Overview of CMC (Ceramic Matrix Composite) Research at the NASA Glenn Research Center

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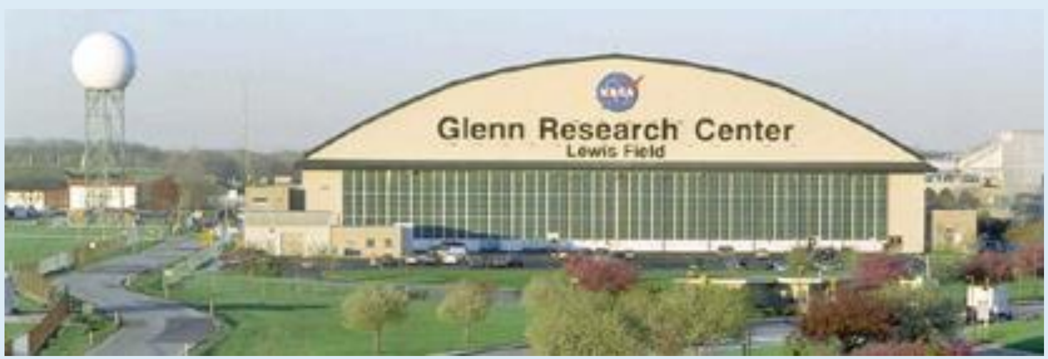


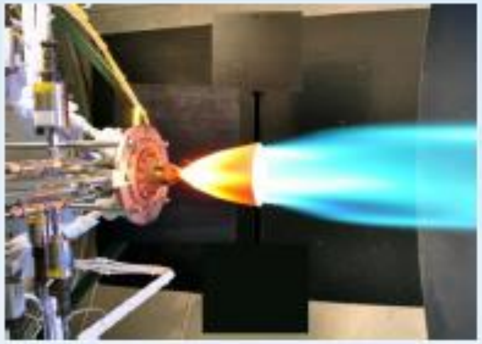
[1] NASA (National Aeronautics and Space Administration) Glenn Research Center
[2] Ohio Aerospace Institute (at NASA GRC)

Ceramics Expo 2016 Cleveland, Ohio April 26, 2016

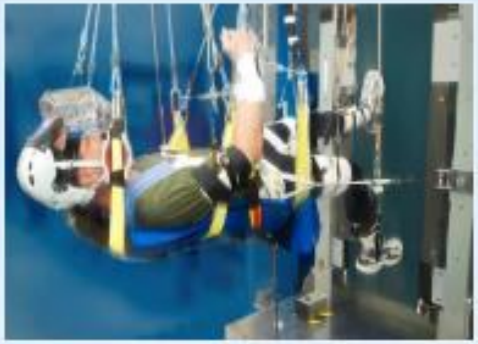
- **John H. Glenn Research Center (GRC) at Lewis Field is one of nine National Aeronautics and Space Administration (NASA) Centers**
- **Originally: NACA (National Advisory Committee on Aeronautics) Engine Research Laboratory (Refr. 1)**

NASA Glenn Core Competencies

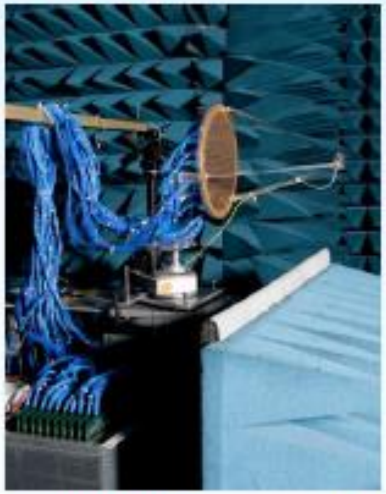
Air-Breathing Propulsion



In-Space Propulsion and Cryogenic Fluids Management



Physical Sciences and Biomedical Technologies in Space



Communications Technology and Development

Power, Energy Storage and Conversion

Materials and Structures for Extreme Environments

Overview

- **SiC/SiC CMCs and EBCs (environmental barrier coatings)**
- **Background information / Applications**
- **Current and Future NASA GRC CMC/EBC Research**

Acknowledgment

The GRC CMC R&D described in this presentation was performed or is being performed primarily by Materials and Structures researchers and technologists

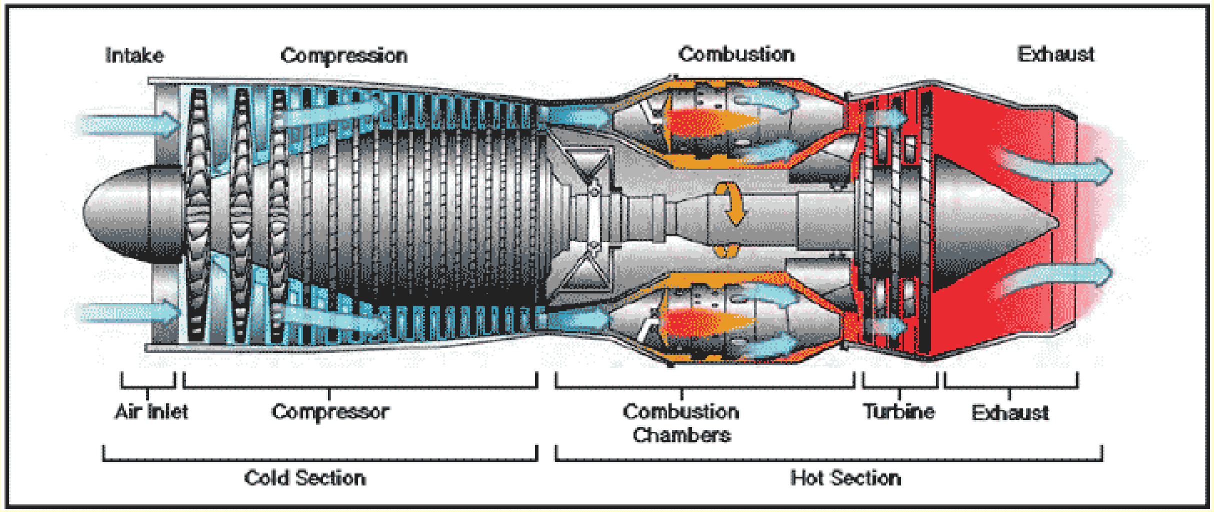
SiC/SiC CMCs: Applications and Need for Coatings

- **SiC/SiC (SiC fiber reinforced SiC matrix) CMCs are being developed for / utilized in aircraft gas turbine engine hot section component applications (T ≥ 2200°F (1204°C))** (Refr. 2, 3).
- **These CMC components will have an environmental barrier coating (EBC), which is a protective, multilayer oxide surface coating to prevent environmental degradation.**

Aircraft Gas Turbine Engine

SiC/SiC w/ EBC

Oxide/Oxide CMC



SiC/SiC Components for Gas Turbine Engines: Benefits

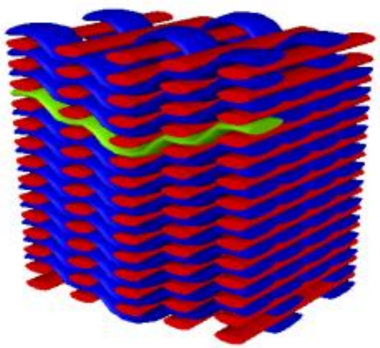
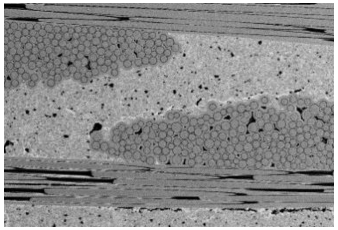
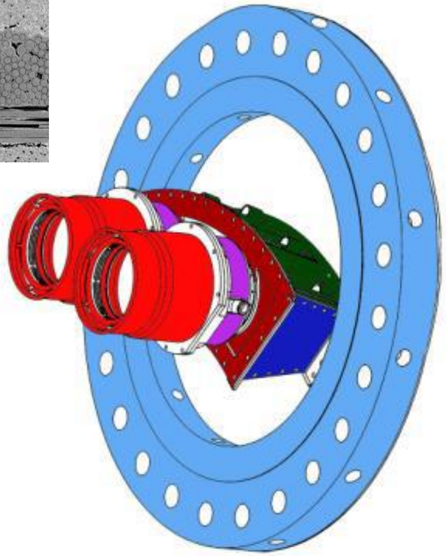
- Reduced component weight (1/3 density of superalloys)
- Higher temperature capability/increased thermal margin
- Reduced cooling requirements
- Improved fuel efficiency
- Reduced emissions (NO_x and CO)

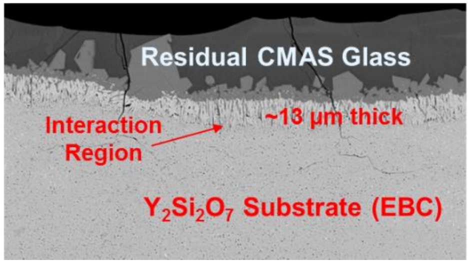
Refr. 2, 4

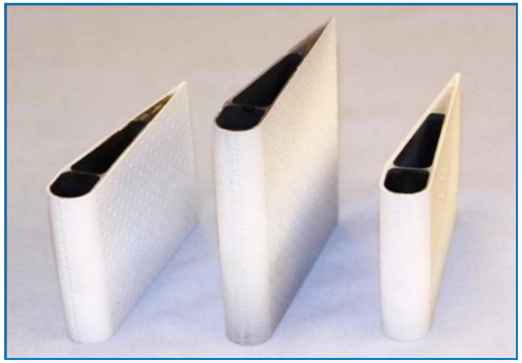
NASA Glenn—
Fiber / CMC / EBC R&D, Leadership, and Teaming

- We have been leaders in the assessment and development of SiC fibers, SiC/SiC CMCs, and EBCs for application in advanced, efficient gas turbine engines for decades.

- We have collaborated with Industry, Academia, and DOD (Department of Defense) Labs for over 25 years.

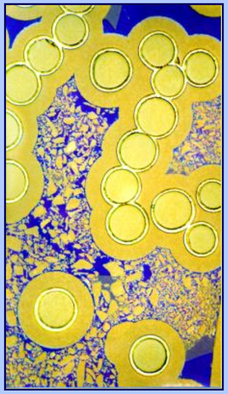




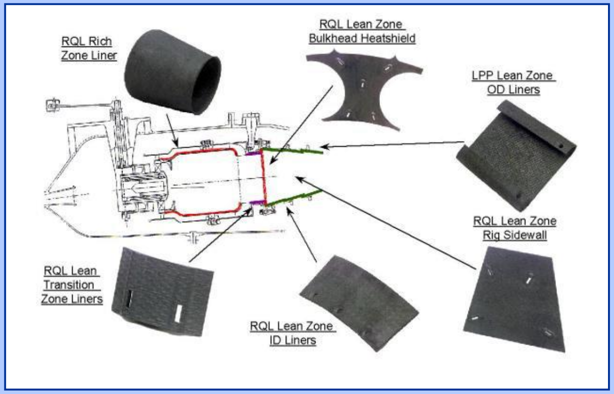



NASA Glenn—MI and CVI* SiC/SiC Development

- ***Early 1990s:*** **The NASA Enabling Propulsion Materials (EPM) Program allowed NASA to work closely with Industry to tackle a broad range of CMC technologies (*including EBCs*) required to reduce NO_x emissions and airport noise through advancements in enabling materials (Refr. 5, 6).**

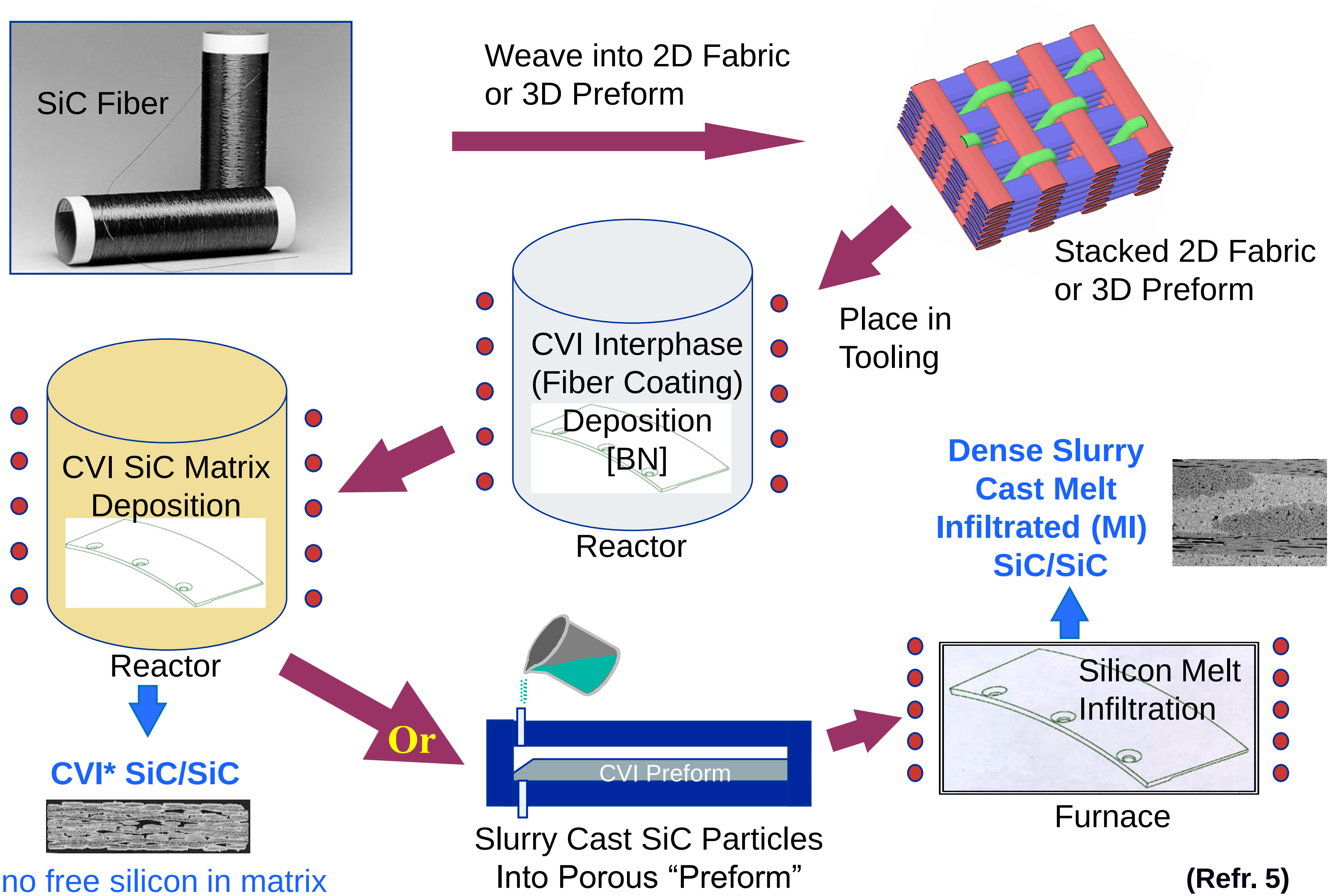




Development of MI (Melt Infiltrated) SiC/SiC for Combustor Liner Application

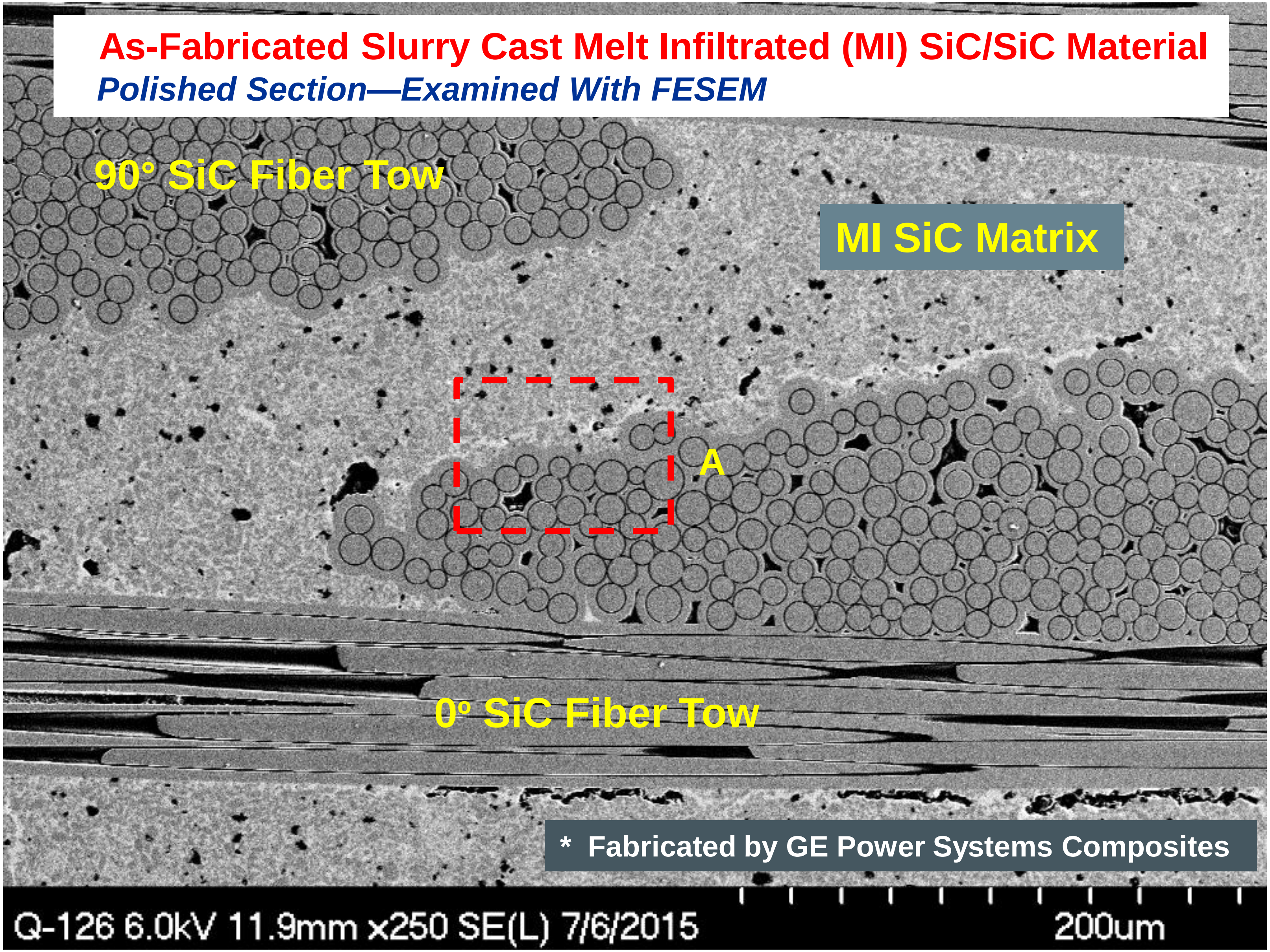
*** CVI— Chemical Vapor Infiltration**

CVI and MI SiC/SiC CMC Manufacturing Processes

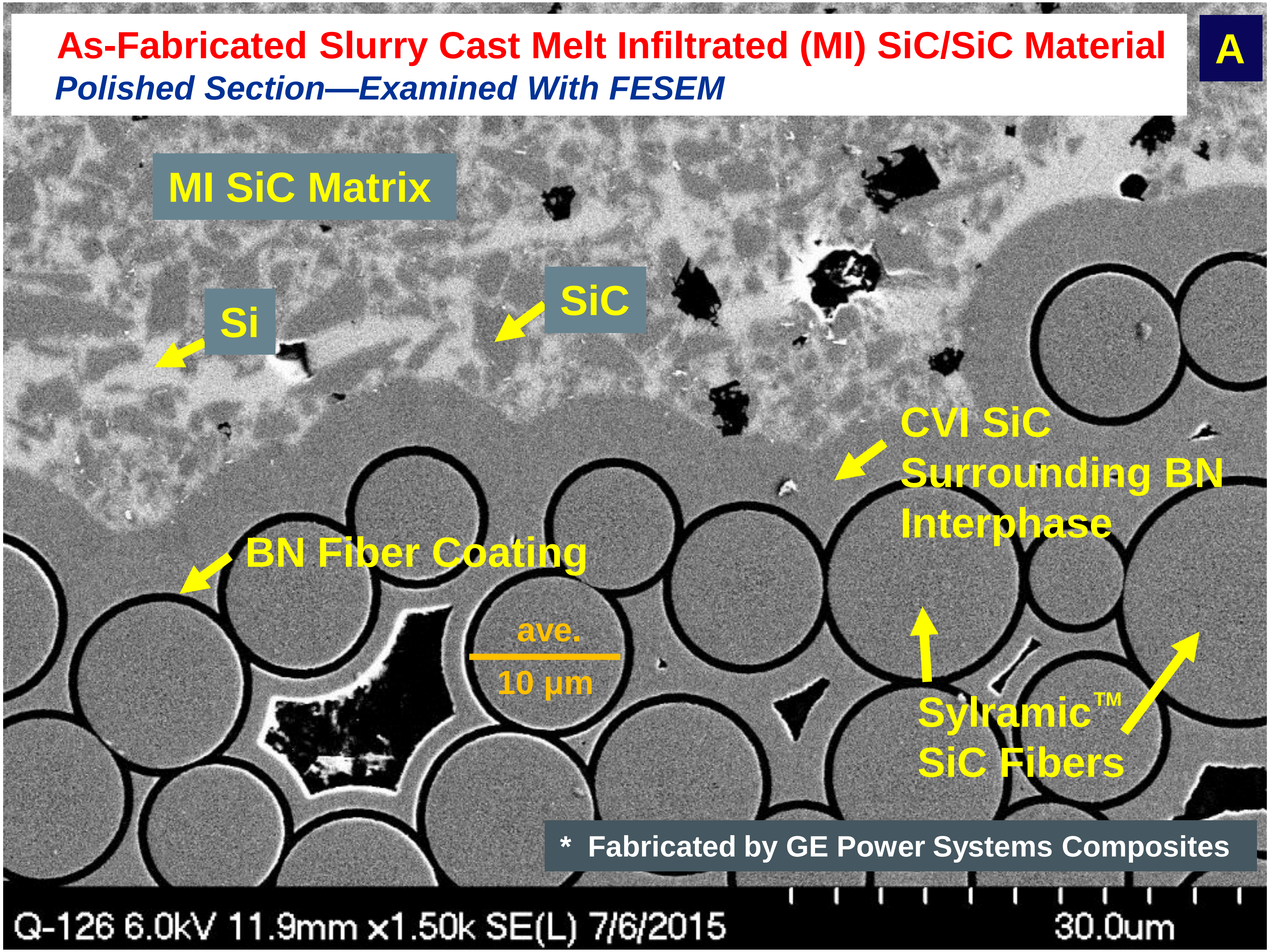


*** CVI— Chemical Vapor Infiltration**

Example of the Microstructure of a 2D SiC/SiC CMC*



Example of the Microstructure of a 2D SiC/SiC CMC*

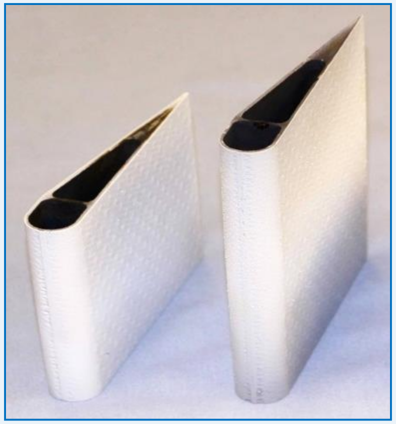


NASA Glenn—SiC/SiC and EBC Development

- The **NASA Ultra-Efficient Engine Technology (UEET) Program** continued the advancement of Melt Infiltrated (MI) SiC/SiC CMC and EBC technology for commercial aircraft engines (Refr. 7 - 10).

MI CMC Vane w/EBC:
NASA UEET Program

Refr. 7, 8



CVI SiC/SiC Vane Test Articles w/EBC:
NASA ERA Project

Refr. 11

- GRC has further developed "High Temperature" SiC/SiC (*no free silicon in matrix*) and EBCs for use above 2600°F (1427°C) in subsequent NASA Programs/Projects including:
  - Next Generation Launch Technology (NGLT) Project
  - Hypersonics Project
  - Supersonics Project
  - Aeronautical Sciences (AS) Project
  - Environmentally Responsible Aviation (ERA) Project
  - Transformational Tools and Technology (TTT) Project

SiC/SiC Components for Gas Turbine Engines: Benefits

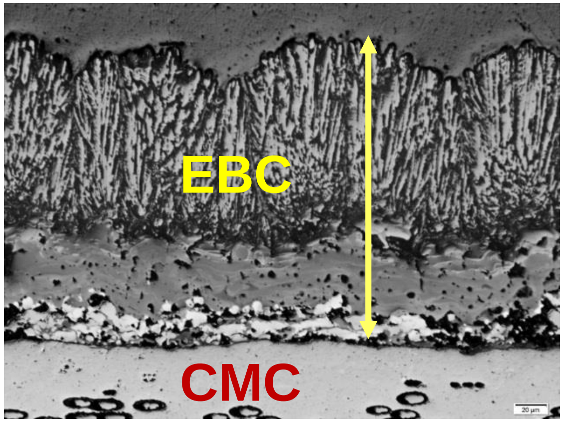
- Reduced component weight (1/3 density of superalloys)
- Higher temperature capability/increased thermal margin
- Reduced cooling requirements
- Improved fuel efficiency → further increase with 2700°F CMC components
- Reduced emissions (NO_x and CO)

Incentive to Increase Engine Operating Temperatures

Current / Future CMC/EBC System Research at NASA GRC

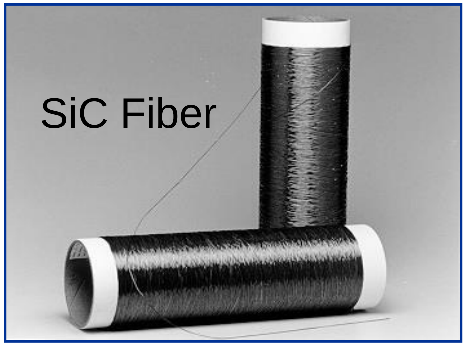
- **2700°F SiC/SiC Development & Characterization**
- **Durable, High Temperature (3000°F) EBC**
- **High Temperature (2700°F Capable) SiC Fiber**
- **SiC/SiC CMC / EBC Durability Modeling & Validation**

Goal:
- **Overall, ICME (Integrated Computational Materials Engineering) Culture**
- **All CMC/EBC Research Involving / Influenced by Modeling**

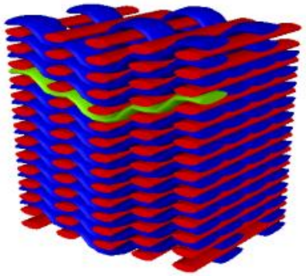


Refr. 12

Hybrid (CVI + PIP) SiC/SiC CMC Manufacturing Process



Weave into 2D Fabric
or ***Designed*** 3D Preform



Stacked 2D Fabric
or 3D Preform

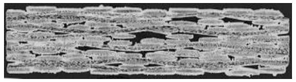
Place in
Tooling

CVI Interphase
(Fiber Coating)
Deposition
[BN]

Reactor

CVI SiC Matrix
Deposition

Reactor



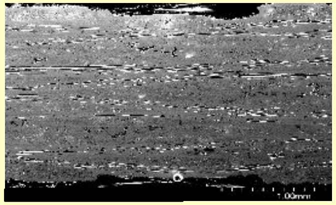
Porous "Preform"

PIP –

Polymer
Infiltration and
Pyrolysis SiC
Matrix

Furnace

Dense Hybrid SiC/SiC
For 2700°F Application



no free silicon in matrix

Refr. 12

High Temperature CMC Testing: Tensile Creep and Fatigue

Example of Rig Used to Test SiC/SiC CMCs

Testing used to validate models for CMC and CMC / EBC samples

Instron Test Rig

- Testing in Air
- Temperatures up to 2800°F (1538°C)
- Creep and Fatigue
- Frequencies up to 1 Hz
- Electromechanical, 50 kN Load Cell
- $MoSi_2$ Element Furnace
- 1 in. Gage Length, Water-Cooled Extensometer

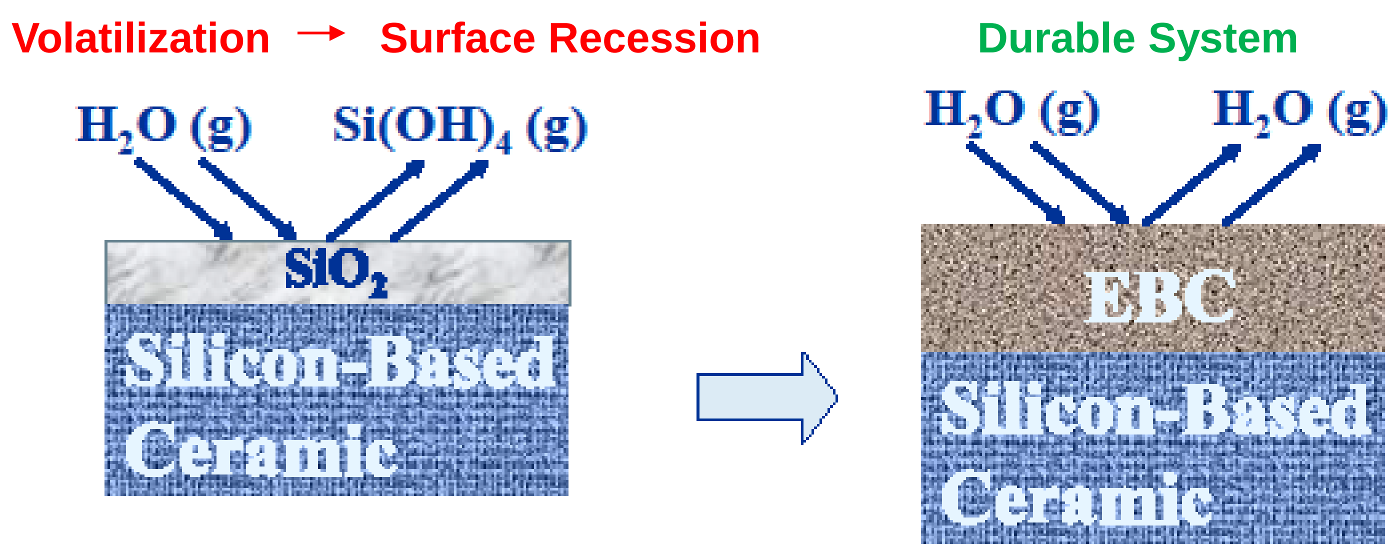
Typically Test 6 in. Long Tensile Specimens

Importance of Environmental Barrier Coating (EBC)

- **Reaction with water vapor from combustion environment causes rapid <u>surface recession</u> of Si-based ceramics, seriously limiting component life**

$$SiO_2\ (s) + 2H_2O\ (g) = Si(OH)_4\ (g)$$

- **An Environmental Barrier Coating (EBC) provides protection from water vapor and enables long life.**



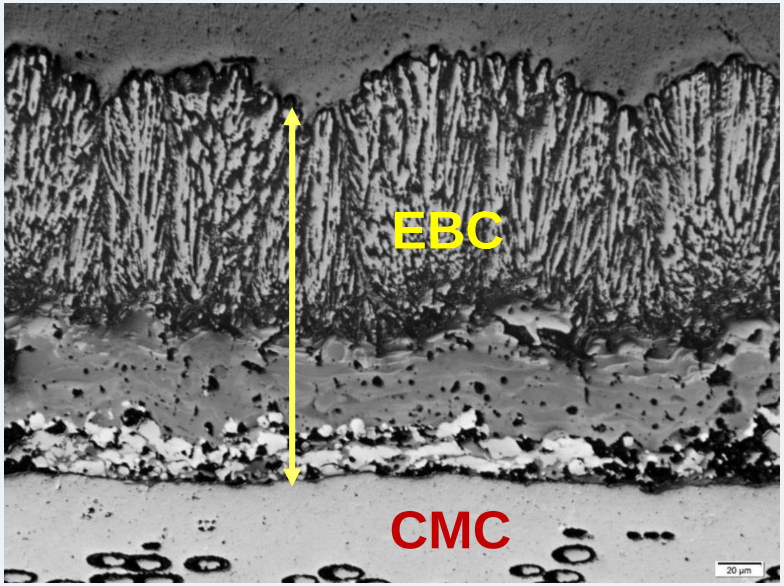
Refr. 1, 10, 13 - 15

Durable, High Temperature EBC for Use With 2700°F SiC/SiC

Issue: - Need for EBC systems with *up to* 3000°F (1650°C) capability that exhibit low thermal conductivity and high temperature durability.
- EBC design (thickness/composition/etc.) is component dependent.

Addressed By: EBC (environmental barrier coating) systems designed with:

– High melting point / oxidation resistant systems capable of up to 3000°F
– Advanced environmental barrier and 2700°F+ capable bond coats
– Controlled surface emittance and radiative properties
– High strength and self-healing capabilities, CMAS-resistant
– Low thermal conductivity 0.5-1.2 W/m-K at 2700-3000°F (1482-1650°C)



Multilayer / Multifunctional EBC

Multicomponent low conductivity, high stability Rare Earth (RE) doped HfO_2, ZrO_2 and Hf (Zr)-RE silicates

Strain tolerant oxide-silicate interlayers

Rare Earth-Silicate and HfO_2-Rare Earth-Alumino-Silicate EBC

HfO_2-Si or RE-Si based bond coats

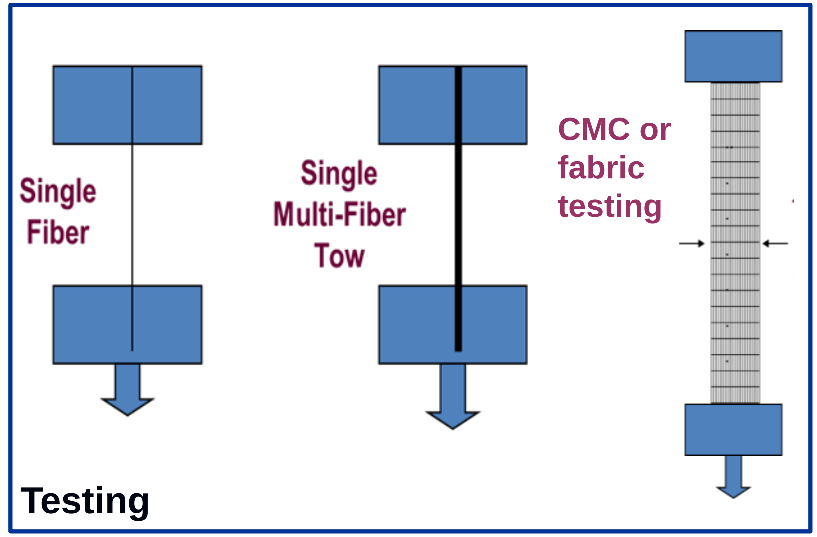
SiC/SiC Composite

Refr. 10

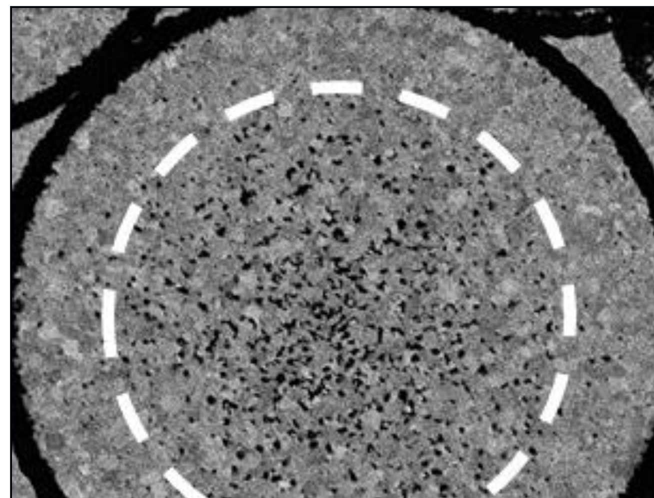
High Temperature (2700°F (1482°C)) SiC Fiber Research

Issue: **SiC/SiC CMCs that will operate at 2700°F will require strong, creep-resistant SiC fibers.**

Addressed By:



- **Determination of key mechanical/structural properties of potential 2700°F SiC fibers to:**
  - **Understand basic mechanisms and *correlation* with microstructure**
  - **Develop analytical fiber and CMC models for time-temperature deformation and rupture behavior**
  - **Identify current limitations and approaches for property improvement**
- **<u>GRC fiber processing</u>: obtain 2700°F SiC fiber with improved microstructure (reduced porosity, specific SiC grain size, etc.) and optimal properties**



Example of Increased Amount of Porosity in SiC Fiber Core

GRC Modeling of CMC/EBC Behavior/Properties/Durability

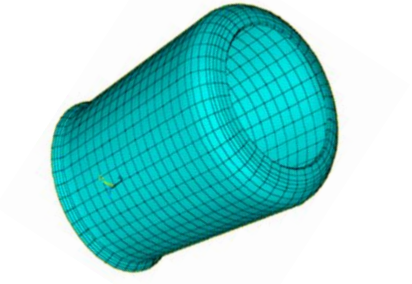
• **Modeling: We have a broad perspective and work with everyone**

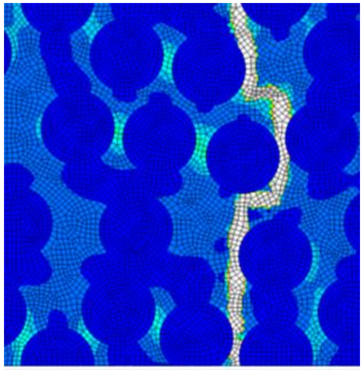
Issue: **Need for a wide range of approaches (different scales) for CMC and CMC/EBC system modeling to provide understanding of behavior / performance; - enabling life prediction and guiding of CMC and EBC durability enhancement.**

Addressed By:

- **Large portfolio of internal codes/software**
- **Multiscale modeling**
- **Computationally-efficient methods/tools**
- **Account for environmental effect: Air, vacuum, inert, steam, CMAS**
- **Creep/fatigue interaction with environment**
- **Unique/creative non-linear modeling capabilities**
- **Proposed use of a model SiC/SiC material system and mini-composites in some studies**
- ***Strong collaboration with industry***

- **Validation of models (CMC and CMC/EBC system)**
- **Understand the effects of the constituents/structure**





Summary

- **NASA's efforts have helped move SiC/SiC CMC and EBC technology forward to the point where CMC components are being introduced in commercial jet engines.**
- **Aircraft gas turbine engines will continue to operate at *higher temperatures*, and there will be a need for higher-temperature (>2500°F/1371°C) SiC/SiC composites and EBCs.**
- **A 2700°F capable fiber is an enabling constituent for a durable 2700°F CMC/EBC system.**
- **Analytical modeling of material behavior is needed to help understand CMC/EBC durability issues, and to provide guidance for material development.**

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Appendix—Back-up Slides

Investigation of CMAS Interactions with EBC Materials

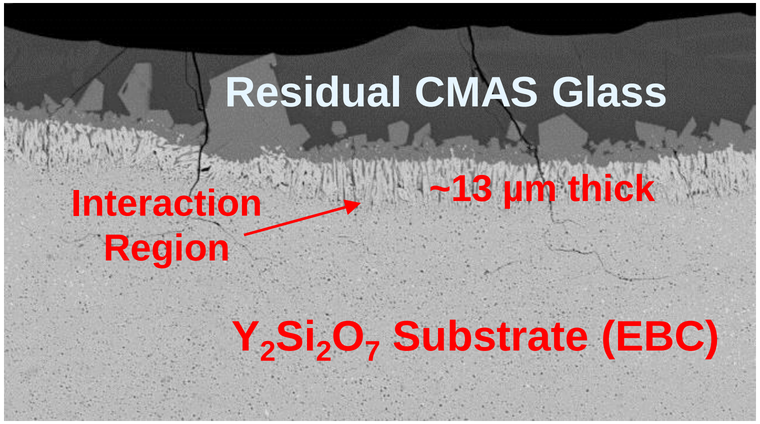
- **CMAS: Calcium magnesium aluminosilicate**

Issue: **Ingested particulates (e.g., sand) can form CMAS glass deposits on EBCs in the engine hot section, with coating degradation occurring due to reaction and infiltration of the coating.**

Addressed By:

- **Characterization of thermal and mechanical properties of CMAS glass provides fundamental knowledge that will help to mitigate damage and improve EBC durability**
- **Evaluation of interactions between heat treated EBC substrates with CMAS glass pellets. EBC materials evaluated include:**
  - **Yttrium disilicate ($Y_2Si_2O_7$)**
  - **Hafnium silicate ($HfSiO_4$)**
  - **Ytterbium disilicate ($Yb_2Si_2O_7$)**

Aircraft Engines Ingesting Sand on Runway



$Y_2Si_2O_7$ Substrate Exposed to CMAS at 1200°C for 20h

Refr. 12

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NASA centers and facilities


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Ames Research Center


Armstrong Flight Research Center


Glenn Research Center


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