- GE CMC Overview
- CMC Nozzle – Phase I Results
- CMC Nozzle – Phase II Plan

John Delvaux
CMC Technical Leader
November 1, 2016

© 2016 General Electric Company. All rights reserved.

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

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

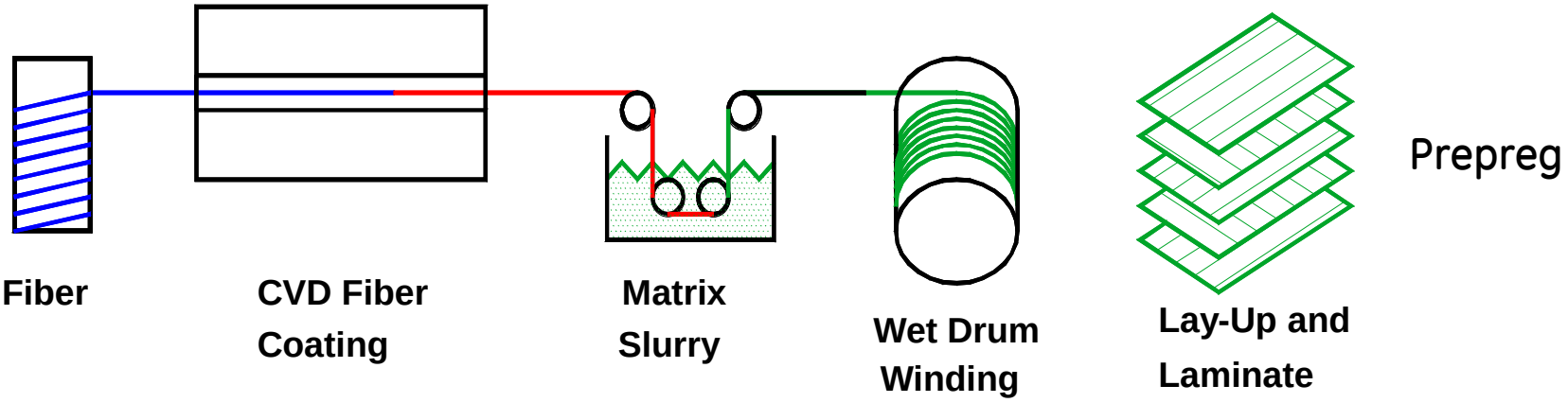
October 27, 2016

Not to be copied, reproduced, or distributed without prior approval.

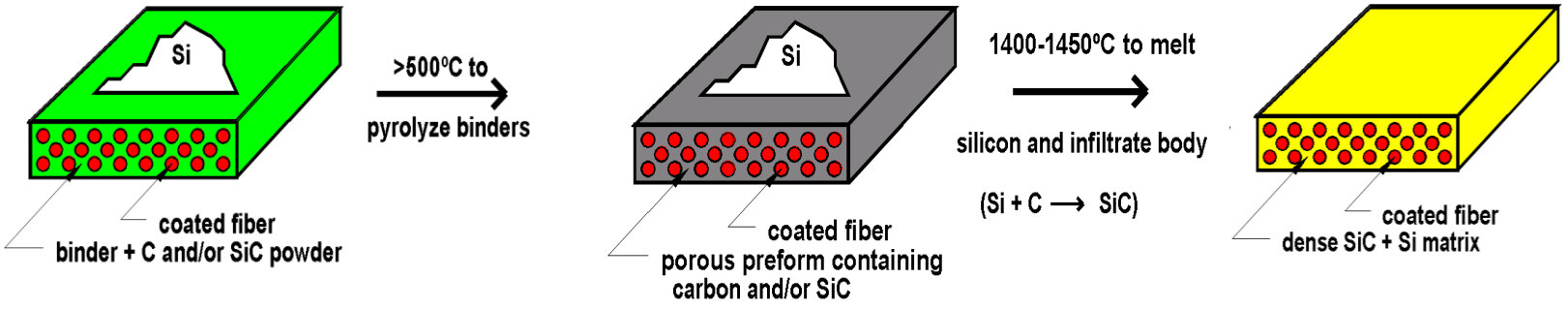
GE INFORMATION - The information contained in this document shall not be reproduced without the express written consent of GE. If consent is given for reproduction in whole or in part, this notice and the notice set forth on each page of this document shall appear in any such reproduction. This presentation and the information herein are provided for information purposes only and are subject to change without notice. NO REPRESENTATION OR WARRANTY IS MADE OR IMPLIED AS TO ITS COMPLETENESS, ACCURACY, OR FITNESS FOR ANY PARTICULAR PURPOSE. All relative statements are with respect to GE technology unless otherwise noted.

GE Ceramic Matrix Composite (CMC) Processing

Preform Fabrication

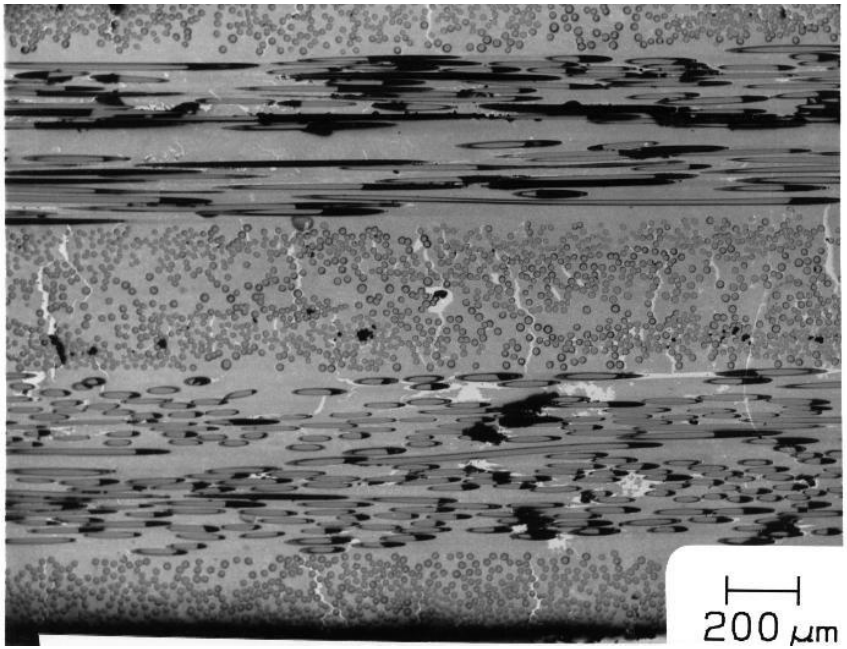


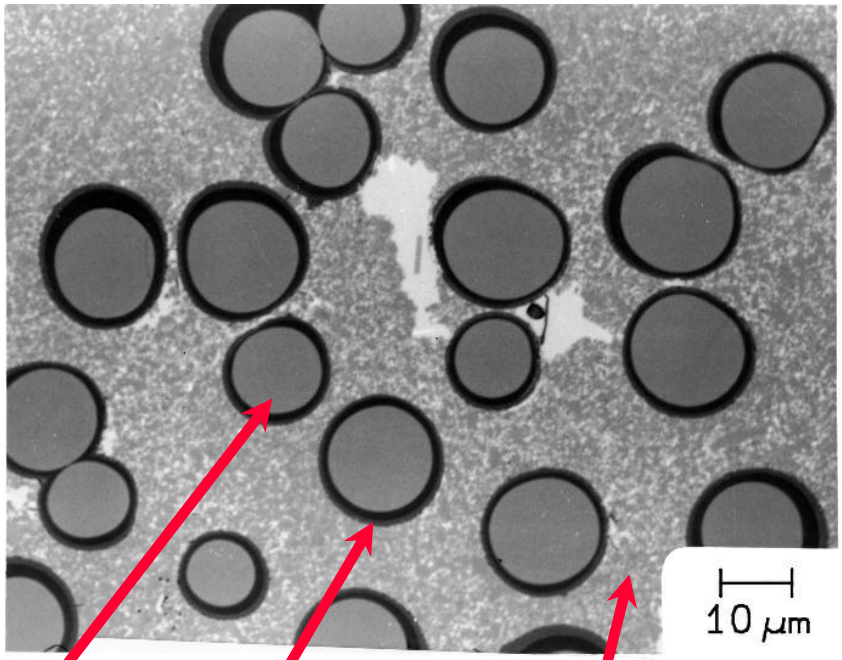
Melt Infiltration



© 2016 General Electric Company. All rights reserved.

Microstructure of Prepreg MI Composites





Fiber

Fiber Coating

SiC-Si Matrix

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

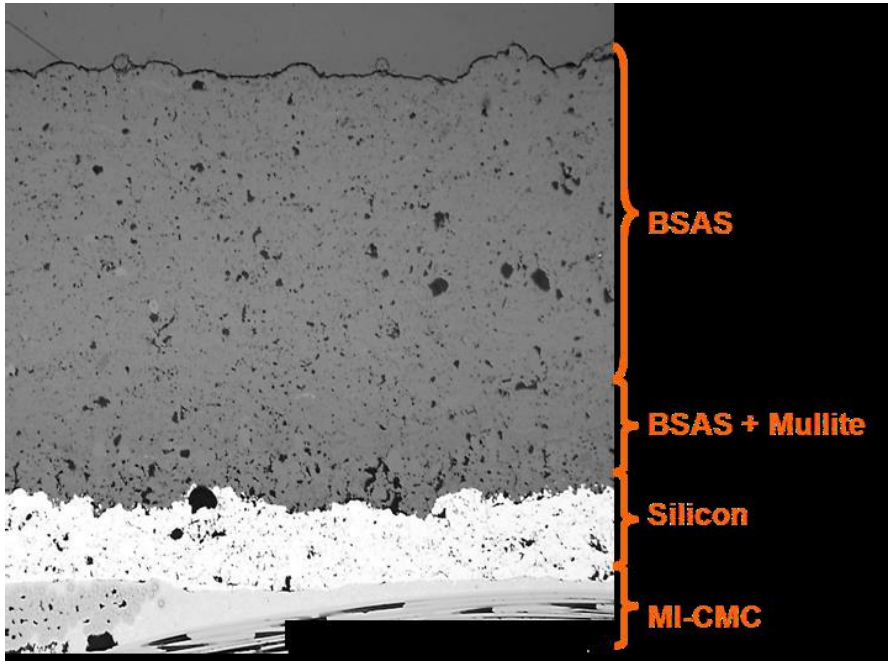
© 2016 General Electric Company. All rights reserved.

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



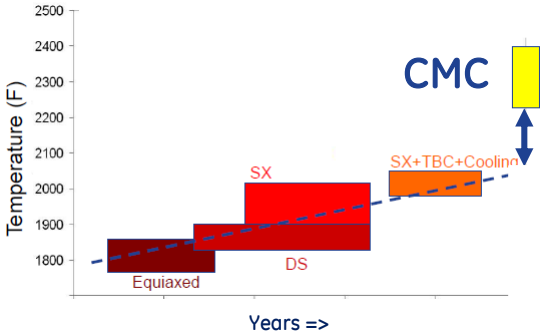
Advanced system

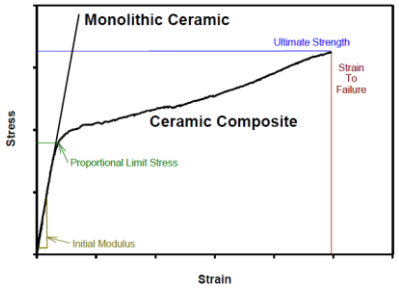
- Retain Si bond coat
- RE silicate layers
  - CTE match
  - recession resistance

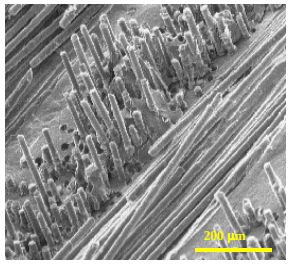
© 2016 General Electric Company. All rights reserved.

GE & DOE Advancing Development of CMC Material for Power Generation

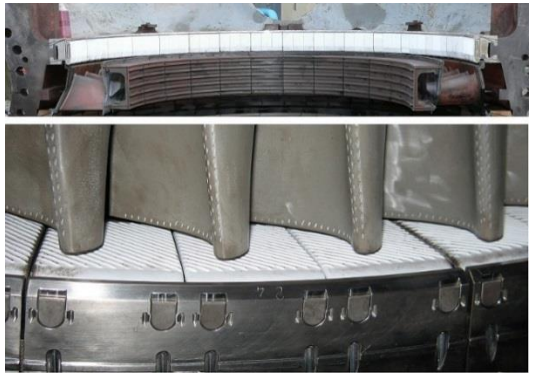
Increased material temperature capability …
… efficiency, output, reduced COE



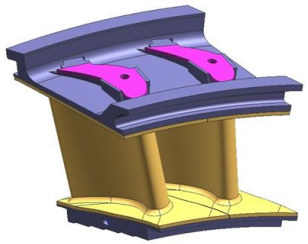




100,000 hrs High-temp testing…
… & toughness demonstrations



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

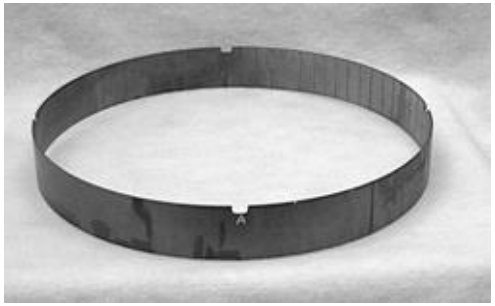


DOE 2014 phase 1 award …
… High Temp CMC Nozzles

© 2016 General Electric Company. All rights reserved.

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

© 2016 General Electric Company. All rights reserved.

First GE Power Application

CMC Stage 1 Shroud for 7F

CMC Technology

Ceramic Matrix Composite (CMC) represents a major step in material capability for gas turbines. With the strength of metals and the temperature capability of ceramics, this advanced material system enables the next generation of gas turbine performance. GE is a global leader in CMC technology development, with a pioneering research and development effort spanning nearly 20 years.
GE has accumulated over 24,000 hours of experience on CMC shrouds in 7F gas turbines, and has achieved FAA certification of CMC hot-section components on the LEAP* engine, the next generation of the CFM56* aircraft engine. This rigorous and thorough technology development path has culminated in the first commercial offering of CMC hardware in the industry.

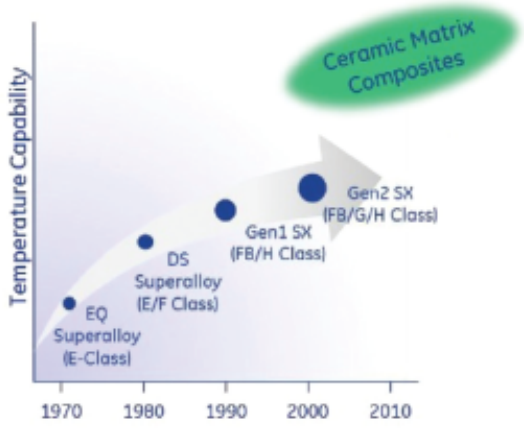


Figure 1 – CMCs represent the next generation in materials

Product Benefits

The 7F CMC shroud provides incremental output and heat rate improvements to the 7F Advanced Gas Path. The product can be applied to a new unit (7F.04, 7F.05) or as an option to a full AGP upgrade. CMC combines unique strength and durability characteristics, resulting in less turbine cooling flow requireme less thermodynamic and aerodynamic losses in the gas path, a higher performance.

Benefits

- Up to 0.6% gas turbine output increase
- Up to 0.2% gas turbine heat rate reduction
- 32,000 Factored Hour/1250 Factored Start Maintenance Inte
- Install as part of AGP upgrade or as a separate enhancement existing AGP configuration

This upgrade can be applied to the following unit configurations:

- 7F.01/.02/.03 with Advanced Gas Path
- 7F.04
- 7F.05

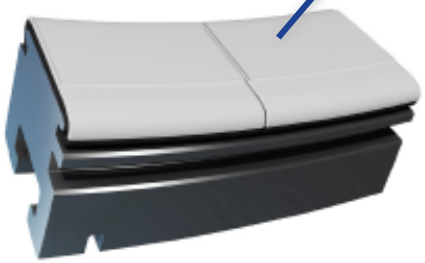
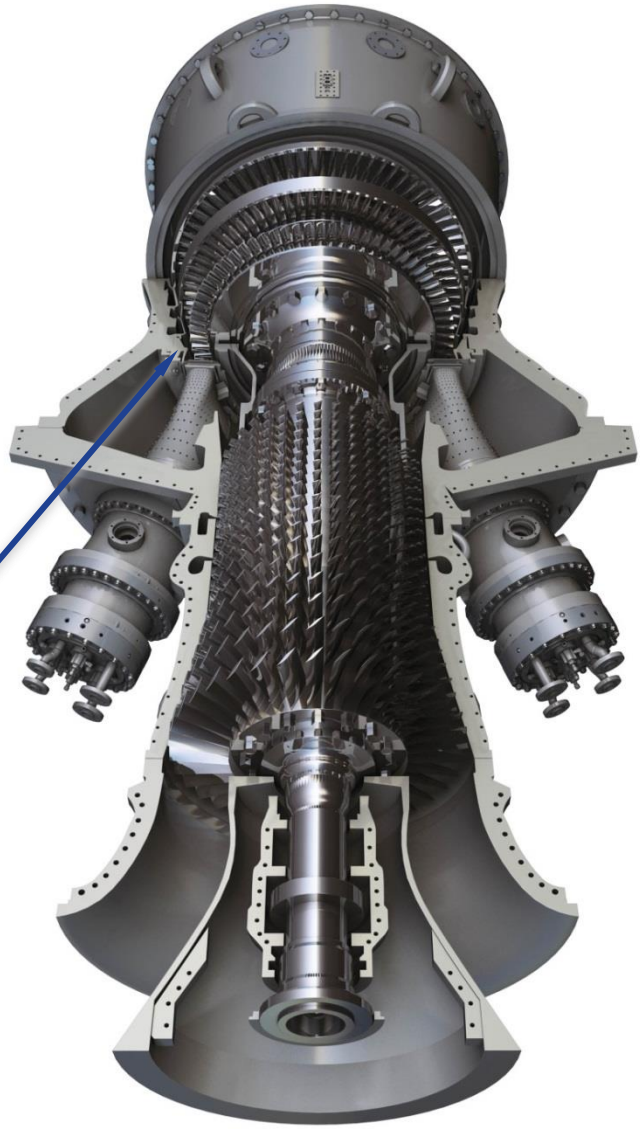


Figure 2 – CMC shroud for the 7F

Typical Customer Brochure



Typical 3-stage F-class Turbine

© 2016 General Electric Company. All rights reserved.

DoE funding for CMCs… Big Impact

BARRON'S October 5, 2015

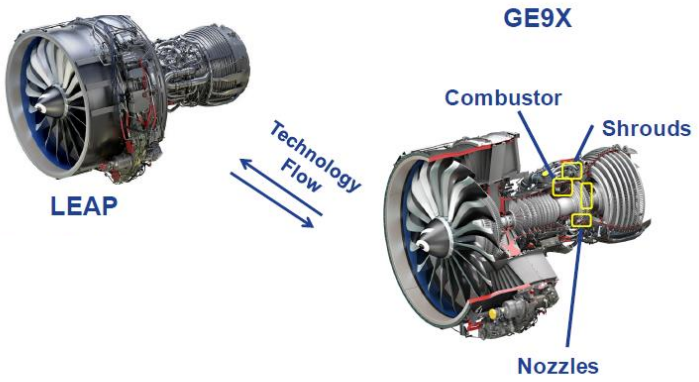
How do you build a better jet engine? You build a better gas turbine.

We believe that GE works better when our businesses work together. It's why we created the GE Store, which includes a network of over 3,600 scientists and engineers in nine technology centers around the world, all working to find innovative solutions to complex problems. One recent success: using heat-resistant ceramic composites from our gas turbines to improve engine efficiency in aircraft. With the GE Store, we're helping industry rocket up the learning curve.

© 2016 General Electric Company. All rights reserved.

Aviation

Commercial Engines



- Engine Orders
- Build Factories
  - Raw Fiber
  - Fiber Coating & Tape

Correa said. For GE, “this is very much past the science experiment and engineering marvel”

GE Power

Aviation Week, September 2016

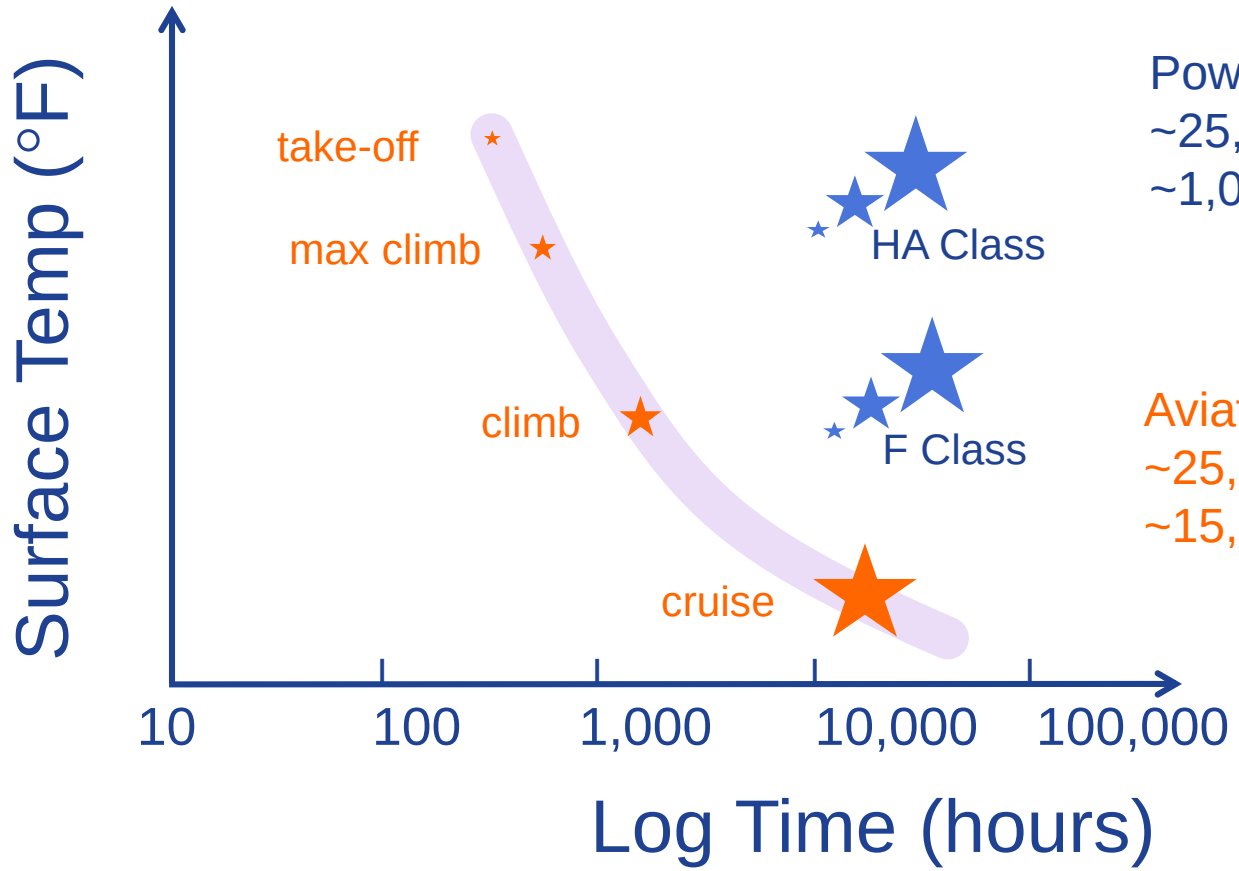
GE Aviation expects to increase its use of CMCs tenfold in the next decade and has been using micro-computed tomography (micro-CT) to study them in better detail.

An upgrade for the GEnx is also being researched to reduce the 787 engine’s maintenance costs. More than 3,000 test cycles have been run on equipment containing a CMC combustor, stage one and two nozzles and CMC shrouds, while another potential upgrade is rotating CMCs that have been tested already for military applications.

Powering the world… opportunity for CMCs

© 2016 General Electric Company. All rights reserved.

Mission Uniqueness… GT Durability Challenge



Power Gen
~25,000h
~1,000cy, 10-100h holds

Aviation
~25,000h
~15,000cy, 0.03-10h holds

Need to demonstrate capable designs

© 2016 General Electric Company. All rights reserved.

CMC Nozzle – Phase I Results

© 2016 General Electric Company. All rights reserved.

GE Solution

Cooled high-temperature CMC nozzles

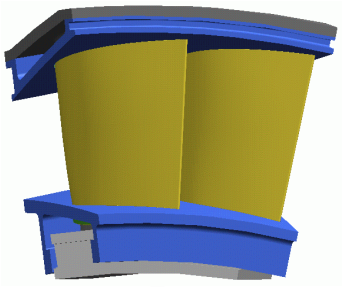
- ✓ Support load following capabilities of modern grid
- ✓ Allow higher turbine inlet temperatures (~3,100°F)
- ✓ Applicable to IGCC with pre-combustion carbon capture
- ✓ Means of improvement – improved cooling designs, improved aerodynamics, better sealing, reduced leakage
- ✓ Leverage advanced manufacturing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

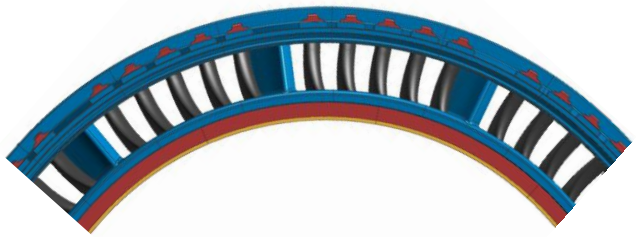
Phase I

- Leverage existing design and analysis knowledge
- Leverage techniques for CMC materials from DOE-funded HH and other internally funded programs
- Utilize extensive analytical evaluations to develop and refine designs for CMC nozzle

© 2016 General Electric Company. All rights reserved.

Nozzle Concepts





Select Attributes

Simple CMC airfoils… high yield

Sealing complexity… performance risk

Loaded CMC… life risk

Cantilevered CMC airfoil… low stress

Loaded metal… life risk

ID endwall gaps… performance risk

CMC… A key technology for a 65% efficient machine

© 2016 General Electric Company. All rights reserved.

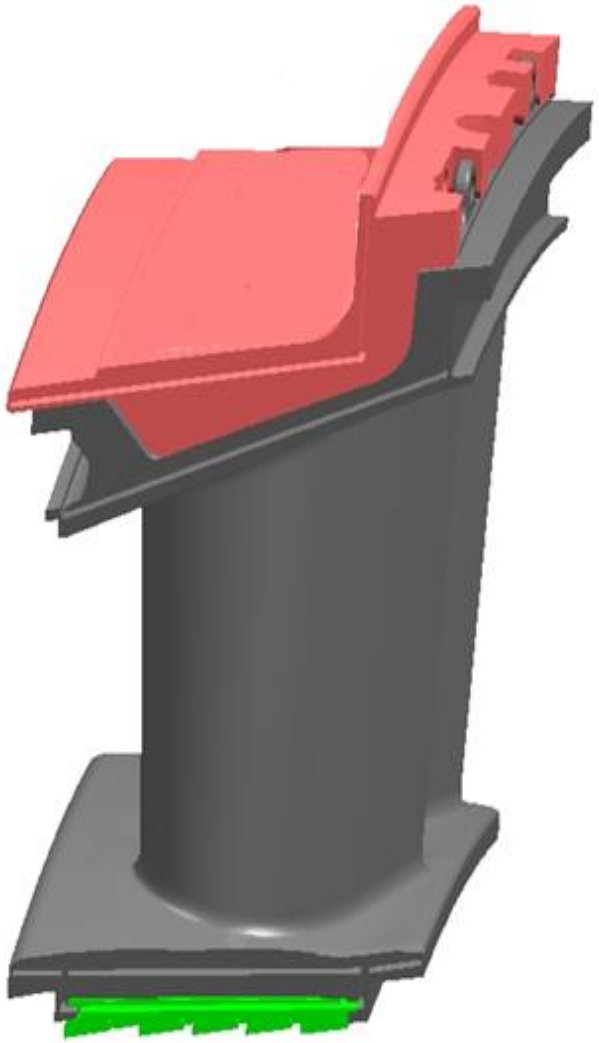
Key Design Attributes

Sealing

- Brainstorming session held with GE Power and Research Center experts
- Benefits and risks for multiple seal types considered.
- Top configurations scored on; sealing capability, reliability, complexity and cost.
- Flow tested cooled metal seals and uncooled ceramic seals

Cooling

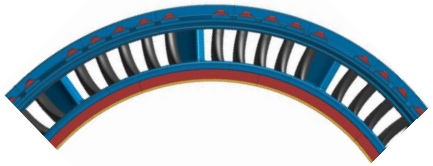
- Fundamental cooling circuits modelled
- Cooling options identified
- Cooling flow savings estimated



© 2016 General Electric Company. All rights reserved.

Bayonet Design

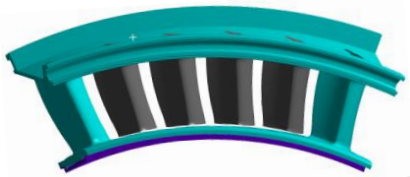
GE Patent US 8,454,303 B2



Challenges

- Aerodynamics
- Large metal casting
- Leakage at ID endwall

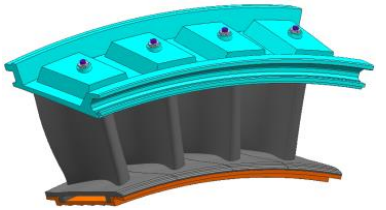
1st iteration

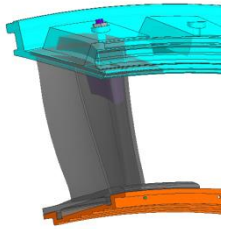


Challenges

- Large metal casting
- Leakage at ID endwall
- Large thermal deformation

2nd iteration





Features

- Cantilevered CMC vanes with integrated endwalls… less leakage
- One piece metal segments … less leakage
- CMC carries all load… more CMC… more cost

© 2016 General Electric Company. All rights reserved.

Traditional Design

CMC carries thermal load

Metal support spar

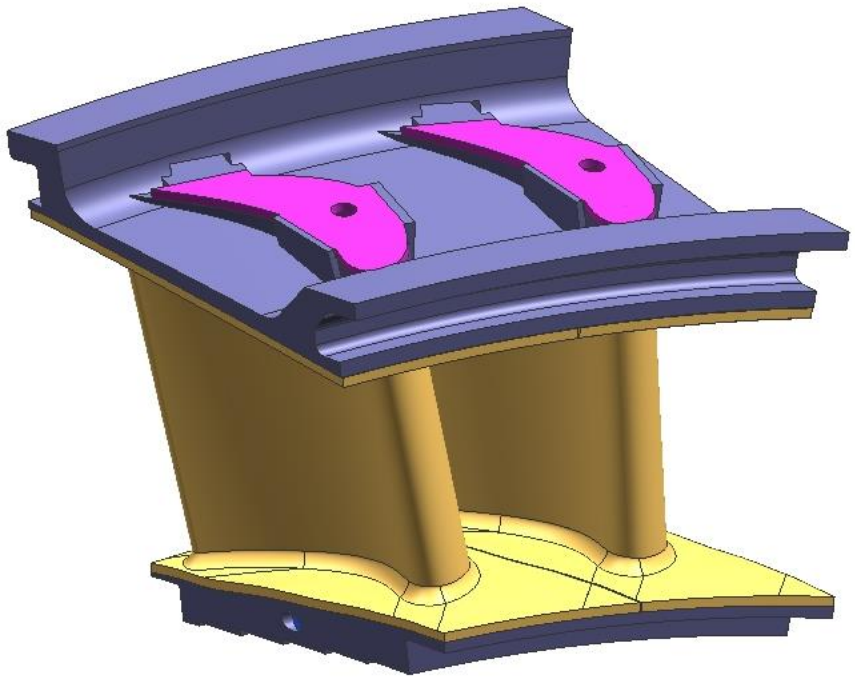
- Carries mechanical load
- Improved dimensional stability

Combined metal inner sidewall and ID sealing structure

- Reduces cost
- Reduces stress in metal

Key Attributes

- Best overall performer
- Lowest risk
- Median cost structure



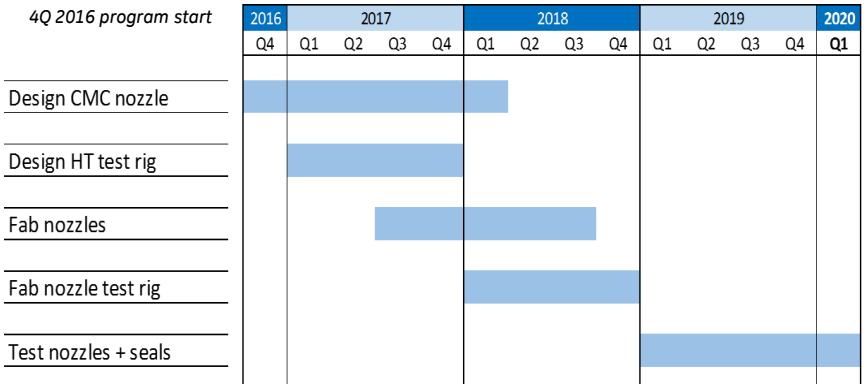
© 2016 General Electric Company. All rights reserved.

CMC Nozzle – Phase II Plan

© 2016 General Electric Company. All rights reserved.

Phase II Overview - Design… Fab… Test

Schedule



Design

Nozzle configuration

- sealing
- cooling
- load paths
- Plies

High temp test rig

Fabricate

Nozzle fab

- tooling
- furnace cycles
- machining
- Coating

Test rig and facility interface

Test

Feature tests with loading frames

- strength
- durability

Full scale, high temperature tests:

- three sealing
- two cooling

© 2016 General Electric Company. All rights reserved.