OAK RIDGE National Laboratory

Ceramic Matrix Composites for Energy Applications: DOE Fossil Energy and Oak Ridge National Laboratory

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ORNL is managed by UT-Battelle, LLC for the US Department of Energy

U.S. DEPARTMENT OF ENERGY

DOE FE funding several projects related to CMCs

- **Siemens**: Additive Manufactured Metallic 3D OX-OX CMC Integrated Structures for 65% Combined Cycle Efficiency
- **Siemens**: Ceramic Matrix Composite Advanced Transition for 65% Combine Cycle
- **General Electric**: High Temperature Ceramic Matrix Composite (CMC) Nozzles for 65% Efficiency
- **Clemson University**: Integrated TBC/EBC for SiC Fiber Reinforced SiC matrix Composites for Next Generation Gas Turbines
- **ORNL**: High-Performance Thermal Barrier Coatings
  - Transitioning to "Next Generation Environmental Barrier Coatings"
- **UTRC** (new): Hybrid Ceramic-CMC Vane with EBC for Future Coal-Derived Syngas Fired Highly Efficient Gas Turbine

ORNL new task on EBC for next generation CMC

- Task began July 2018
- Environmental barrier coating to protect CMC
  - SiC forms SiO_2, SiO_2 forms $Si(OH)_4$ vapor in steam
- Focus on next generation CMC at ≥1425°C (2600°F)
  - No Si bond coating
  - CVD SiC substrates
- **Partner with Stony Brook Univ. to make coatings**
  - RE silicates
- Building new cyclic rig for **>1500°C steam testing**
  - Automated system for 1-20 h cycle times
- “breaking not making”

Past, Present & Future: ORNL Making CMCs

Malden Mills CMC liner for CHP (1999)
-Solar Turbines
-ORNL
-Pratt & Whitney
-BF Goodrich
-Honeywell
-ANL

After CFCC, GE invested 15 yr & $1.5B in CMCs

Gen-1: Si-MI SiC matrices

SiC/SiC to engine market >25 yr

CVI matrices → Gen-2 Si-free SiC/SiC

New ceramics → UHT Beyond SiC

ORNL future

CFCC begins

CFCC ends

2016 LEAP engine

1960 1970 1980 1990 2000 2010 2020 2030

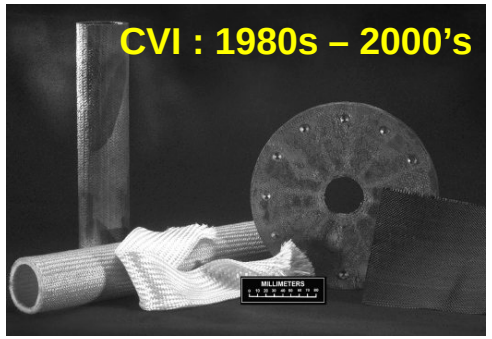
ORNL: Vapor coating of ceramic fuel particles

ORNL Developed forced-flow, thermal-gradient, CVI process

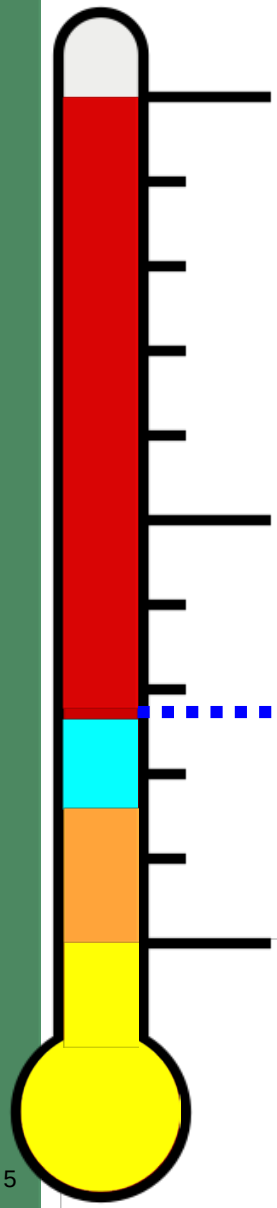
(1992-2002) DOE Continuous Fiber Ceramic Composite (CFCC) Program led by ORNL in close collaboration w/ industry (e.g., GE).

- Advanced CVI
- Interfaces & coatings
- Characterization
- Oxidation testing

ORNL Recent: SiC/SiC for accident tolerant nuclear fuels, CVD ZrC for Space Power.



New opportunities for CMCs



Max Temp	Application	Agencies
2200ºC	**Spacecraft, Rocket, Missile, Re-entry**	(Aerospace, DOD)
2000ºC	**Hypersonic craft, propulsion**	(DARPA, DOD, industry)
1700ºC	**Utility Gas Turbines (≥65% eff.)**	(DOE-FE)
	Transformational Power Generation	(DOE-FE)
	Accident Tolerant Nuclear Fuels	(DOE-NE)
1480ºC	**Aero Turbines (not cooled)**	(industry, DOD)
1350ºC	**Aero Turbines (NEW – ceramics)**	(industry, DOD)
1175ºC	***SX superalloys + coatings***	

State of the Art in CMCs (SiC/SiC) for Turbines (≤1300°C)

Thermally Stable Ceramic Phase(s) + **Complex STRUCTURES** + **Complex PROCESSING** = **Remarkable Hi-T PROPERTIES (tough, structural ceramics)**

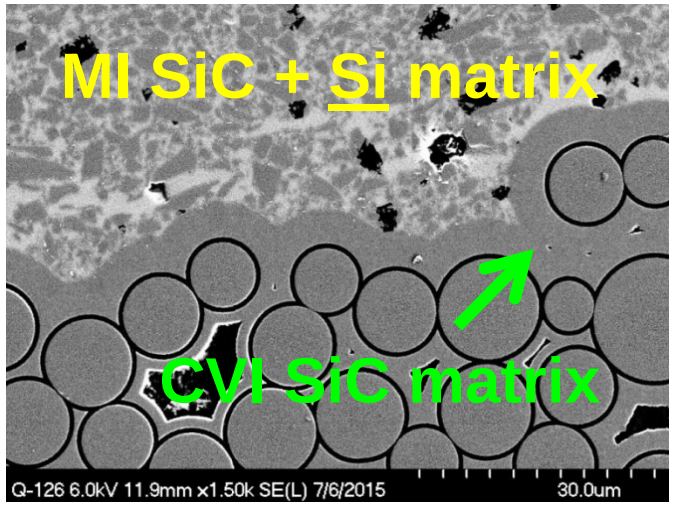
SiC continuous fiber weaves (~10 μ dia.)

Interface coatings (<1 μm)

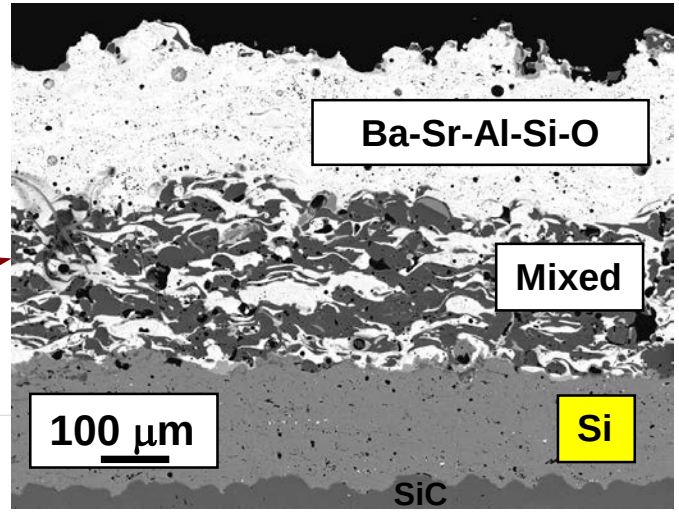
SiC matrix

Protective SiO_2 scale

Environmental barrier coating (EBC)



Si



Si

Barriers to higher T

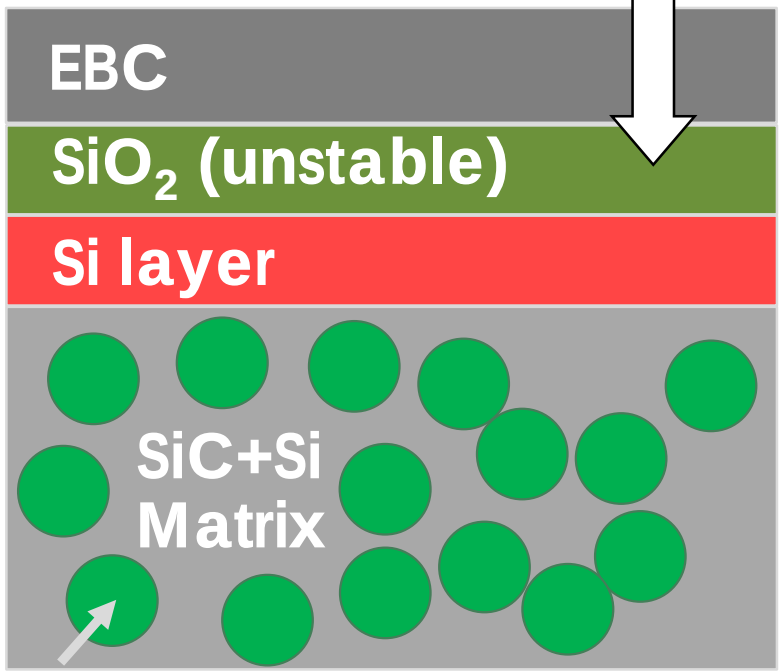
- Si melts @1414°C
- SiC oxidizes to SiO_2
- SiO_2 volatizes in H_2O
- Ceramic synthesis

MI = melt infiltration
CVI = chemical vapor infiltration

New paradigm: develop a more stable matrix for SiC fibers

<1300°C

oxygen + water vapor



SiC Melt Infiltration
(state-of-the-art, ~30yrs)

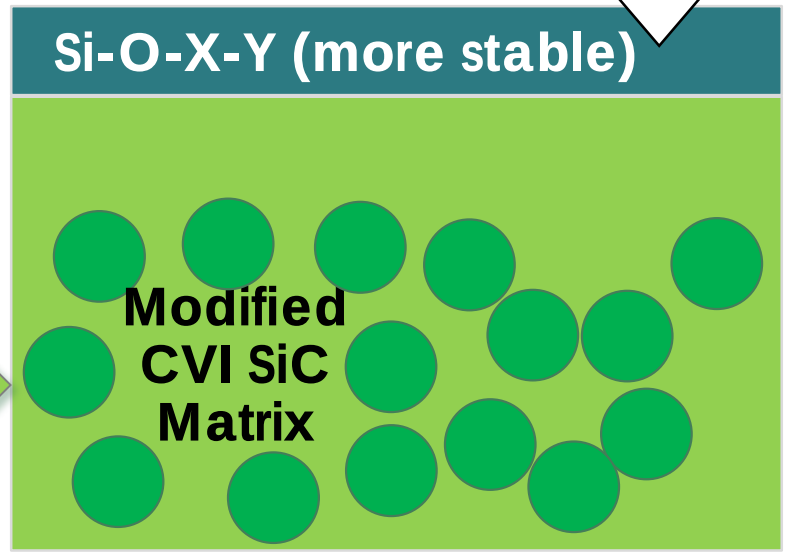
Matrix Modification

Path 1:SiC+A,B = known elements to form a targeted silicate during oxidation

Path 2:SiC+X,Y = computationally Predicted elements to form an oxide predicted to be more stable

>1500°C

oxygen + water vapor



SiC+A-B Vapor Deposition
SiC+X-Y Vapor Deposition

Protective silicate that is more stable than SiO_2 in water vapor at >1500°C?

1,271 ternary (Si-O-X) and 3,901 quaternary (Si-O-X-Y) silicates are reported

ORNL Big Picture Objectives for CMCs

- Enable higher temperature CMC systems by researching pathways to improved non-oxide matrix ceramics and coatings
- **Move beyond SiC as a CMC matrix material**
  - starting by modifying SiC
- Exploit flexibility of ceramic compositions offered by chemical vapor synthesis
- Harness the power of modern computational materials science
  - High performance computing
  - Data analytics/Artificial intelligence
  - **Predict superior compositions that form more stable reaction products**