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

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November 1, 2016
This material is based upon work supported by the Department of Energy under Award Number DE-FE0024006.

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October 27, 2016

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GE Ceramic Matrix Composite (CMC) Processing

Preform Fabrication

- Fiber
- CVD Fiber Coating
- Matrix Slurry
- Wet Drum Winding
- Lay-Up and Laminate

Prepreg

Melt Infiltration

- Coated fiber (+ C and/or SiC powder)
- Porous preform containing carbon and/or SiC
- Dense SiC + Si matrix

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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

\[ \text{SiO}_2 + \text{H}_2\text{O} \rightarrow \text{Si(OH)}_x \text{ (gas)} \]

Baseline System

Advanced system
- Retain Si bond coat
- RE 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 2014 phase 1 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
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.

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 requirements, 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 to 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 1 - CMCs represent the next generation in materials

Figure 2 - CMC shroud for the 7F

Typical Customer Brochure

Typical 3-stage F-class Turbine

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DoE funding for CMCs... Big Impact

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

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

Powering the world... opportunity for CMCs

Aviation Week, September 2016
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
CMC Nozzle – Phase I Results
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
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
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
Bayonet Design

Challenges

- Aerodynamics
- Large metal casting
- Leakage at ID endwall

Features

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

GE Patent US 8,454,303 B2
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
CMC Nozzle – Phase II Plan
Phase II Overview - Design… Fab… Test

Schedule

4Q 2016 program start

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- Design CMC nozzle
- Design HT test rig
- Fab nozzles
- Fab nozzle test rig
- Test nozzles + seals

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