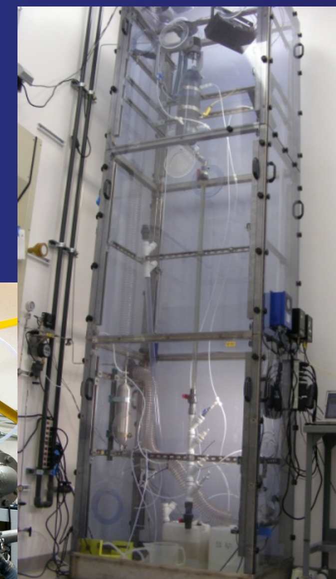
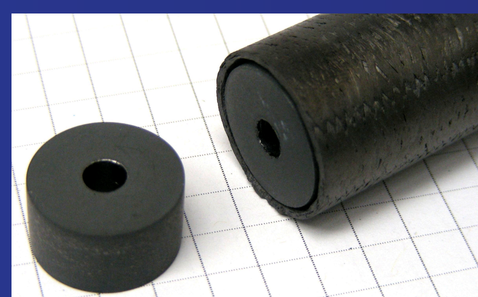
Advanced Fuel Technologies at General Atomics

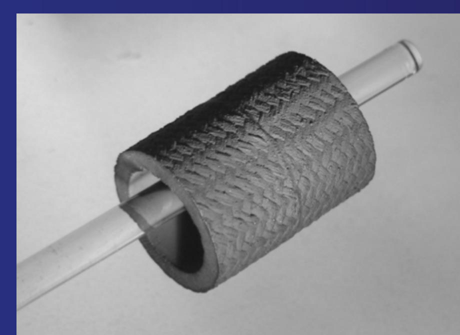
By
Dr. Christina A. Back



Presented at
OECD/NEA Workshop on Accident Tolerant Fuels of LWRs

Paris, France

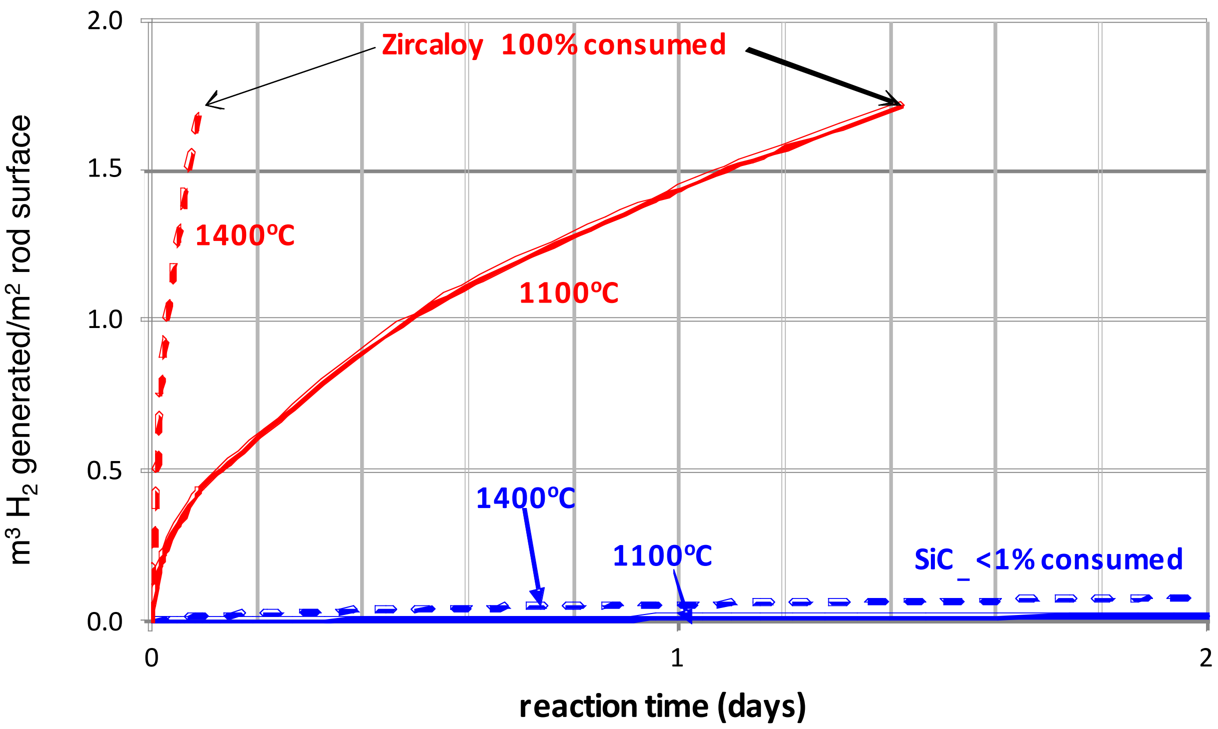




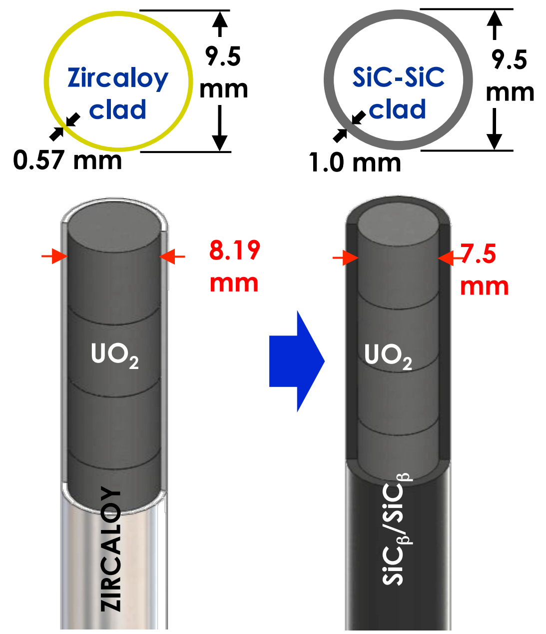
10 December 2012

SiC Composite Clad for Light Water Reactors Can Make a Major Improvement in Safety

- $Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 + 595$ kJ/g-mole
- $SiC + 4H_2O \rightarrow SiO_2 + CO_2 + 4H_2 + 264$ kJ/g-mole



Eliminate hydrogen explosions

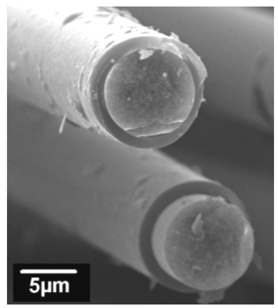


β-SiC Composite (SiC_β/SiC_β) Is an Attractive Material for Nuclear Applications

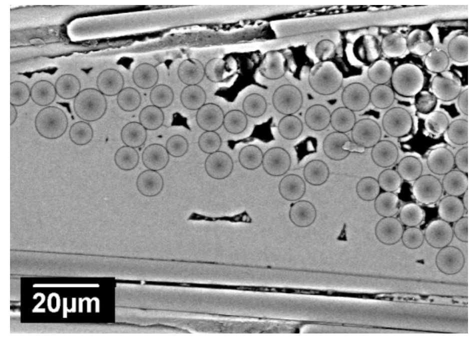
<u>β-phase (diamond) compared to α-phase (hexagonal) SiC</u>

- Much better resistance to irradiation damage
- Higher strength in irradiated material at high temps (>1200°C)
- Better corrosion resistance

crystalline SiC_β fiber



pyrocarbon interface



SiC_β matrix infiltration

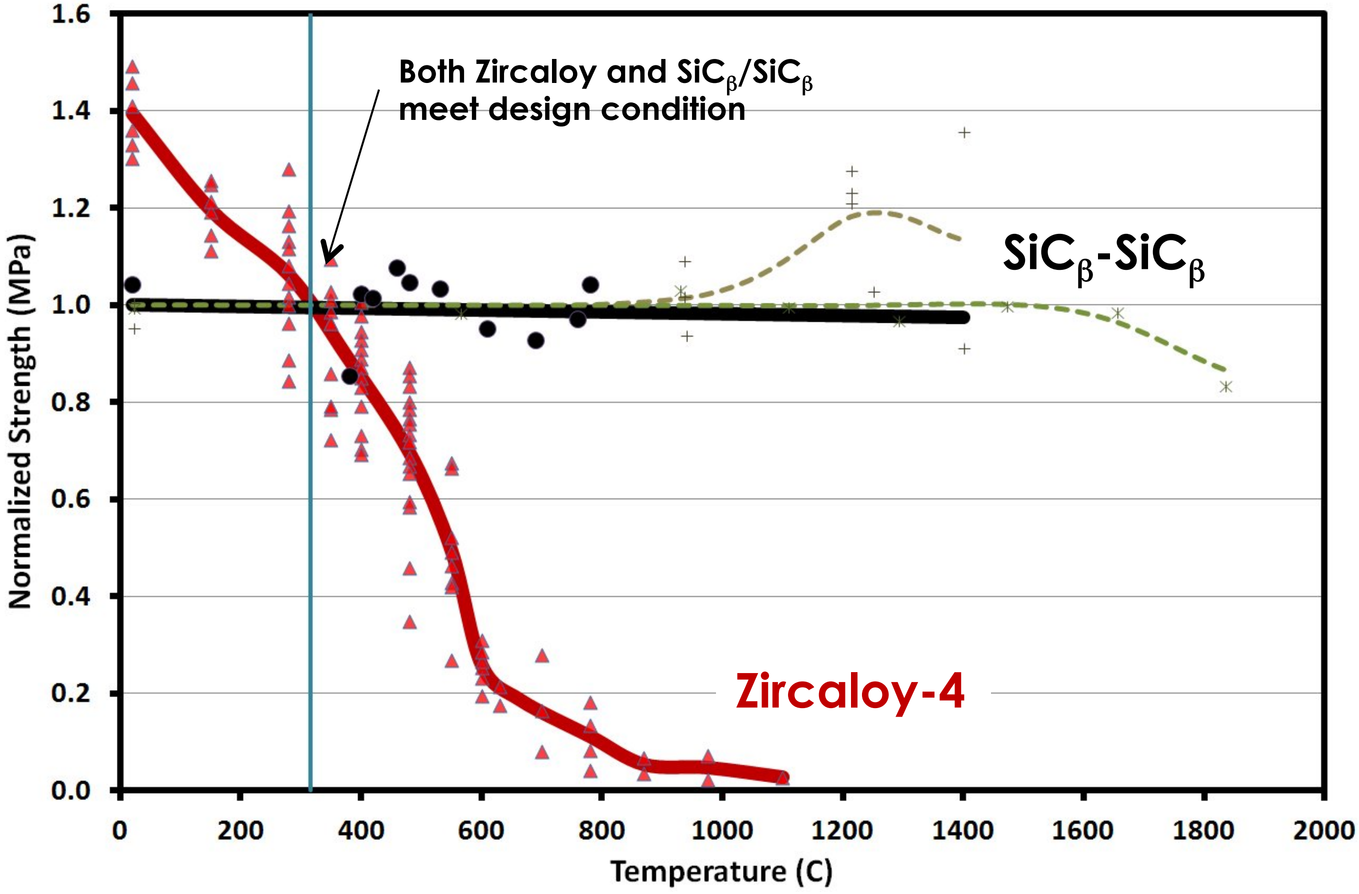
SiC_β/SiC_β component

Properties	Zircaloy-4[a,b]	SiC_β/SiC_β[c]
Density @ 25°C, g/cc	6.56	2.8 – 3.0
Design tensile stress @316°C, MPa	~450	120-250
Usable tensile strength above 800°C, MPa	None	120-250*
Irradiated fracture toughness @316°C, Mpa-$m^{0.5}$	< 45	25-37
Reaction rate with air at 1200°C, $mm/s^{0.5}$	0.45	0.0026
Reaction rate with H_2O at 1200°C, $mm/s^{0.5}$	5.9	0.005
Thermal absorptions per source neutron, barns/n	7.21E-04	3.27E-04
DPA limit	~10	> 40
Unirradiated thermal cond. at 316°C, W/m-K	18	$\perp$ 25

a - F Azzarto, *JNM* (1969)
b – E Ibrahim, *JNM* (1984)
c – Y Katoh, *JNM* (2007)

SiC-SiC Improves LWR Safety Through High Temperature Strength

- CVD SiC, stoichiometric SiC fiber, and SiC-SiC composites can hold fission gas pressure beyond 1500°C and shape beyond 2000°C
- Zircaloy shows ~90% drop in strength at 800°C



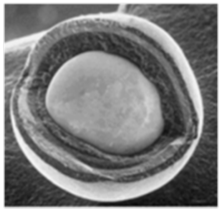
SiC-SiC composites maintain mechanical properties at high temperatures

- Strength
- Stiffness
- Toughness

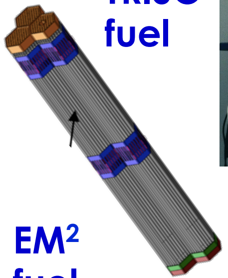
Geelhood, et al., PNNL-17700 (2008)
Gulden, J. Amer. Ceram. Soc. (1969)
Katoh, et al., J. Nuc. Mat. (2010)
Hironaka, et al., J. Nuc. Mat. (2002)
Hasegawa, et al., J. Nuc. Mat. (2000)
Snead, et al., J. Nuc. Mat. (2007)

GA has a 40 Year History of Nuclear Fuel Development with Emphasis on Use of SiC for "Accident-Tolerance"

- **Improving Nuclear Fuel Clad via Silicon Carbide Composite (SiC_β/SiC_β)**
- **Developing SiC_β/SiC_β clad fuel rod for a new reactor concept, EM^2**
- **Making substantial investment in people & equipment to develop SiC_β/SiC_β fab processes**
- **Vested interest in LWR fuel supply – mining, U_3O_8 supply and UF_6 conversion**



TRISO fuel



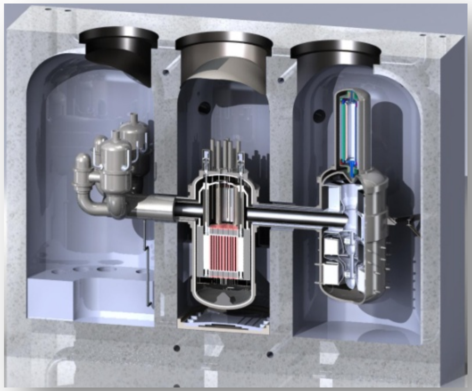
EM^2 fuel

SiC/SiC fabrication development lab

Rio Grande Resources
U.S.A and Canada

Heathgate Resources
Australia

Nuclear Fuel Services



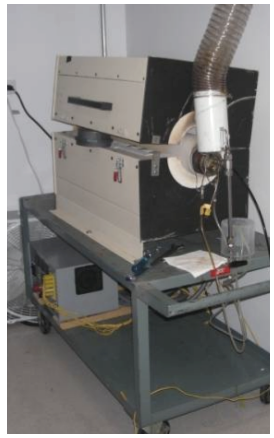
EM^2 reactor

GA Sol-Gel Fabrication Laboratory Produces High-density Uranium Fuels

Sol-gel column

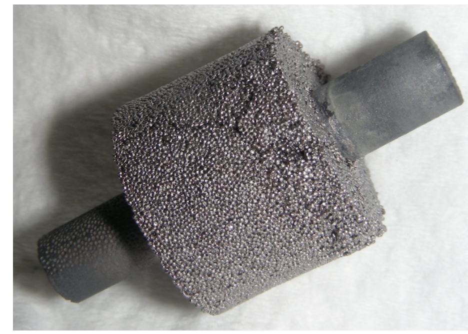
drying

calcining



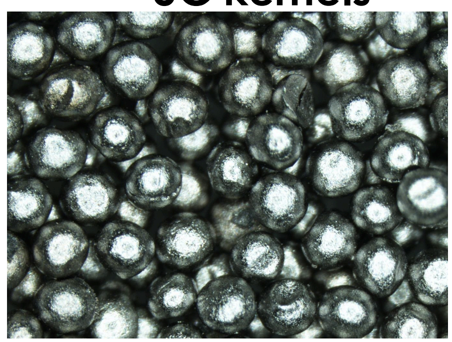
sintering

UC pellets

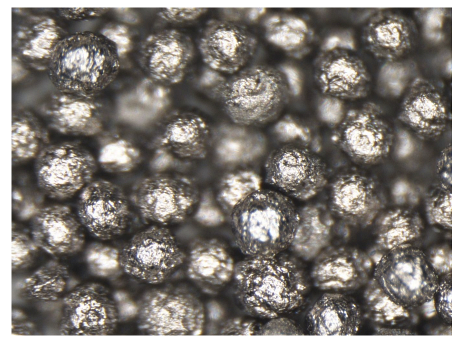


Sol-Gel particles with carbon

UC kernels

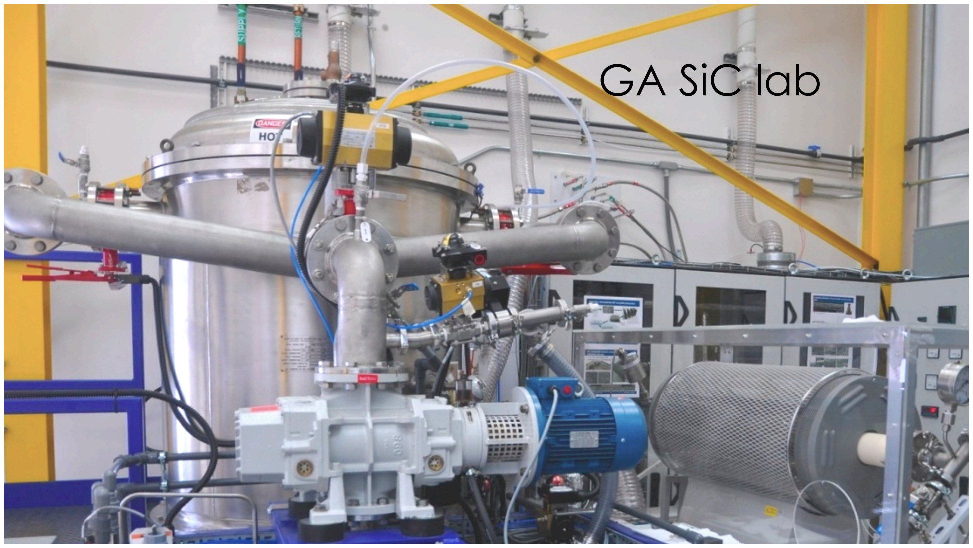


UN kernels

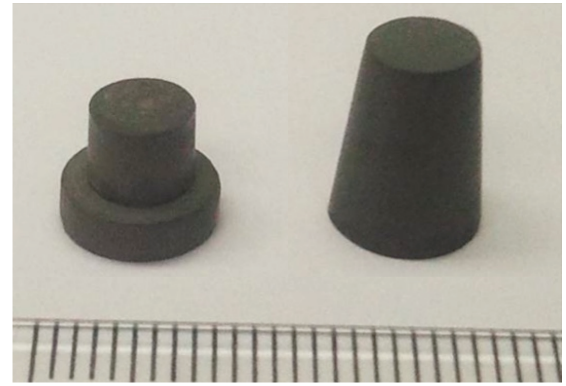


- Materials achieve highly uniform composition
- Kernel size and morphology can be controlled

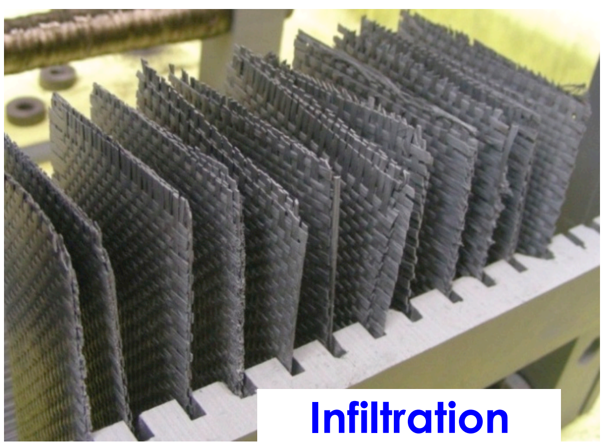
GA SiC_{β}/SiC_{β} Development Addresses All Aspects of Fuel Cladding Fabrication



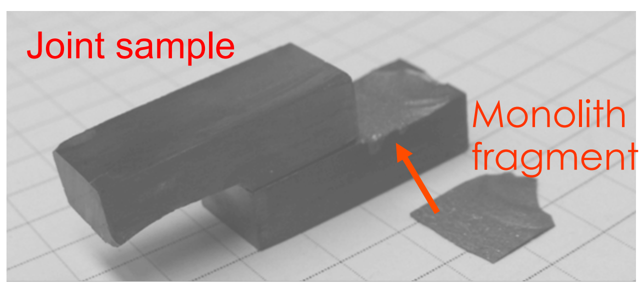
Composite tubes



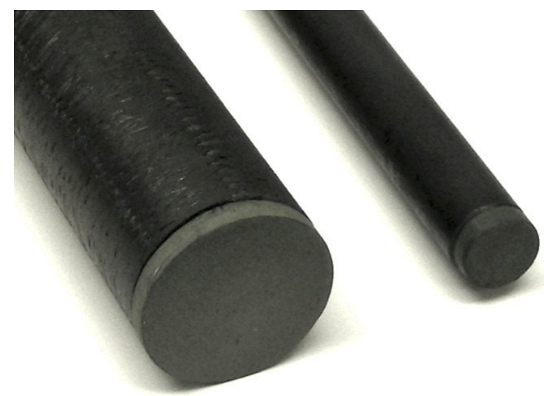
End plug fabrication



Infiltration



High strength joint is β-SiC

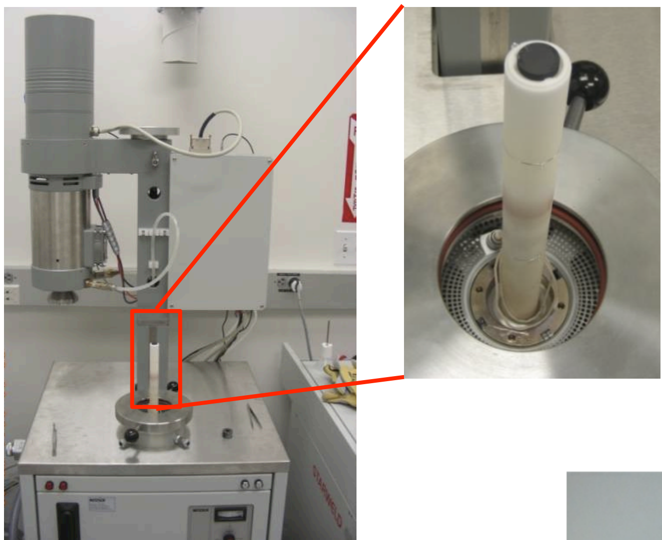


Prototypes

Many Resources Are Used to Measure Critical Parameters

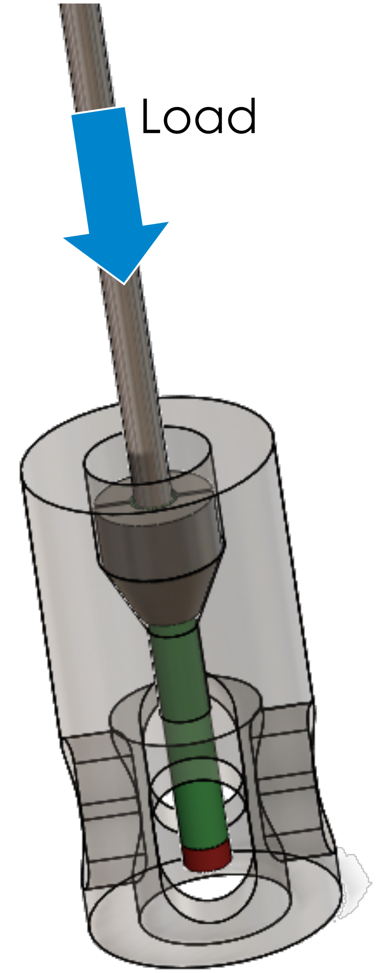
Commercial analysis equipment

Thermal conductivity



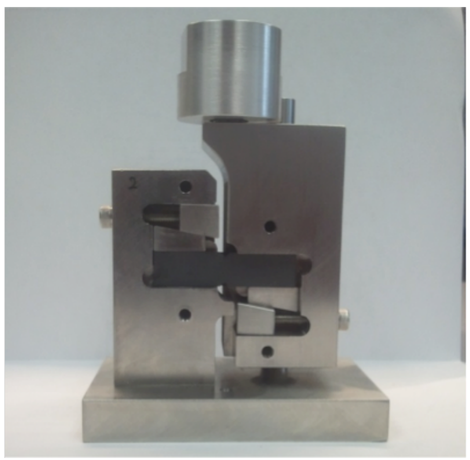
Custom test rigs

End plug push-out test assembly



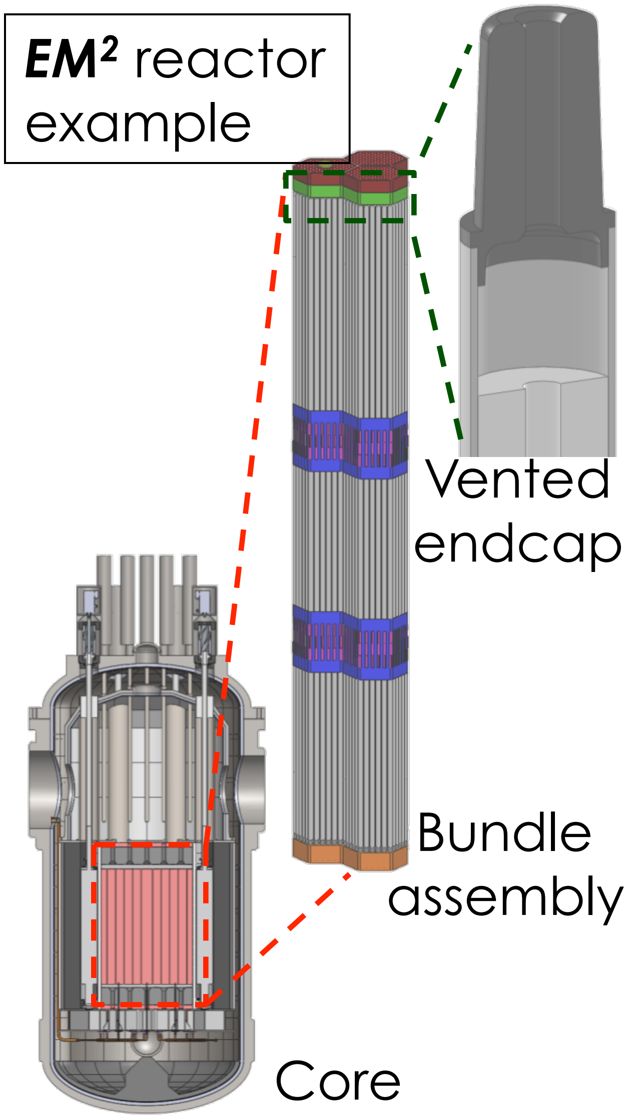
Specialized fixtures

Iosipescu mechanical testing



Advanced Reactor Concepts Pose Research Challenges in Cladding Development and Testing

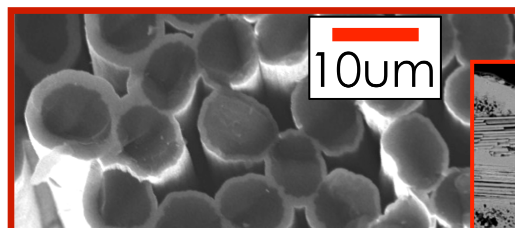
***EM*^{2} reactor example**



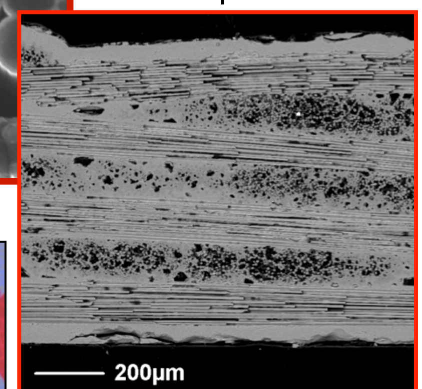
Challenges:

- Survive high dpa
- Achieve high thermal conductivity
- Retain structural integrity with joints
- Withstand fuel swelling and thermo-chemical interactions

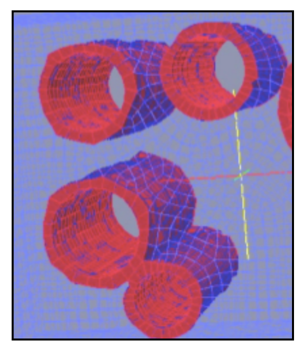
- **Coated fibers in EM^2 bundle**



composite

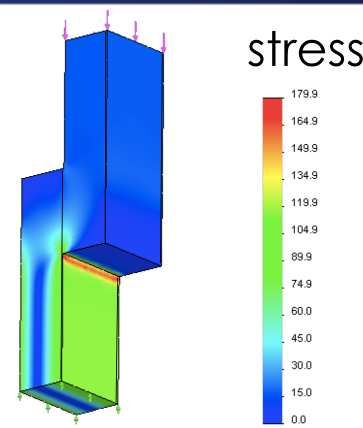


- **GA modeling capabilities accelerate process development**

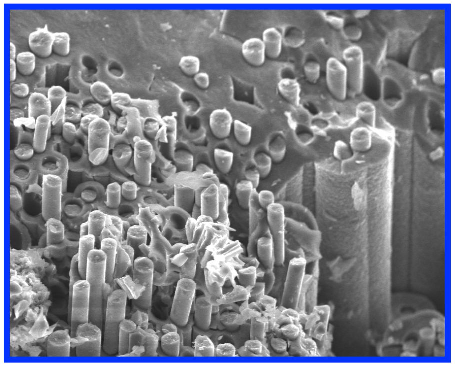


Development of SiC-SiC Composites Is GA's Primary Focus for Accident Tolerant Fuel Work

- **Design to provide strength, impermeability**
  - Meet performance and safety requirements



- **Research to accelerate SiC-SiC fabrication time**
  - Reduce fabrication cost
  - Achieve high density for improved material properties
  - Model fabrication to aid process optimization

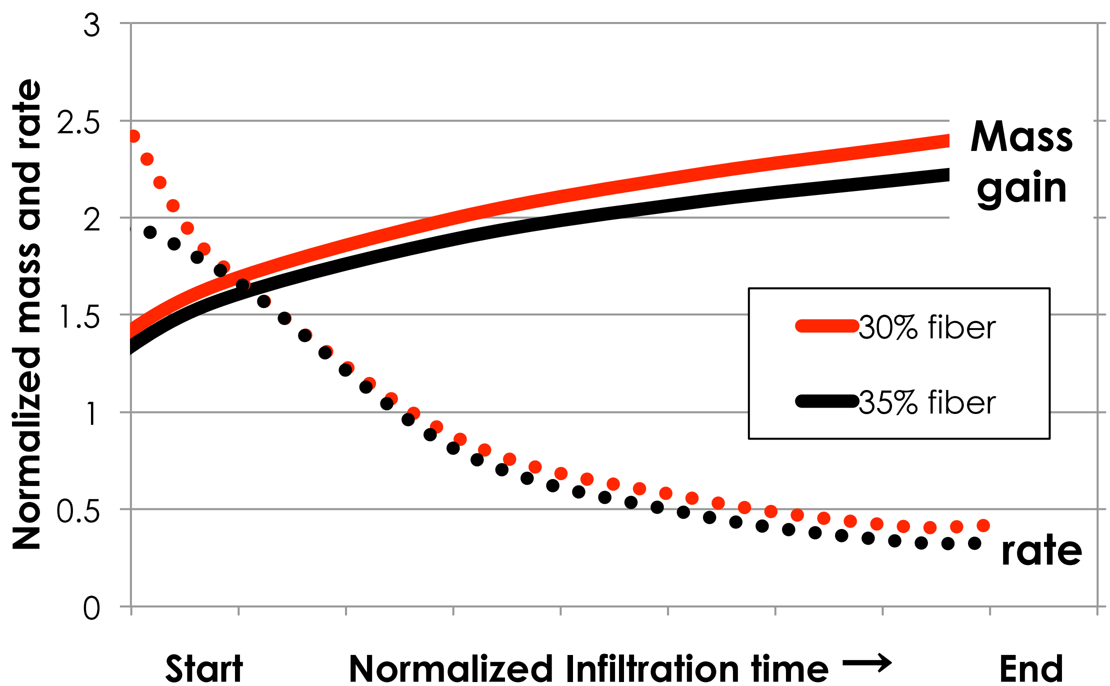


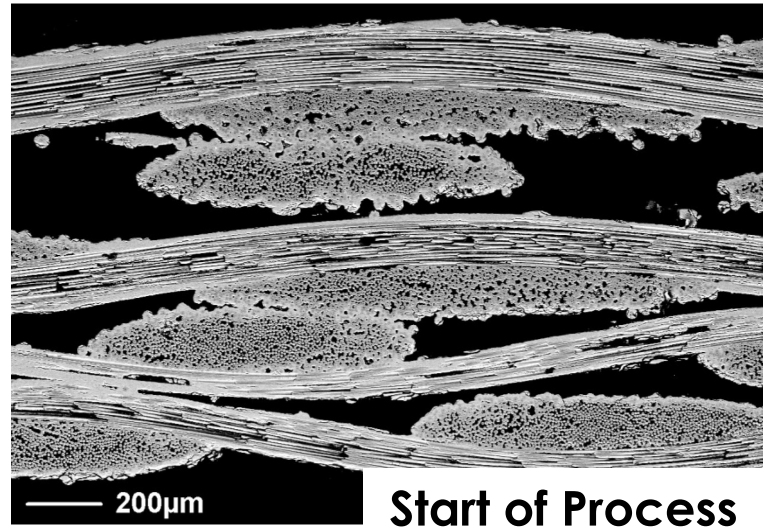
- **Research to produce irradiation resistant joints**
  - Ensure joint material is compatible with the parent composite material
  - Improve irradiation resistance, thermal expansion, relative density, mechanical properties, etc

- **Measure and characterize materials and parts**

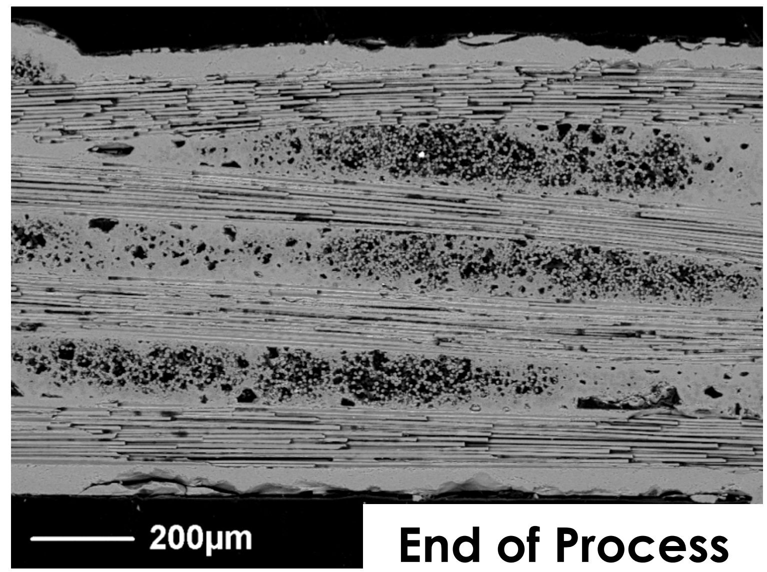
CVI Processing Parameters Are Being Optimized for Composite Fabrication

- **Diffusion of MTS between fibers**
  - Affected by sample geometry, depletion, and spatial variation
- **Trade-off between processing time and uniformity**





Start of Process

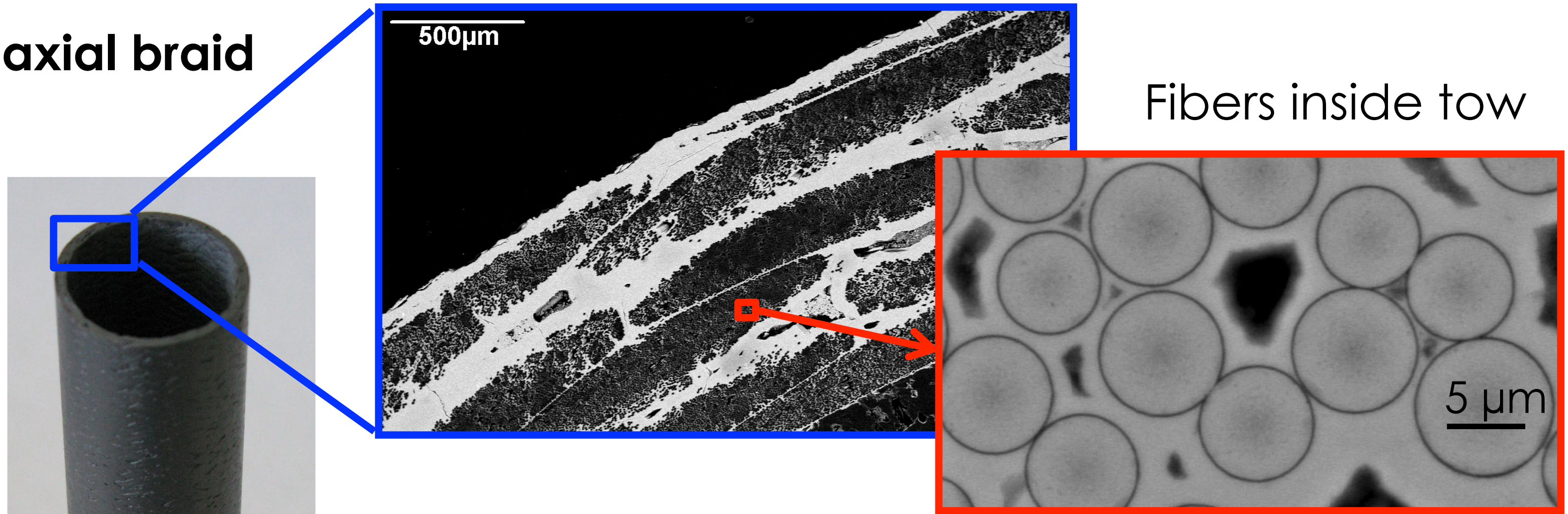


End of Process

Cylindrical Prototypes Have Been Infiltrated and Polished

Bi-axial braid

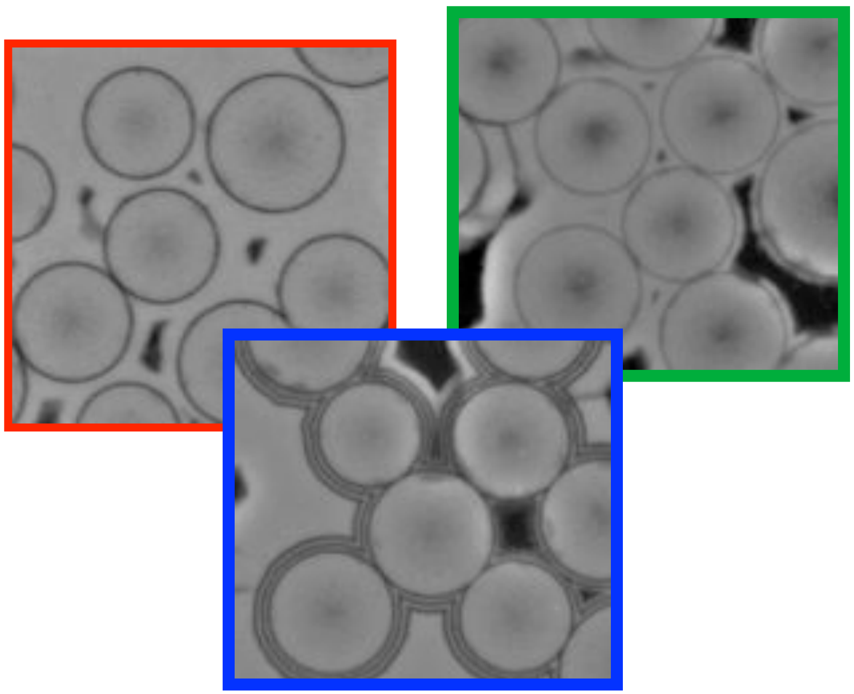
1/2 foot

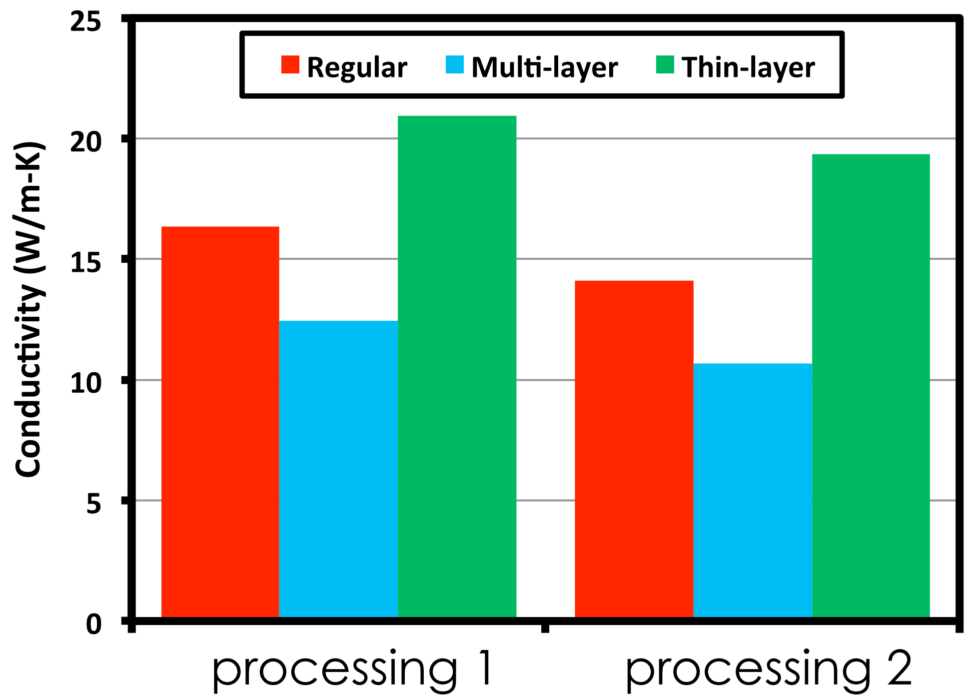


Polished Tube

GA Experiments Show Interfaces Have Strong Effect on Thermal Conductivity

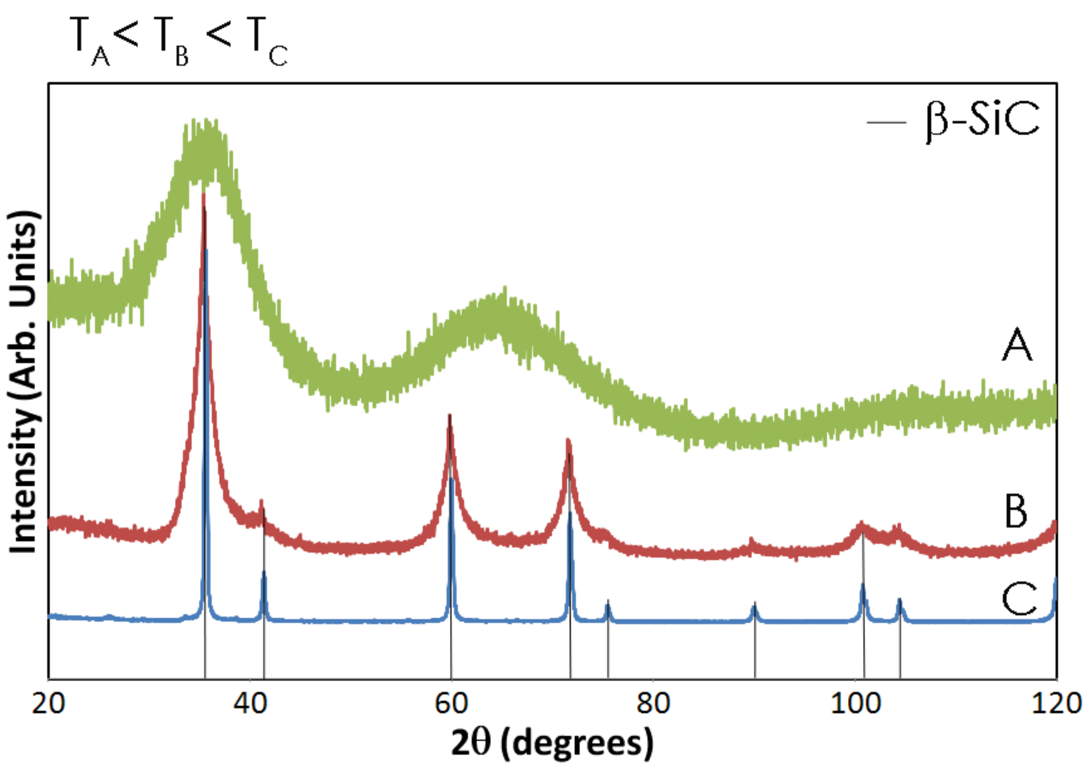
- **Multi-layer interface showed lower thermal conductivity compared to thin or regular pyrolytic carbon interface**
  - Normalized to density, multi-layer conductivity is ~24% lower than the regular interface; the thin interface is ~9% higher
- **Density differences do not account for the effect**





GA Makes Robust Joints With Polymer-derived β-SiC Material

- **Larger crystal size undergo fewer irradiation induced structural changes and amorphization than finer crystal structures**



- **XRD analysis and peak broadening evaluation**

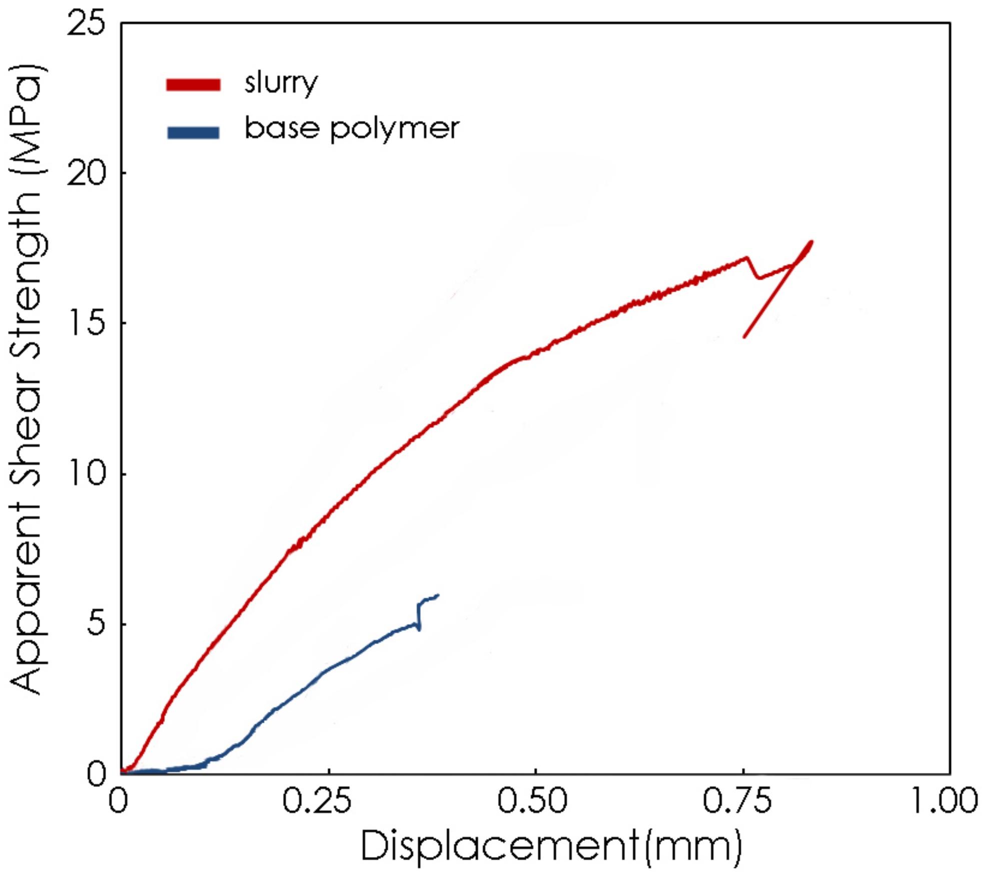
Scherrer: **$D=\lambda/(\beta\cos\theta)$**

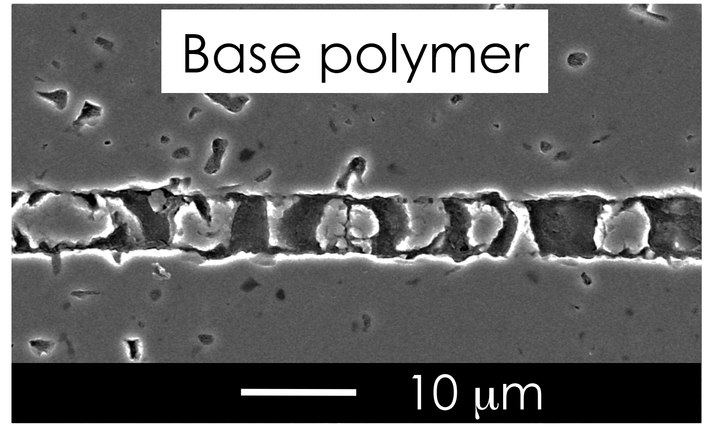
D=Crystal grain size
λ=wavelength of radiation
β=integral breadth of peak

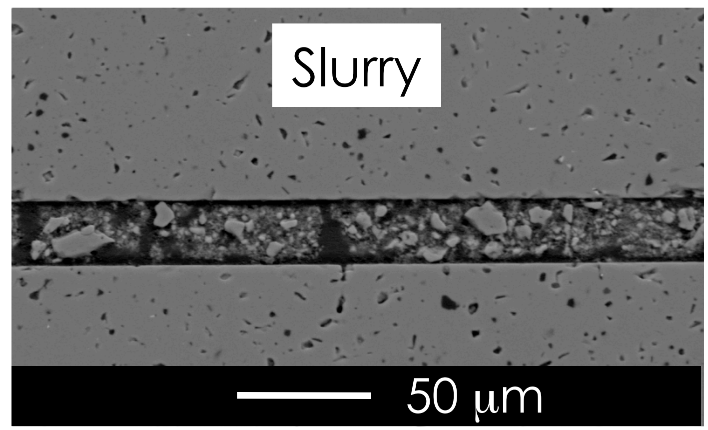
  – Control of crystal size ~10 nm at T_B to ~100 nm at T_C
  – Tyranno SA3 SiC fibers D_{avg}~100-200nm exhibit good irradiation performance

100 nm grain size is targeted for nuclear applications

The Strength of Polymer-derived Joints Can Be Enhanced by Improving Joint Density



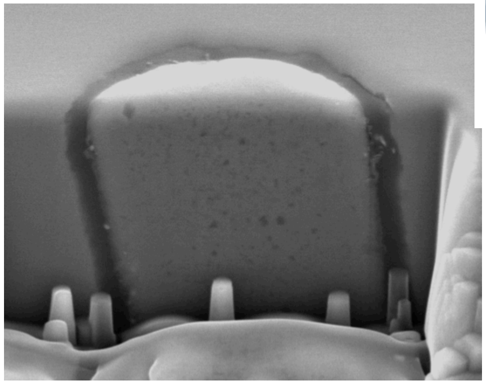




- **Use of polymer alone leads to high porosity and low joint strength**
- **Addition of SiC powder decreases porosity, crack nucleation sites**

GA is Drawing from Industry, Academia and National Labs to Meet the Technological Challenges

- **University of California, Berkeley** – Use of Focused Ion Beam and Transmission Electron Microscopy techniques to study matrix cracking

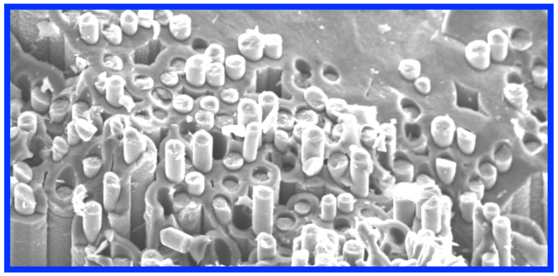


- **San Diego State University** - SiC joining through spark plasmas sintering

- **Matech** – SBIR involvement to perform characterization of fibers

SAN DIEGO STATE UNIVERSITY

MATECH GSM
Global Strategic Materials



- **University of California at San Diego** – Development of fatigue testing

- **Brookhaven National Laboratory** - 3-D X-ray tomography of SiC

BROOKHAVEN NATIONAL LABORATORY

UCSD

Contact Information

Christina A. Back

tina.back@ga.com

(858) 455-2025

This work supported by General Atomics internal funding