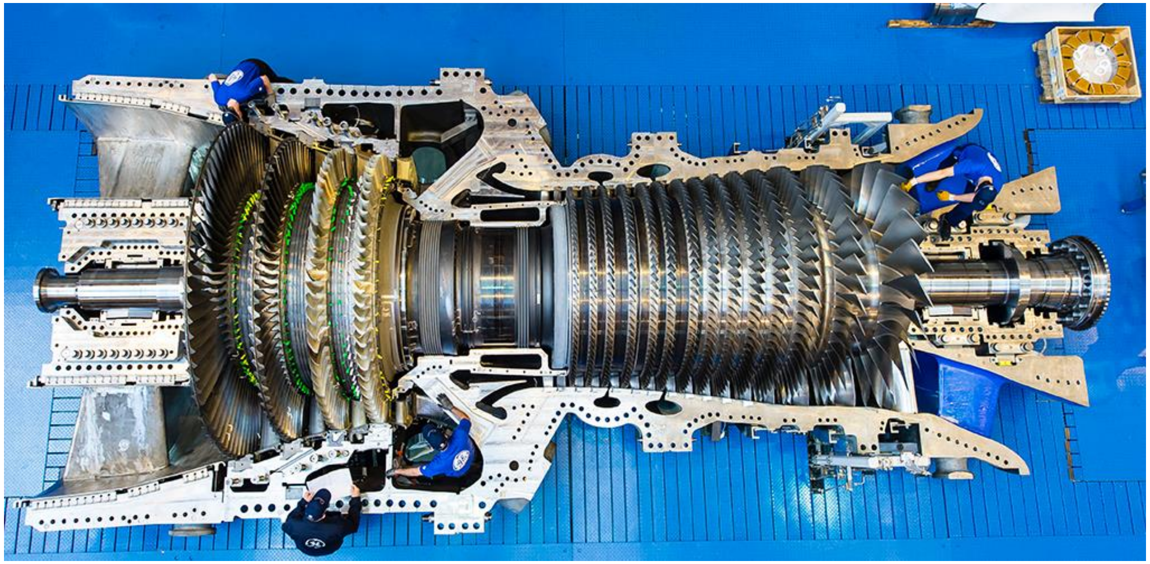
Nozzle Design Evolution

CMC Nozzle Maturation

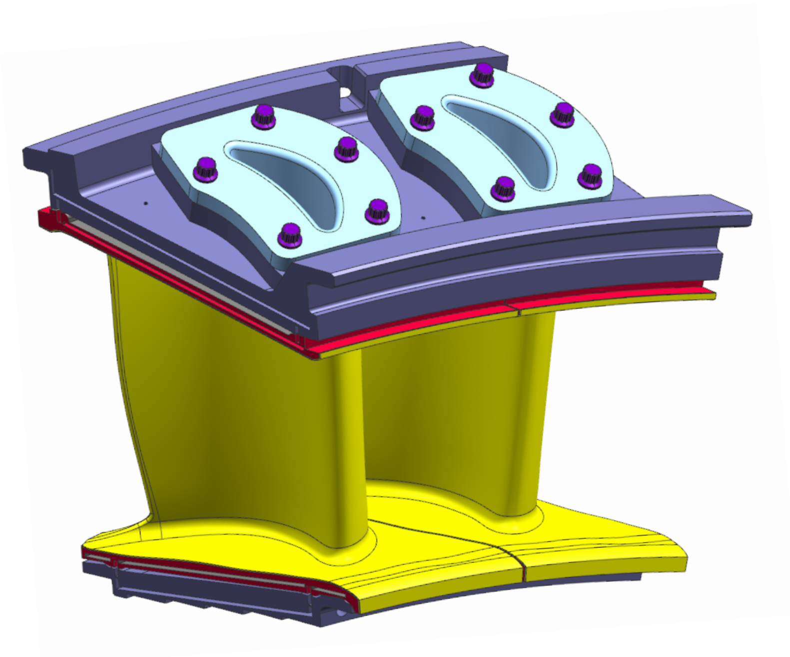
- Actual engine test hardware
- Same HGP geometry as metal nozzles
- Can fit future HA class GTs

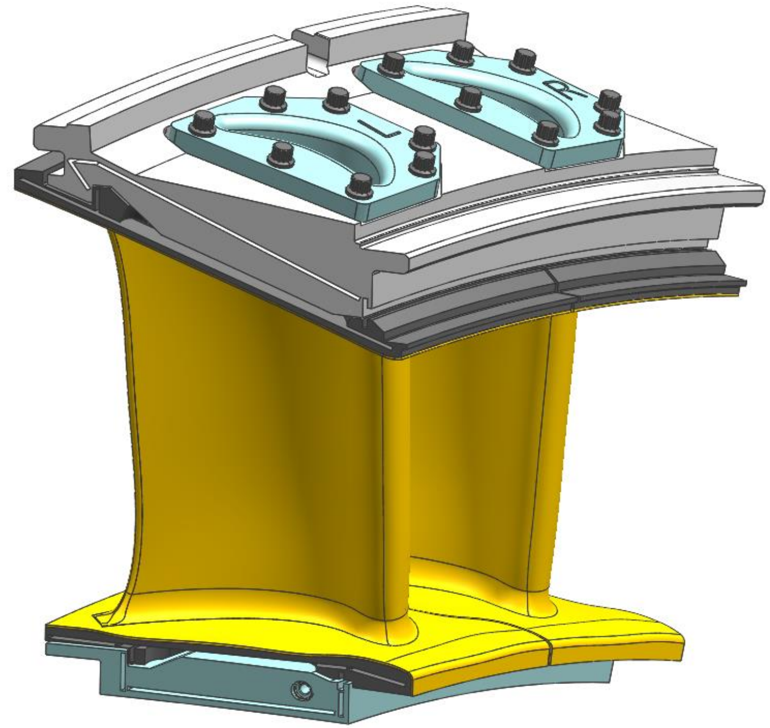
Proposed Engine Test Assembly





CMC Nozzle Evolution





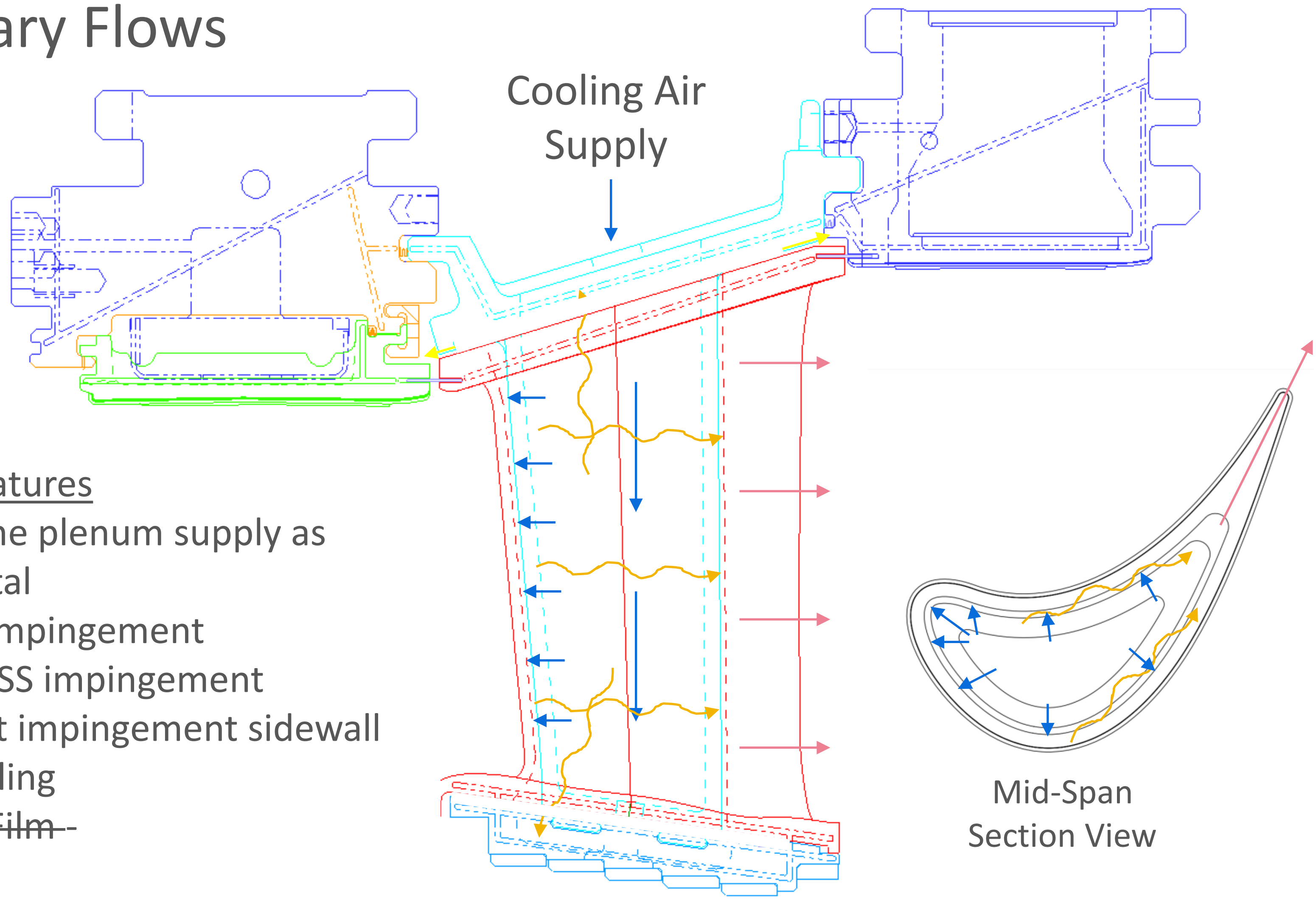
2017

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

Current

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

Secondary Flows



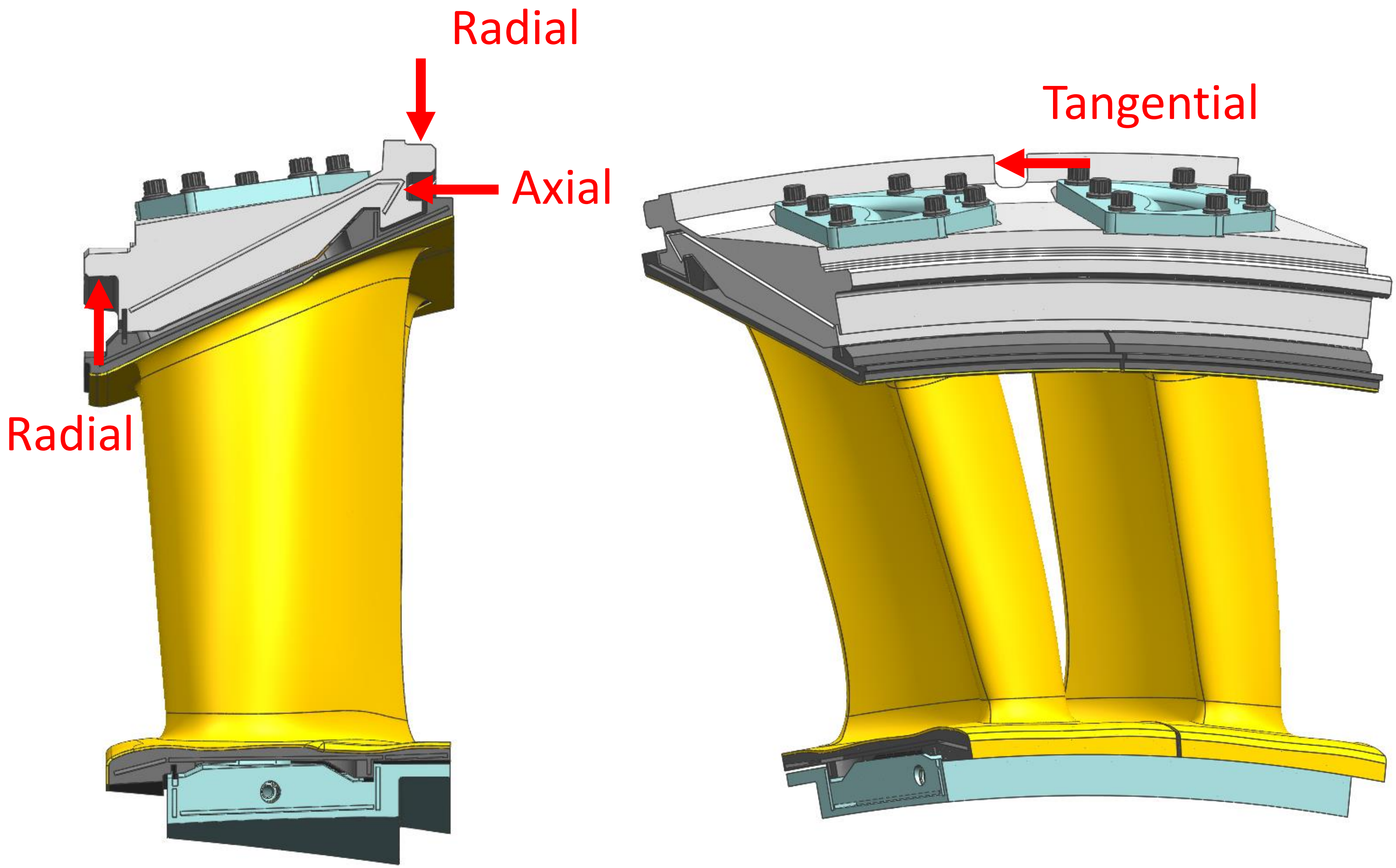
<u>Main Features</u>

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

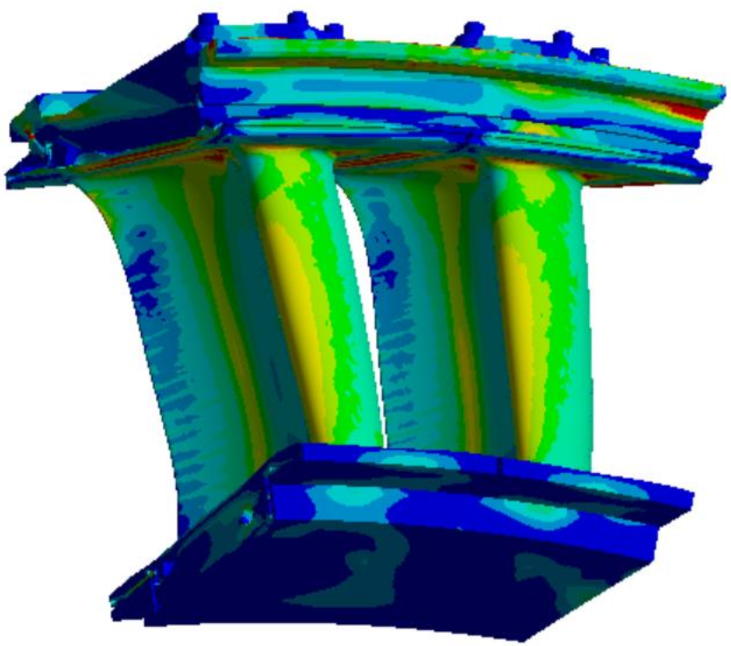
Bulk Temp	Metal to CMC Delta
Vane	400F

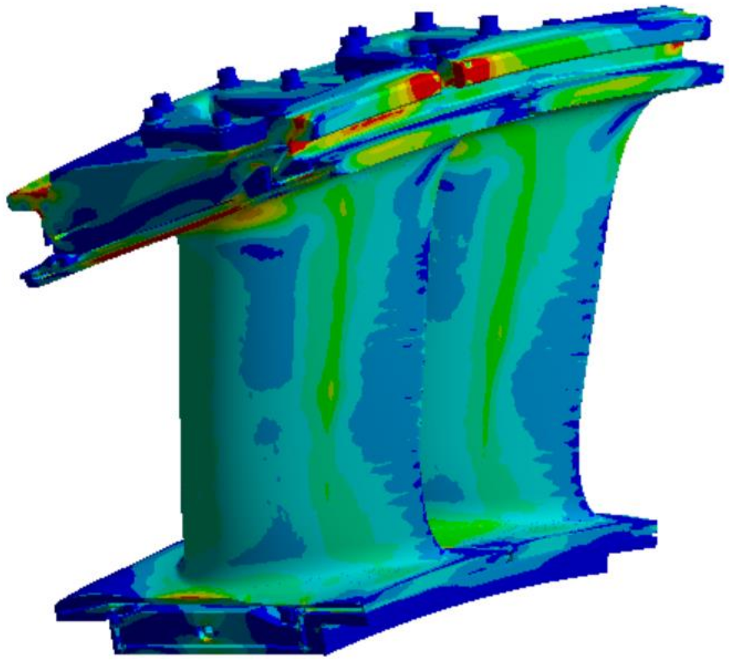
Higher allowable operating temperatures reduces cooling flow

CMC S2N Total Reaction Loads



CMC Nozzle Loads and Stresses – Structural Analysis





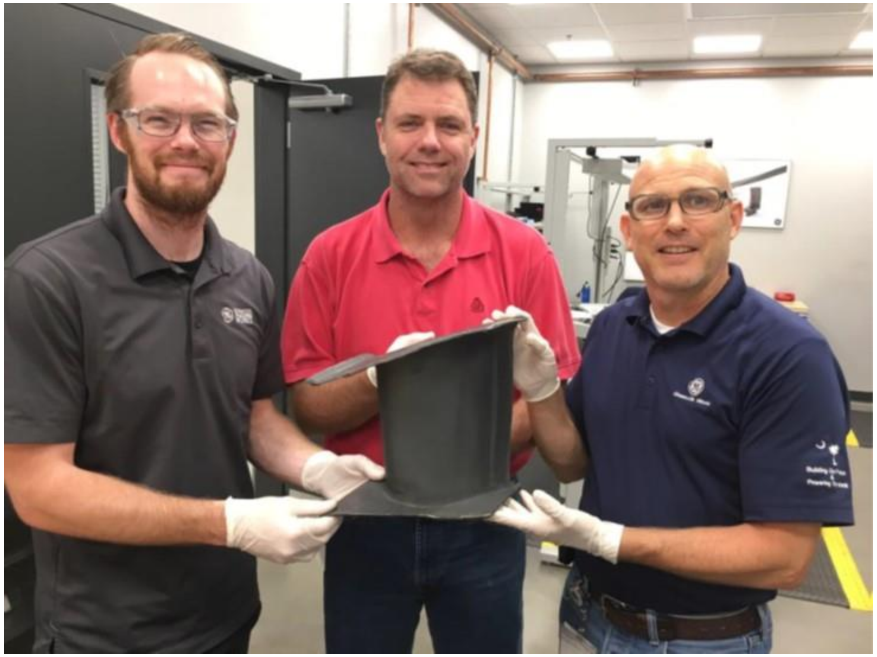
Meets engine test operational requirements

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

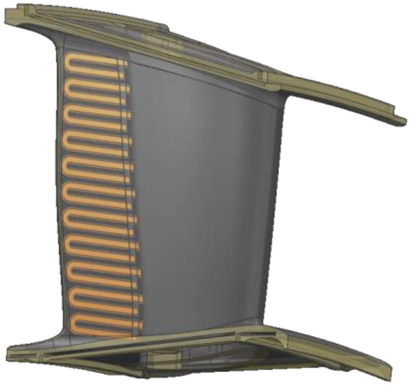
TE Cooling

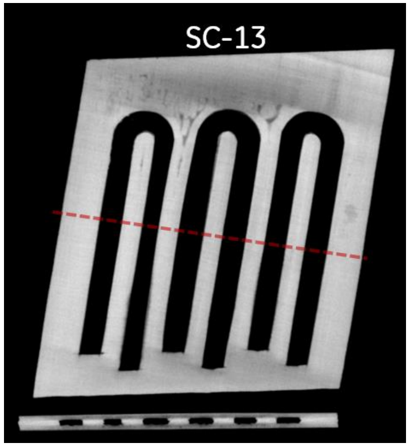
Electric Discharge Machining (EDM)

- 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

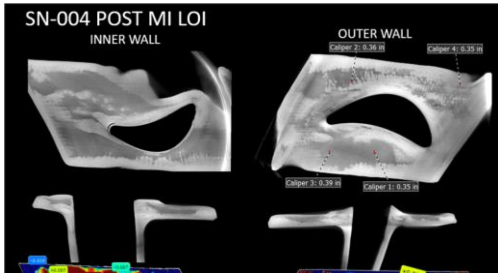




End Wall Success

- Significant lack of infiltration LOI observations in 2017 vane end walls
- End wall build trial to explore build and autoclave parameters
- Full-scale, full-featured (FSFF) end wall build. Excellent melt-infiltration densification results.

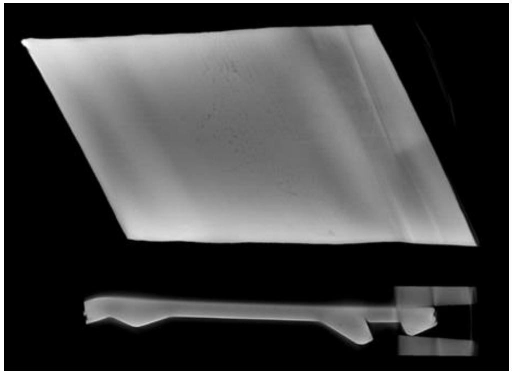
CT Scan – 2017 End Wall LOI



End Wall Trial

Blue Light Scan
FSFF End Wall

CT Scan – FSFF End Wall



Success of FSFF End Wall build adds confidence for future vane builds

Clemson Surface Treatment

CMC Sealing Surface Finish Improvement (Clemson University)

2019 Project Objectives

Improve the surface finish of EDM seal slots in CMC parts by applying a glassy ceramic coating.

CTQs

	Target	Status		
Roughness	*<150 μin Ra*	*<50*	●	*coated "smooth" surface*
Thickness	*.02-.05 in*	*.002*	●	*thin, but fills voids, self-leveling*

Business Impact: Reduce seal leakage by 1/2

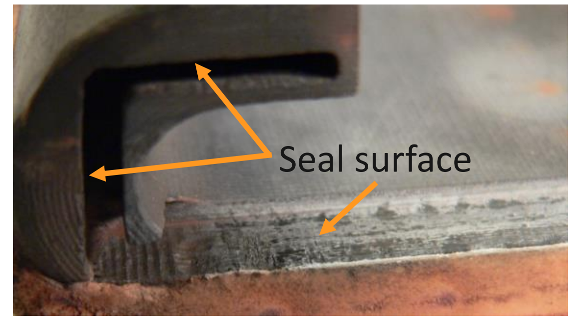
Key Milestones

	Finish	Status		
Characterize Compositions	*Mar-19*	*Mar-19*	✓	*Complete*
Coat Test Nozzle Seal Slot	*2020*	*2020*	●	

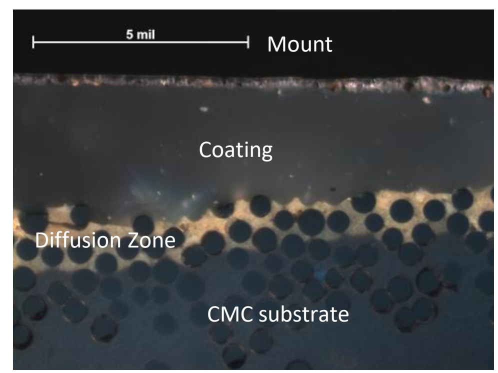
Coating formulation defined and successfully applied to coupons.

● Per Plan ● Risk with recovery plan ● Risk, expect schedule/ budget overrun

Issue: rough sealing surface due to voids and different erosion rates between matrix and fiber

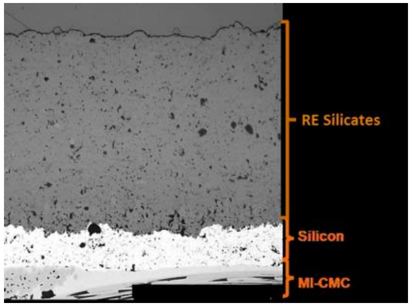


Goal: smooth surface using vitreous layer



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

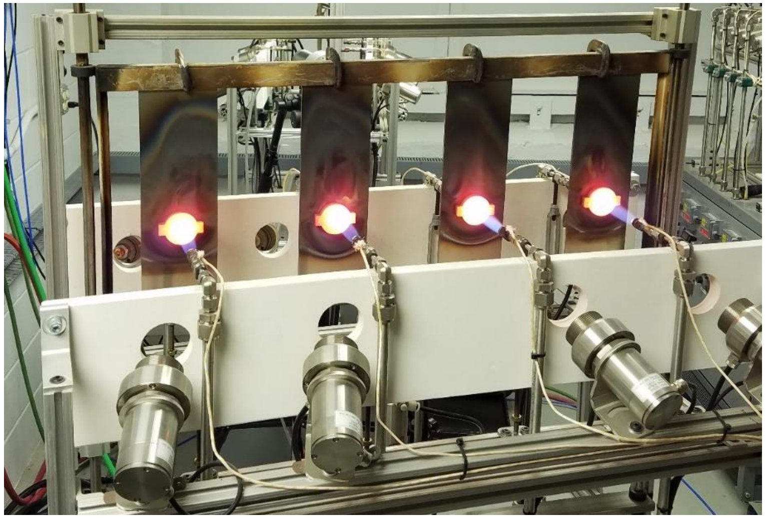
- Design requested thick EBC for added thermal barrier effect
- 2-4X the thickness of previous Power field experience

Test conditions

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

EBC Durability Testing

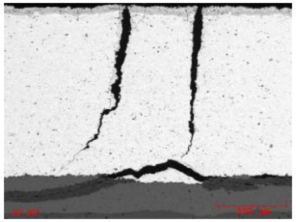
+8000 hour High Temperature Sample Testing



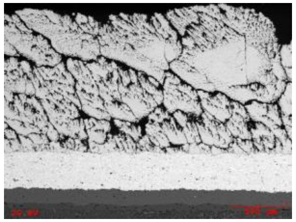
Testing Results To-date

Observations

- Thicker coating show propensity for crack
- Thinner show less propensity for cracks
- New method shows no propensity to crack



Thicker coating



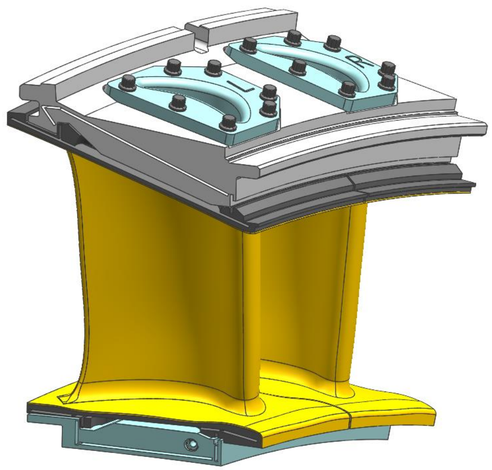
New Method

Next Steps

Next Steps… effect of tape delay

Ultimate Objective

Deliver one instrumented stage 2 CMC nozzle segment assembly and mating hardware for tech demo



What does not change

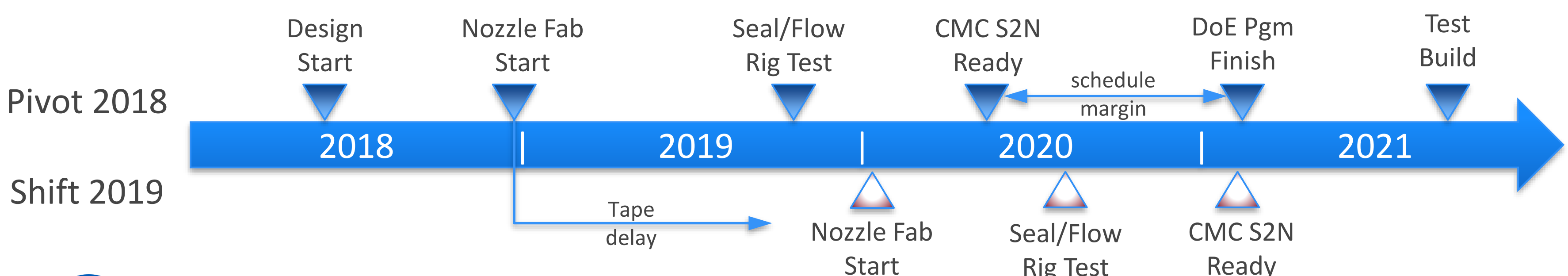
- Receive CMC tape
- EBC durability test
- Design/build feature test rig
- Design/build flow bench

What moves into 2020

- Fabricate engine test parts
- Feature test
- Bench flow test
- Instrument nozzle assembly

Key Milestones

- Feature test for strength
- CMC nozzle fab complete
- Instrumented S2N assembly



Q&A
Discussion