Printed SiC for Nuclear Applications

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TCR Fuels Thrust Lead

18 May, 2022

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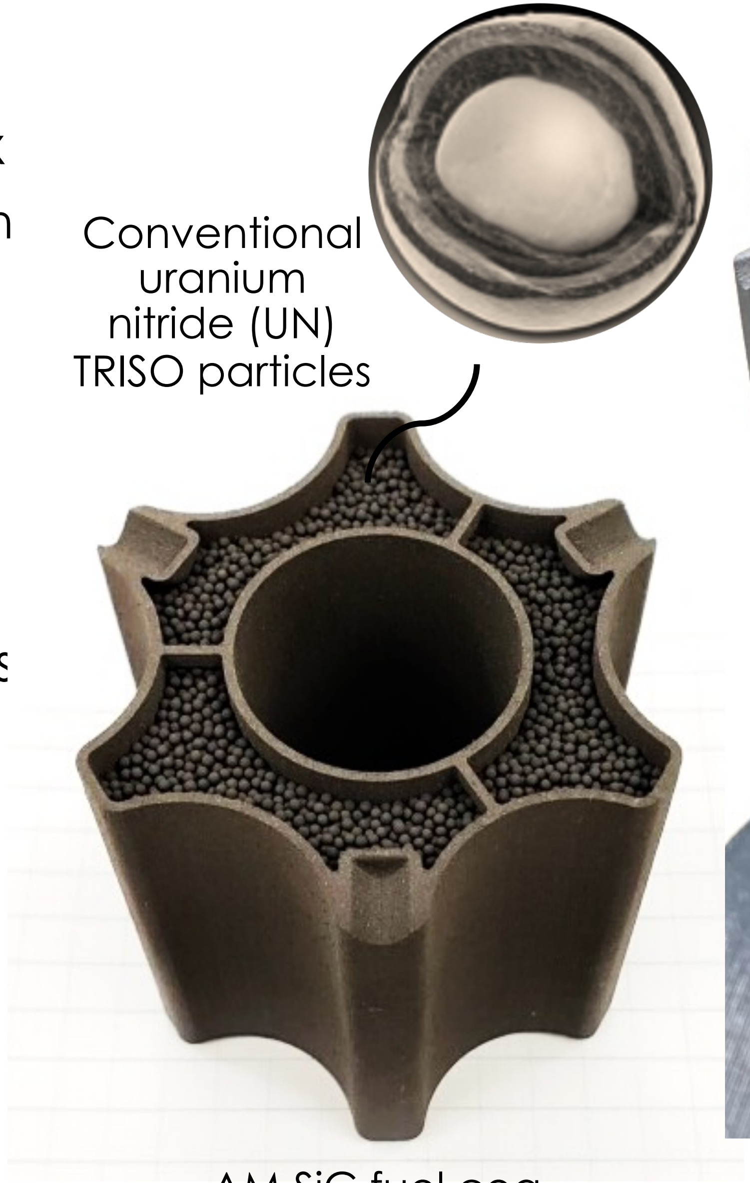
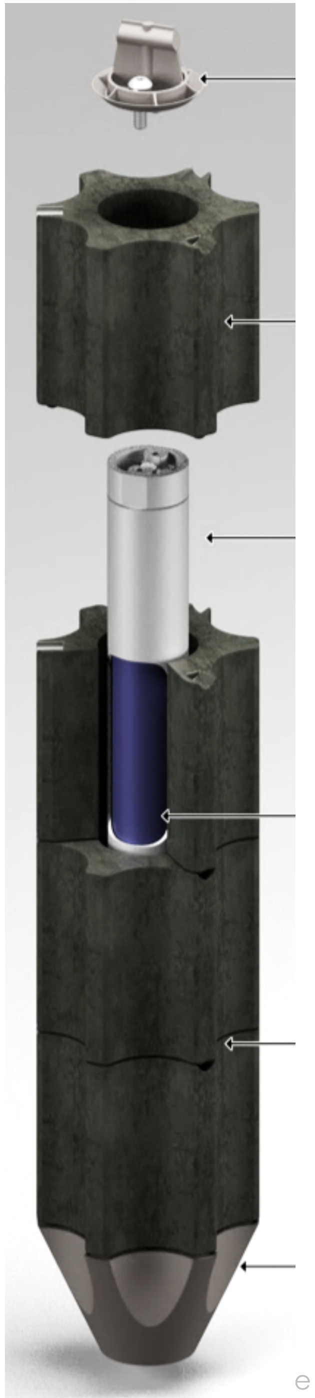
Transformational Challenge Reactor (TCR) Fuel

- Conventional UN TRISO particles in AM SiC matrix
  - Multiple barriers to fission gas release: TRISO, SiC matrix
  - Radiation-tolerant, oxidation-resistant SiC matrix
- High density of U (fuel) and H (moderator) results in compact core size
  - Large (800 μm), dense UN kernel
  - Fabrication process allows high particle packing (up to 60%)
  - AM cog shape maximizes fuel volume



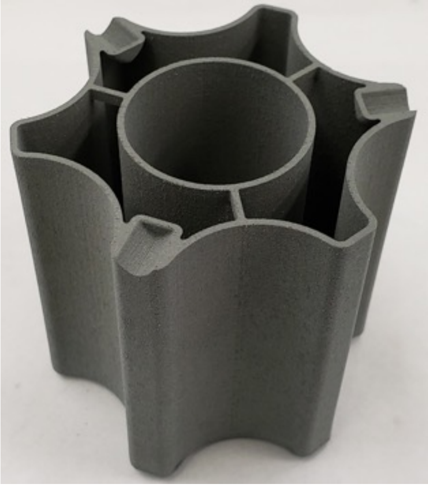
AM SiC fuel cog during fabrication

Assembled fuel element

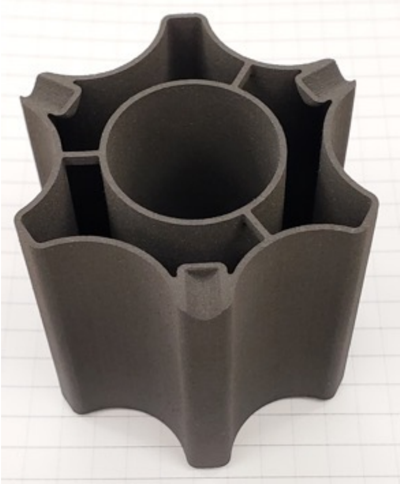


TCR Fuel Fabrication Process

Preform Fabrication (Binderjet)



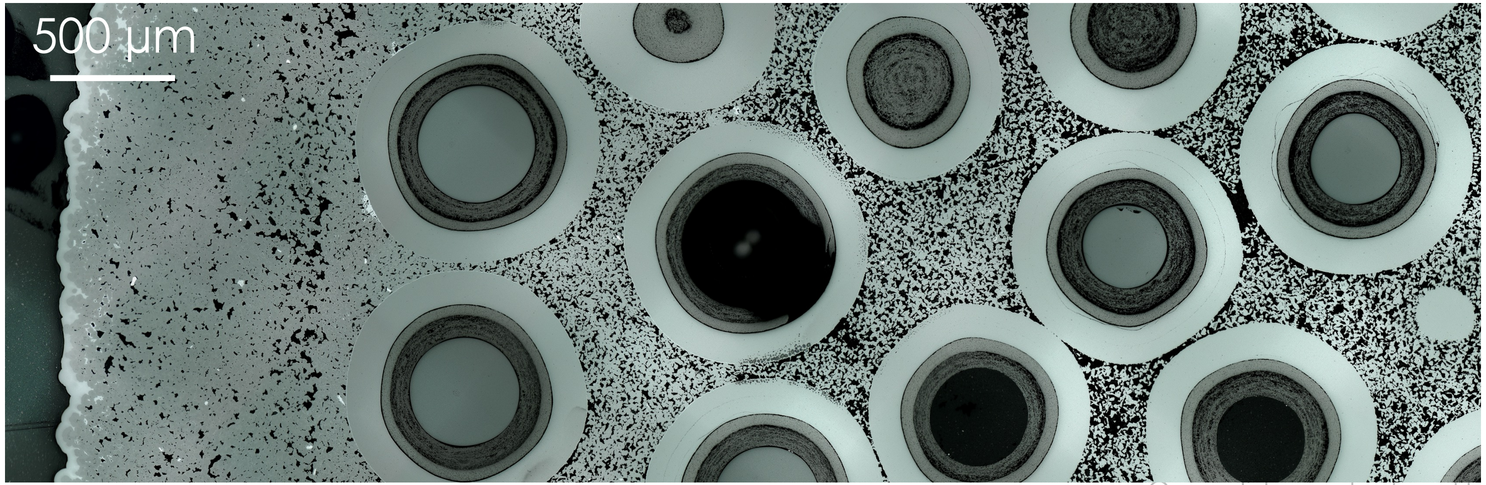
Partial Densification (CVI)



Fuel Particle and SiC powder Loading

Final Densification (CVI)

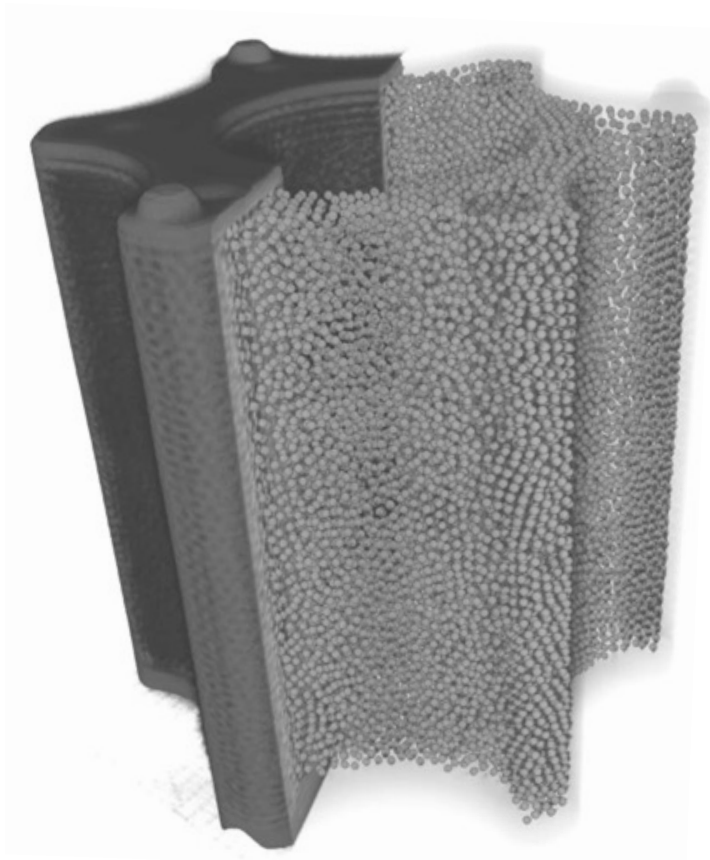
Typical microstructure of CVI SiC surrounding coated particles (surrogates)



X-ray computed tomography (XCT) provides as-fabricated particle distributions to simulate effects on neutronic/thermal hydraulic performance

Image of sectioned cog

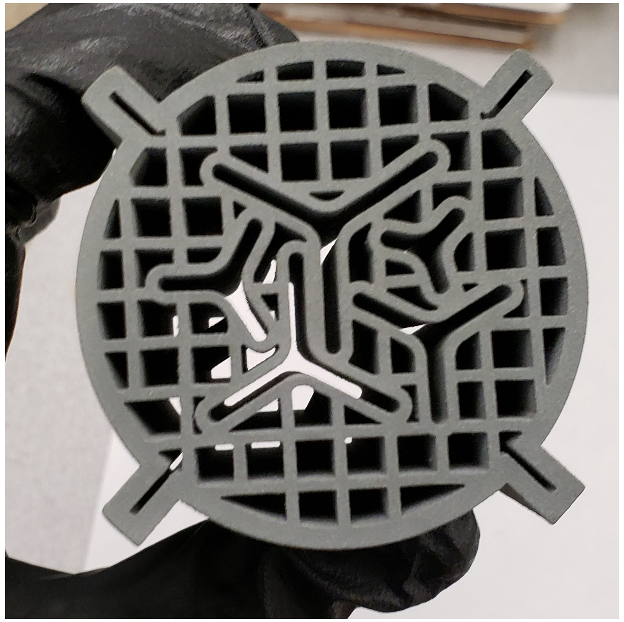
XCT visualization



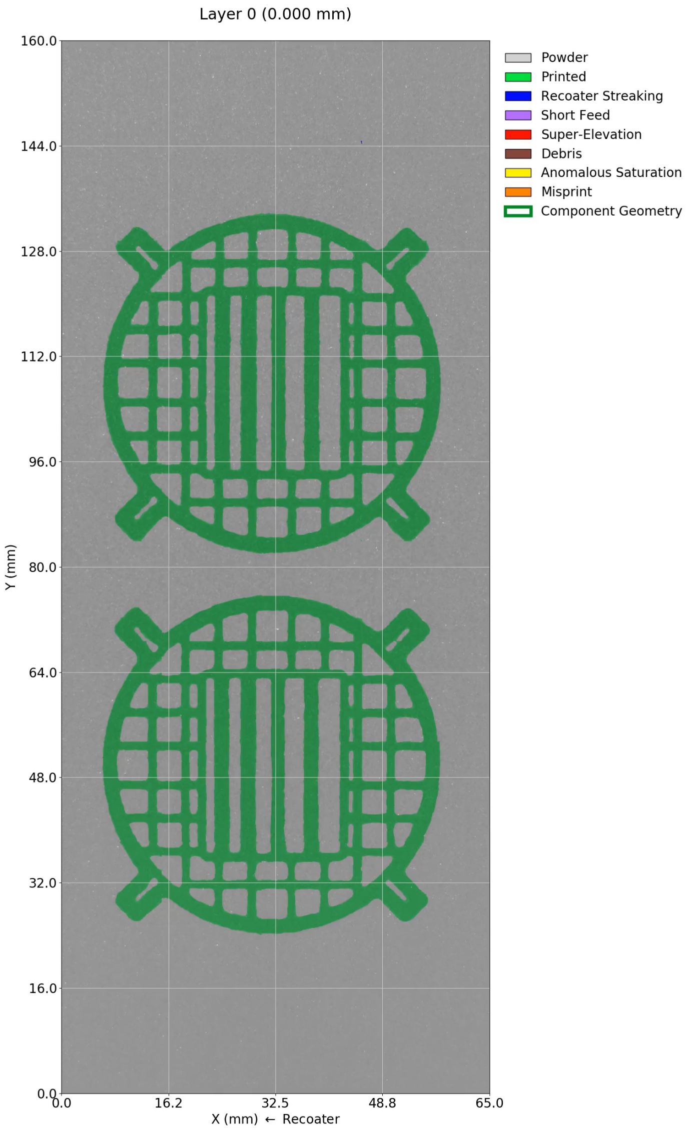
Particle locations from XCT

In situ monitoring during binder jet printing using Peregrine

- ORNL-developed software monitors printing process layer-by-layer
- Automatically identifies defects and alerts user



TCR component after binder jet (left) and CVI (right)



OAK RIDGE National Laboratory

Intellectual property developed by TCR is major component of U.S. industry fuel development and reactor demonstrations

(19) **United States**
(12) **Patent Application Publication**
Petrie et al.
(10) **Pub. No.: US 2021/0230076 A1**
(43) **Pub. Date: Jul. 29, 2021**

(54) EMBEDDING SENSORS IN 3D-PRINTED SILICON CARBIDE

(71) Applicant: **UT-Battelle, LLC**, Oak Ridge, TN (US)

(72) Inventors: **Christian M. Petrie**, Oak Ridge, TN (US); **Brian C. Jolly**, Oak Ridge, TN (US); **Kurt A. Terrani**, Oak Ridge, TN

(52) U.S. Cl.
CPC ***C04B 37/021*** (2013.01); ***C04B 35/565*** (2013.01); ***C04B 35/63*** (2013.01); ***C04B 37/042*** (2013.01); ***G01D 11/245*** (2013.01); *C04B 2237/62* (2013.01); *C04B 2235/3826* (2013.01); *C04B 2237/365* (2013.01); *C04B 2237/403* (2013.01); *C04B 2237/408* (2013.01); *C04B 2235/6026* (2013.01)

(19) **United States**
(12) **Patent Application Publication**
Terrani et al.
(10) **Pub. No.: US 2021/0158978 A1**
(43) **Pub. Date: May 27, 2021**

(54) 3D PRINTING OF ADDITIVE STRUCTURES FOR NUCLEAR FUELS

(71) Applicant: **UT-Battelle, LLC**, Oak Ridge, TN (US)

(72) Inventors: **Kurt A. Terrani**, Oak Ridge, TN (US); **Andrew T. Nelson**, Oak Ridge, TN

B33Y 80/00 (2006.01)
G21C 21/02 (2006.01)
G21C 3/62 (2006.01)

(52) U.S. Cl.
CPC ***G21C 3/048*** (2019.01); ***B33Y 10/00*** (2014.12); ***G21C 3/623*** (2013.01); ***G21C 21/02*** (2013.01); ***B33Y 80/00*** (2014.12)

(19) **United States**
(12) **Patent Application Publication**
Terrani et al.
(10) **Pub. No.: US 2020/0156282 A1**
(43) **Pub. Date: May 21, 2020**

(54) ADDITIVE MANUFACTURING OF COMPLEX OBJECTS USING REFRACTORY MATRIX MATERIALS

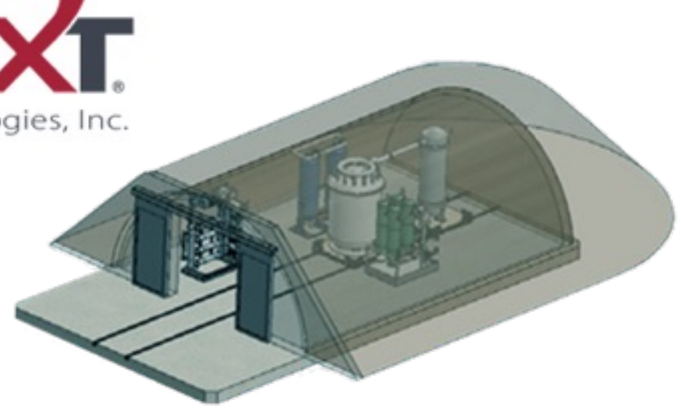
(71) Applicant: **UT-Battelle, LLC**, Oak Ridge, TN (US)

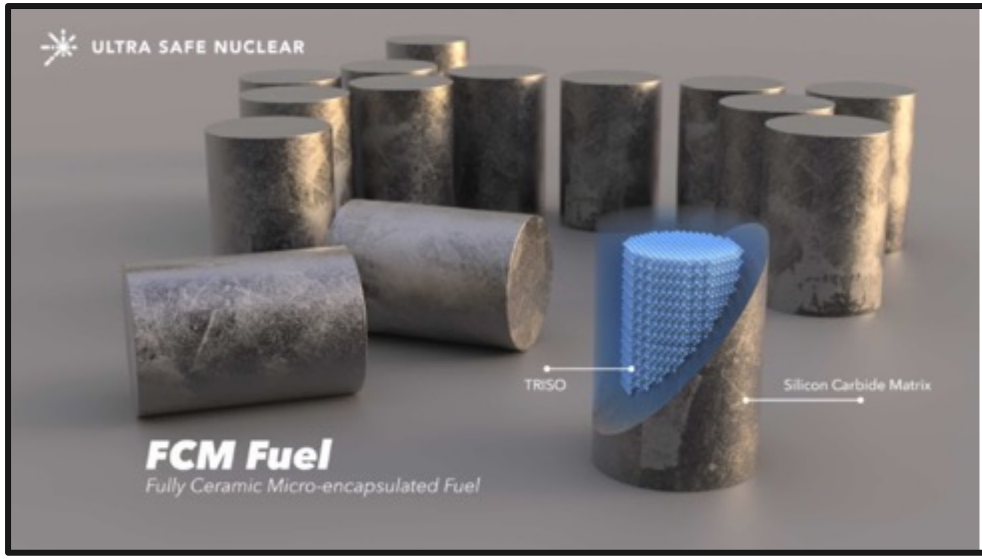
(72) Inventors: **Kurt A. Terrani**, Knoxville, TN (US); **Michael P. Trammell**, Knoxville, TN (US); **Brian C. Jolly**, Knoxville, TN

(52) U.S. Cl.
CPC ***B28B 1/001*** (2013.01); ***B22F 7/02*** (2013.01); ***B22F 3/1021*** (2013.01); ***B22F 3/1007*** (2013.01); ***C04B 35/573*** (2013.01); ***G21C 3/324*** (2013.01); *C04B 2235/614* (2013.01); ***C04B 35/52*** (2013.01); *B22F 2302/105* (2013.01); *B22F 2998/10* (2013.01); *B22F 2301/20* (2013.01); *C04B 2235/77* (2013.01); ***C04B 35/5622*** (2013.01)

BWXT ARDP BANR design will utilize TCR's fuel fabrication process to achieve fuel packing fractions significantly higher than traditional TRISO

BWXT
BWX Technologies, Inc.





Ultra Safe Nuclear has licensed TCR intellectual property and is constructing a fuel fabrication facility in Oak Ridge, TN

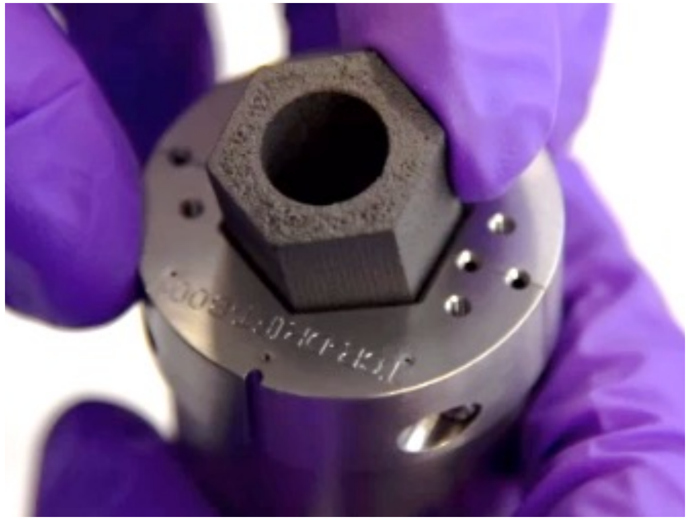
Integral and separate effects irradiation testing of AM fuels and materials at ORNL, INL, and MIT

	Purpose	Separate Effects		Integral Effects
		Core and Matrix	Fuel Particle	Fuel Element
ORNL HFIR	Steady-state dose/burnup accumulation	AM SiC AM 316L YH_x	Loose UN TRISO particles (MiniFuel)	UN TRISO particles in a mini AM SiC compact (MiniFuel)
MIT NRL	Fission gas retention at low burnup		Loose UN kernels Loose UN TRISO particles	UN TRISO particles in a mini AM SiC compact
INL TREAT	Integral fuel performance during transient over-power			Transient pulsed irradiation of UN TRISO particles in a mini AM SiC compact

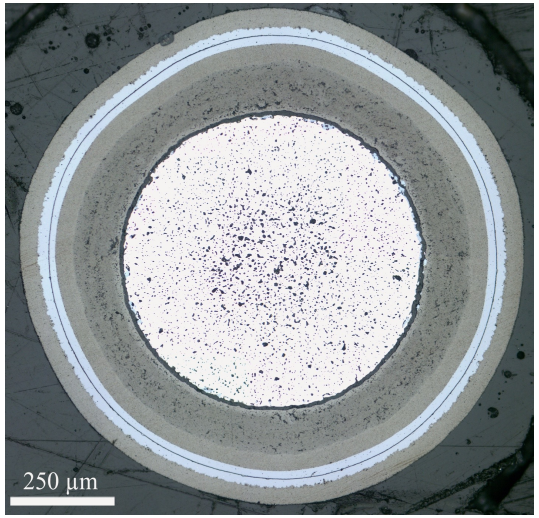
Assembly of MITR test of integral fuel compacts

AM SiC HFIR samples

HFIR-irradiated AM 316L

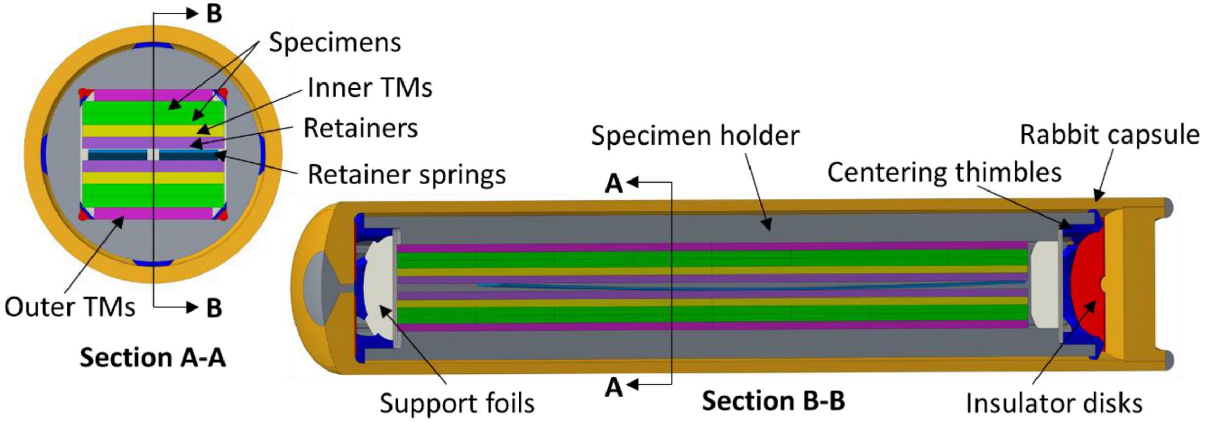


Assembly of TREAT test of integral UN TRISO particles in AM SiC compacts

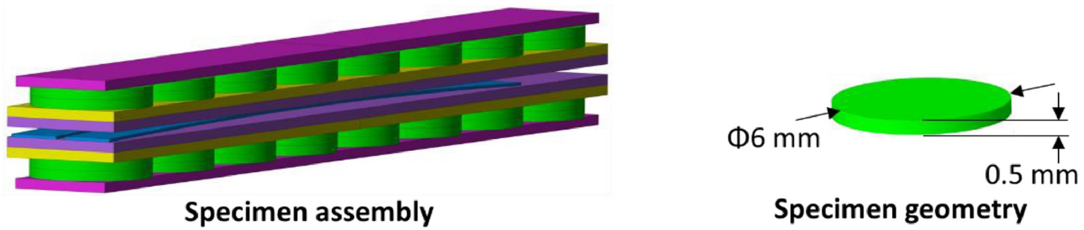


HFIR-irradiated UN TRISO

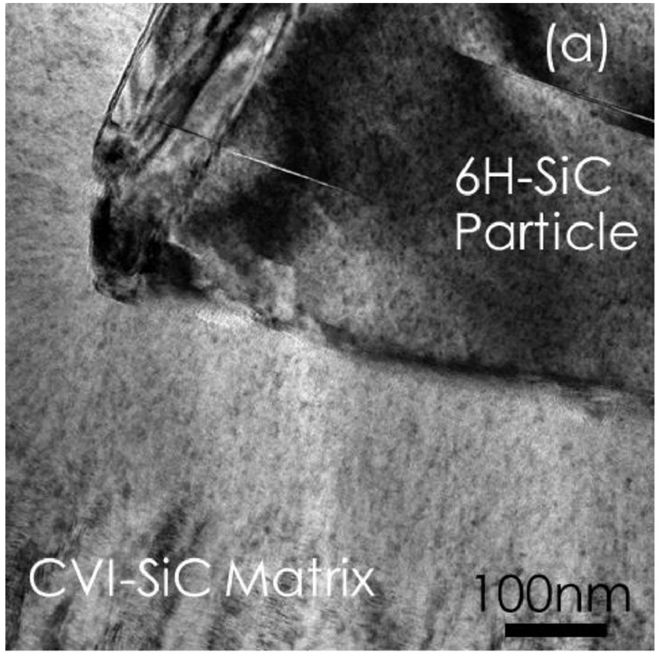
2.3 dpa HFIR irradiation of AM SiC



HFIR capsule design



Post-irradiation STEM-BF image showing black spot damage in 6H-SiC particle but no defects in CVI SiC

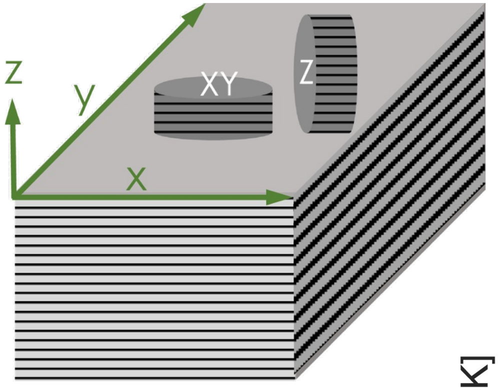


Minimal change in strength or Weibull modulus after irradiation

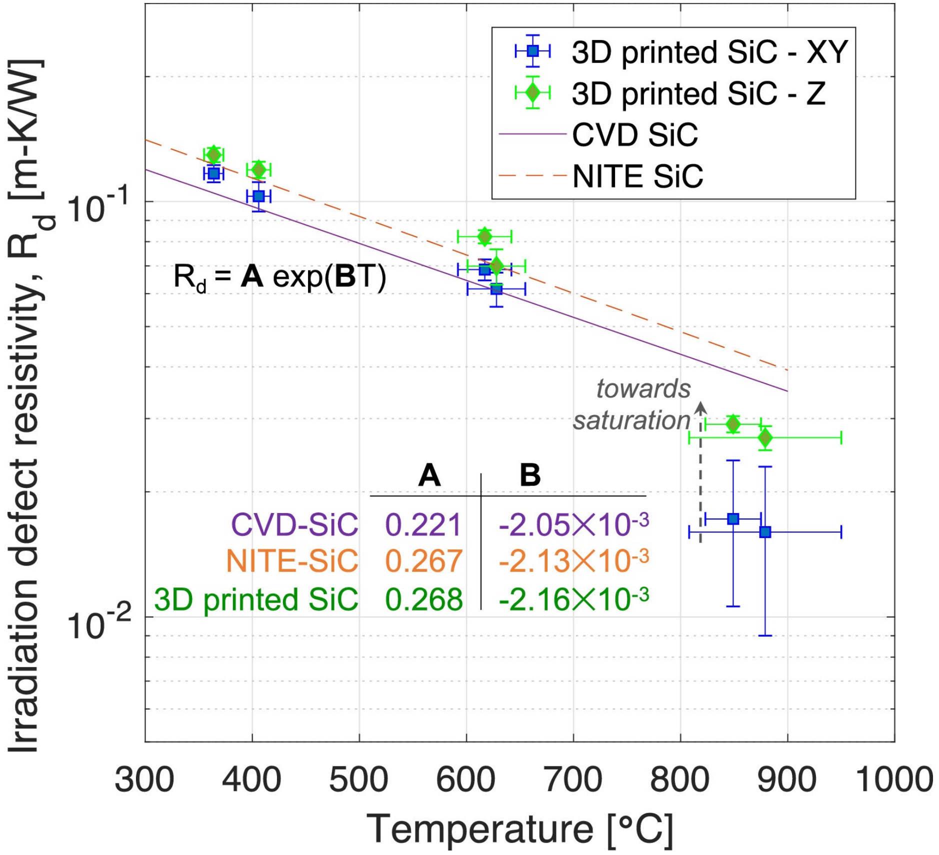
Irradiation temperature	Orientation	Characteristic strength [MPa]	Weibull modulus	Number of tests
Unirradiated	XY	264	8	23
	Z	274	13	7
406 ± 11 °C	XY	266	9	7
	Z	276	5	8
628 ± 27 °C	XY	289	7	8
	Z	258	10	8
879 ± 71 °C	XY	283	9	7
	Z	276	21	8

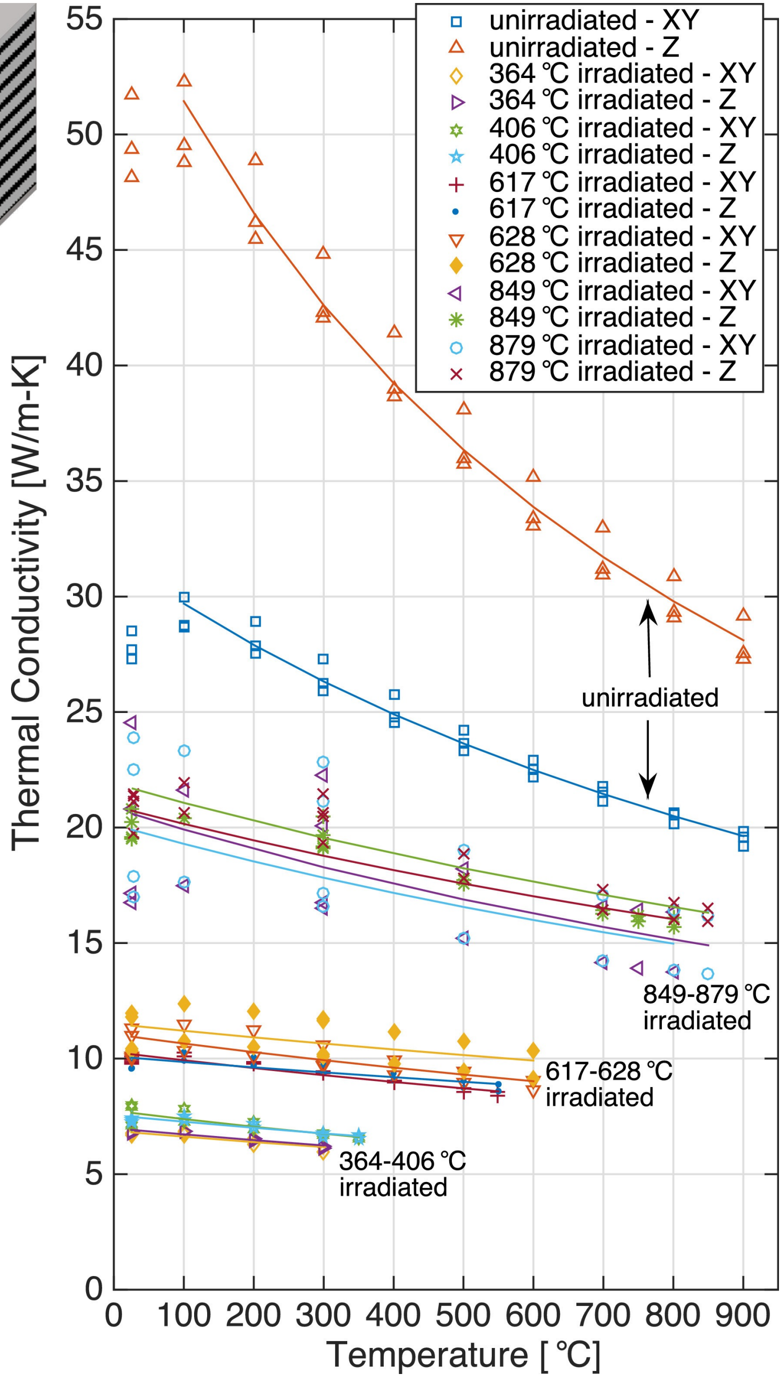
Terrani, K. A., et al. "Irradiation stability and thermomechanical properties of 3D-printed SiC." *J. Nucl. Mat.* **551** (2021) 152980.

Neutron radiation effects on AM SiC thermal properties



- Initial anisotropy disappears after irradiation
- Irradiation defect resistivity (change in inverse thermal conductivity) consistent with reference CVD and NITE SiC

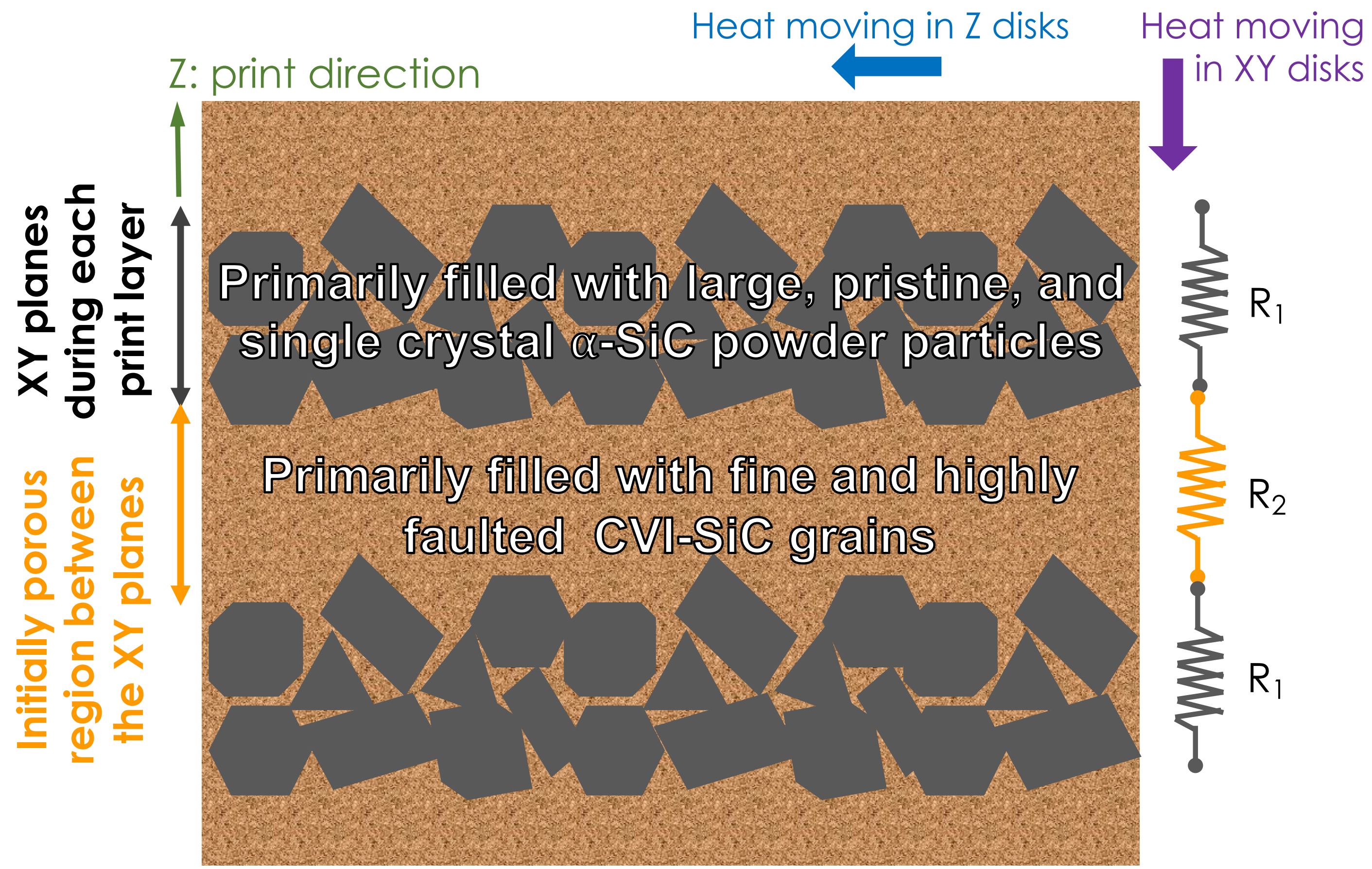


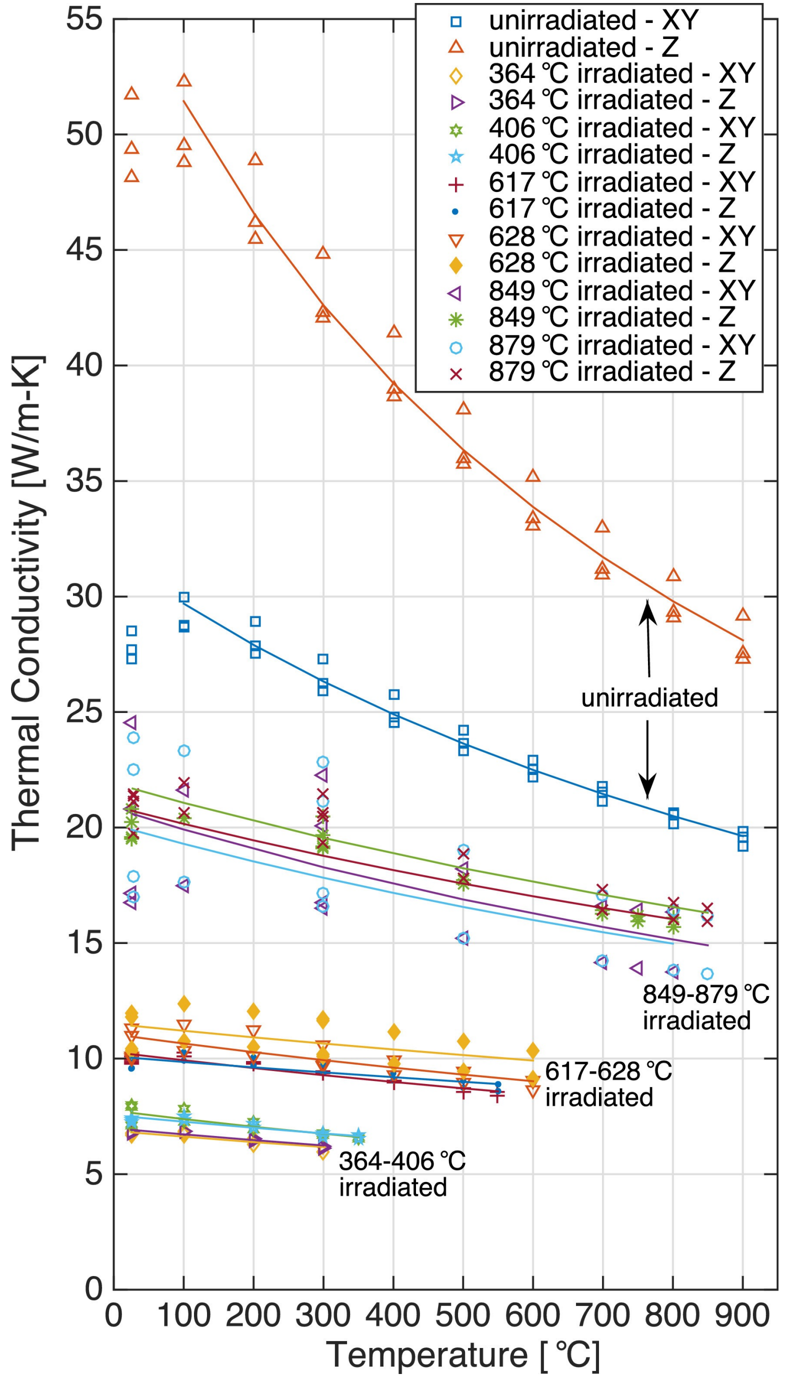


Terrani, K. A., et al. "Irradiation stability and thermomechanical properties of 3D-printed SiC." *J. Nucl. Mat.* **551** (2021) 152980.

Neutron radiation effects on AM SiC thermal properties

- Competition between phonon scattering in highly faulted CVI regions vs. irradiation defect resistivity





Terrani, K. A., et al. "Irradiation stability and thermomechanical properties of 3D-printed SiC." *J. Nucl. Mat.* **551** (2021) 152980.

Irradiation testing of integral TCR fuel compacts

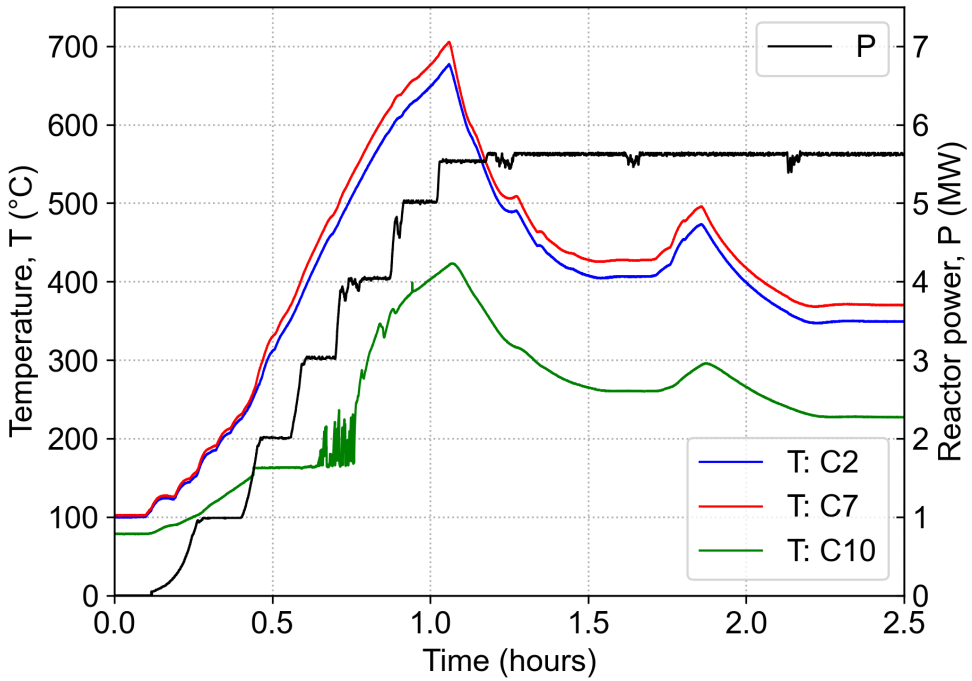
- Series of low burnup tests in MITR to evaluate fission gas retention
  - Bare UCN kernels
  - Loose UCN TRISO
  - Integral compacts with UCN TRISO in AM SiC
- Fission gas release (FGR) from UCN TRISO not expected but was observed from integral compacts with simultaneous nuclear + electrical heating and high temperature ramp rates

Summary of irradiation tests

Test	Fuel	Heating	Thermal neutron fluence (10^{18} n/cm^2)	Steady-state temperatures	Typical temperature ramp rate	Fission gas release?
2PH1-BARE	Bare UCN	Nuclear	0.03	No logged temperature data		Yes
2PH1-TRISO	Loose UCN TRISO					No
3GV-COMP1a	Compacts C1, C3, C8		1.01	131–171 °C	1–2 °C/min	
3GV-COMP1b			0.14	178–236 °C		
3GV-COMP1c			1.11	175–231 °C		
3GV-COMP2	Compacts C2, C7, C10	Nuclear + electrical	1.09	228–365 °C, briefly >700 °C	10–11 °C/min	Yes
3GV-COMP3	Compacts C4, C5, C9		1.24	727–749 °C	1–4 °C/min	No
3GV-TRISO1	Loose UCN TRISO		1.05	325–350 °C	7–8 °C/min	
3GV-TRISO2			1.10	670–750 °C	6–7 °C/min	

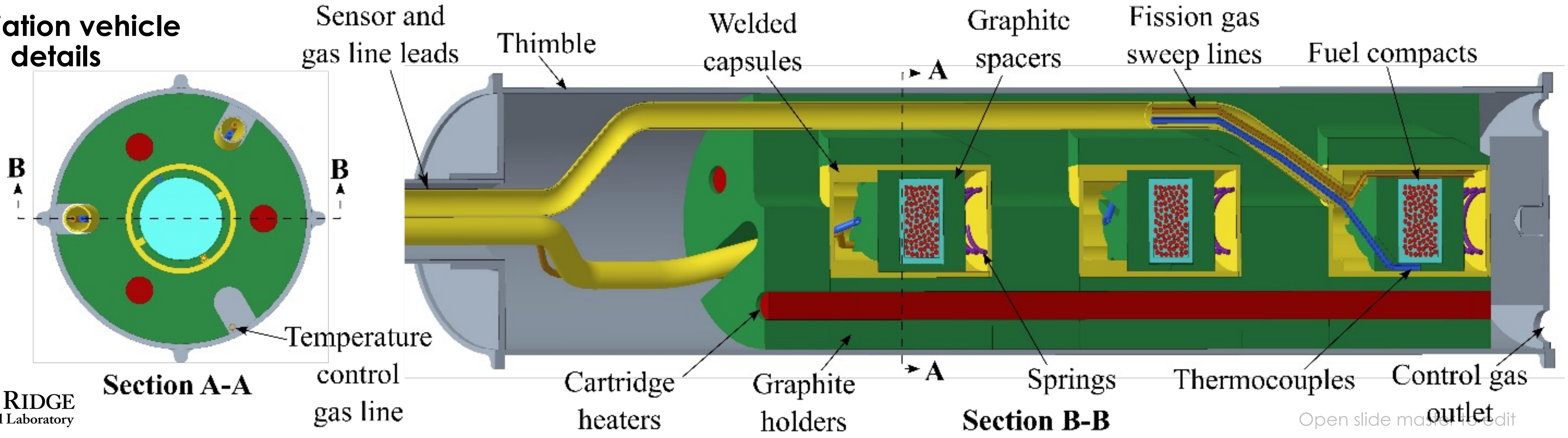
Details from test that showed FGR

- Compacts had ~1400 particles, average matrix density ~86% of theoretical, and ~50% particle packing fraction
- Fission gas sampled independently in all three capsules
- Temperature ramped quickly to ~700°C then backed down to 227–370°C (due to issues with heaters) and held for 24 hours
- One thermocouple also showed erratic behavior during initial temperature ramp

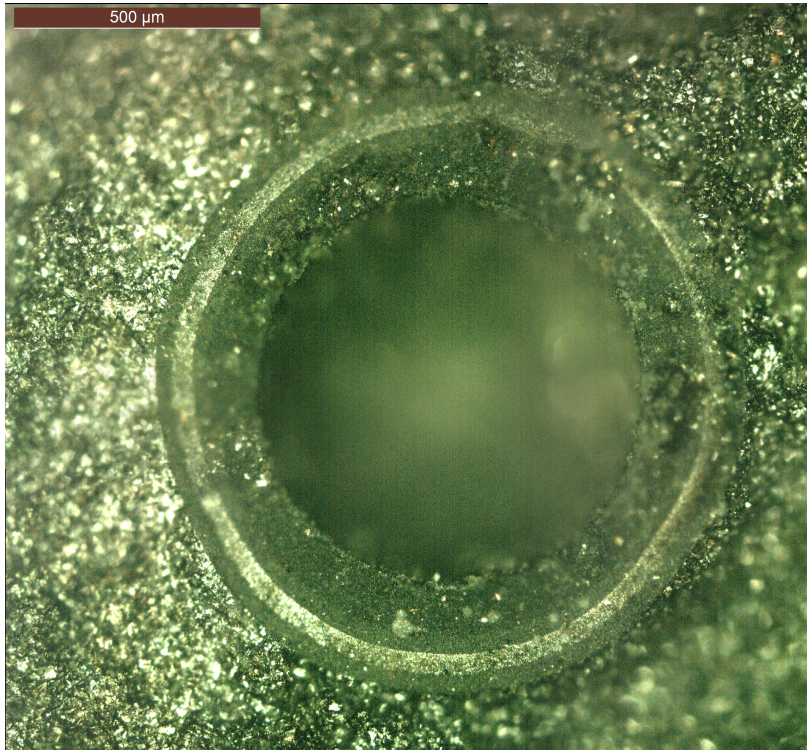


Temperature transient at start of test

Irradiation vehicle details



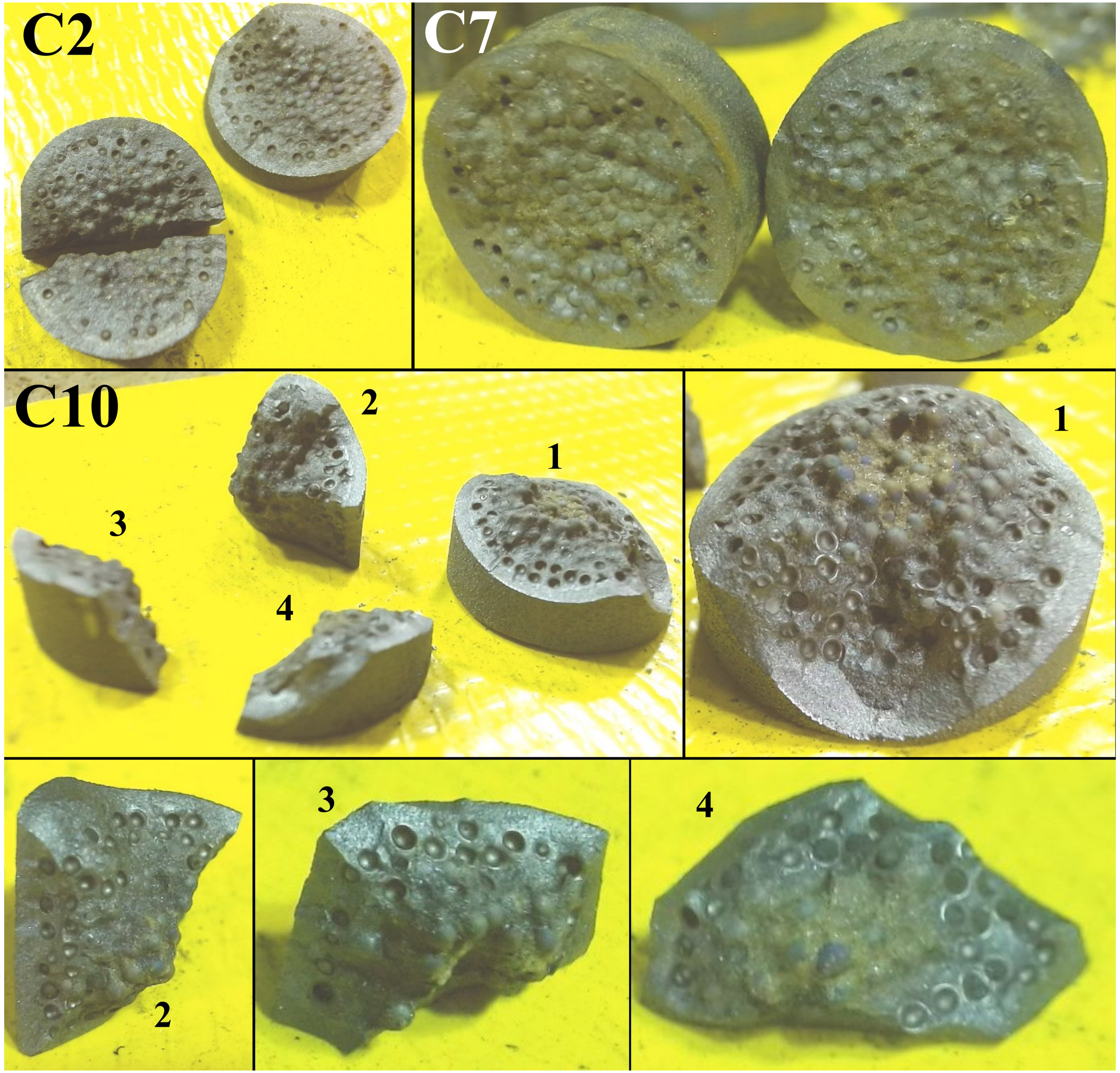
Post-irradiation examination



Crack propagation through coating layers

Summary of FGR measurements

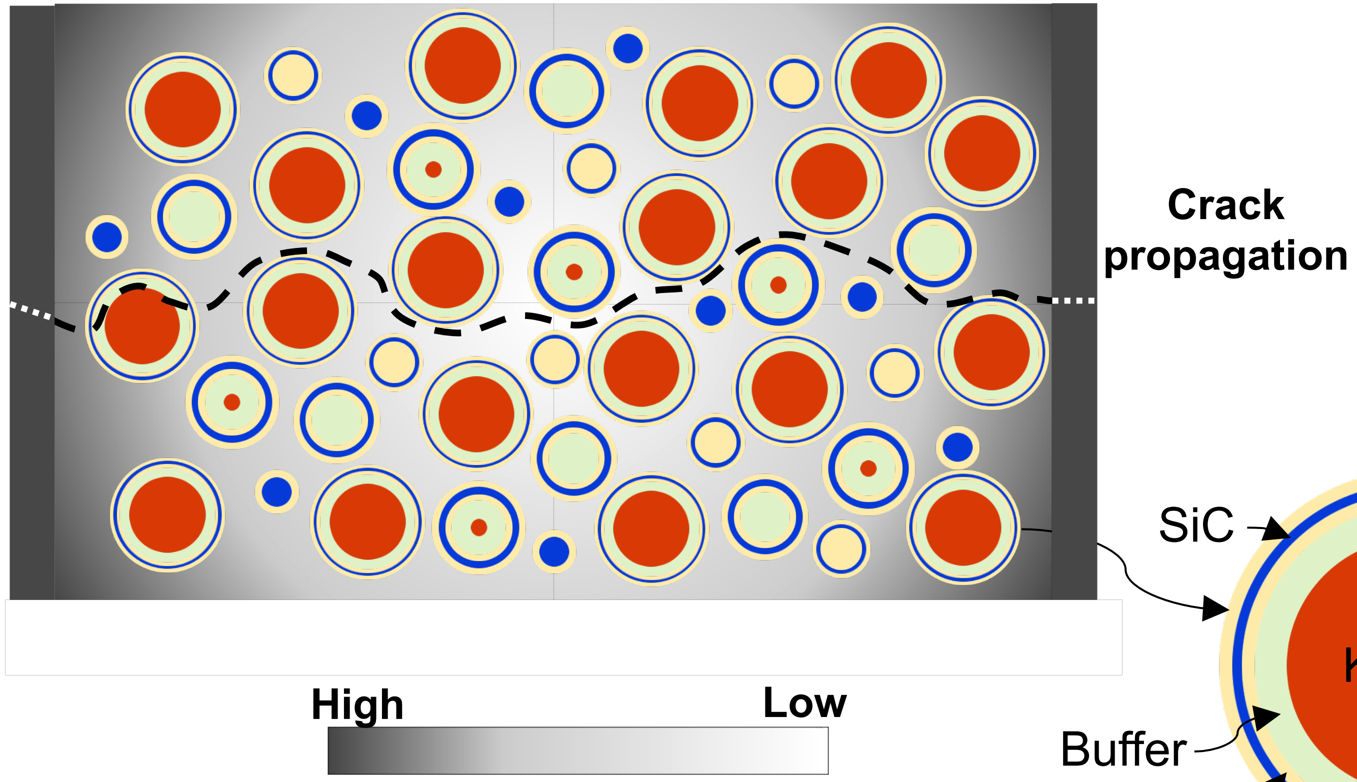
Parameter	C2	C7	C10
Measured ^{85}Kr release (µCi)	0.02	0.01	0.19
Calculated ^{85}Kr inventory (µCi)	38	38	38
Measured ^{85}Kr release (%)	0.05%	0.03%	0.50%
Calculated particle failures	51.3	25.7	494.1

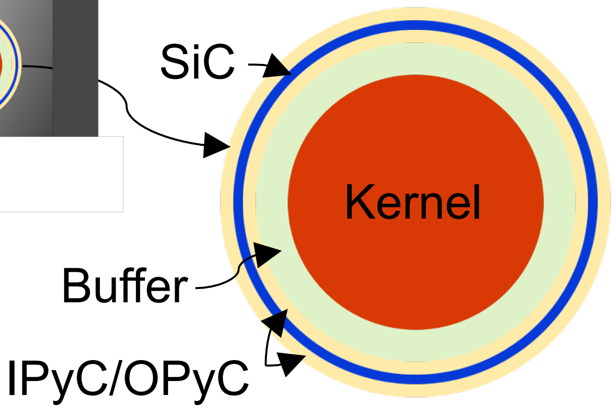


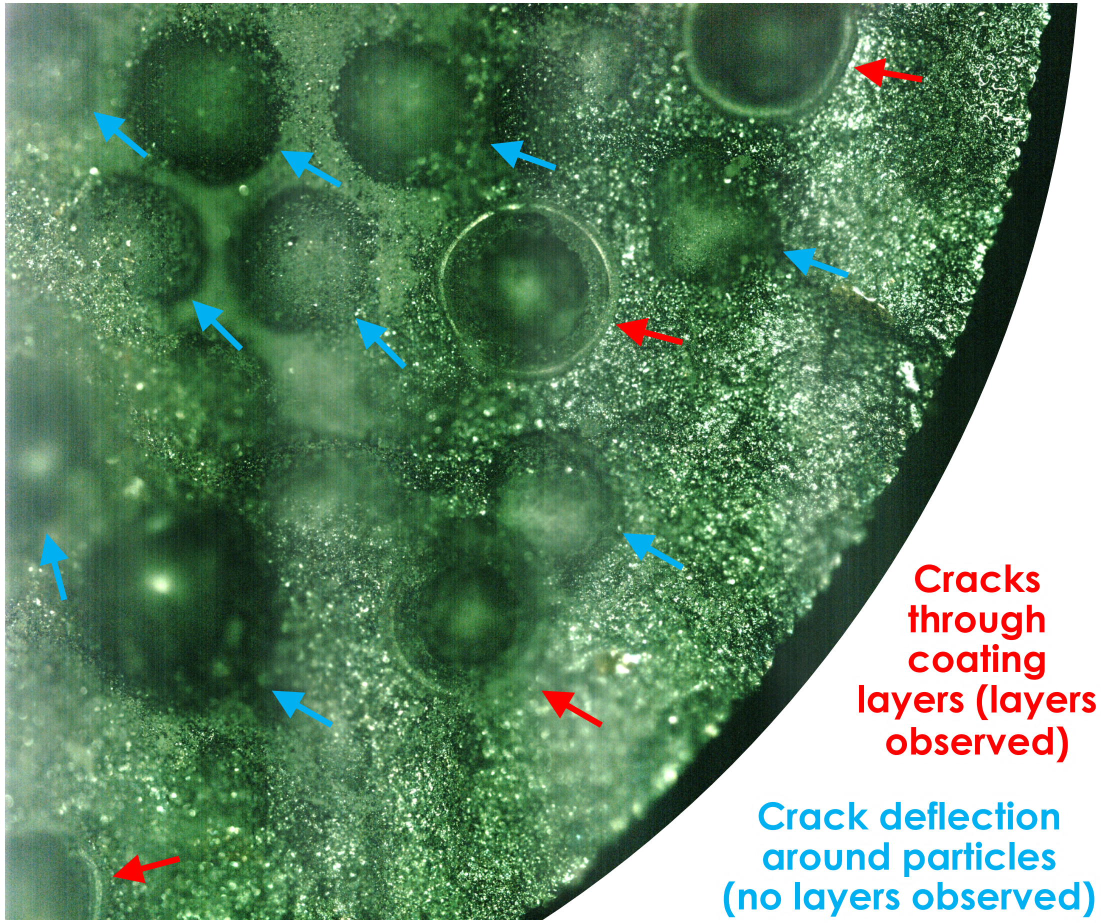
Post-irradiation images of compacts with closer views of each of the four large fragments from C10.

Crack propagation

- Crack propagated through particle coating layers only in the outer region with higher matrix density
- Suggests crack can deflect around particles when matrix is porous



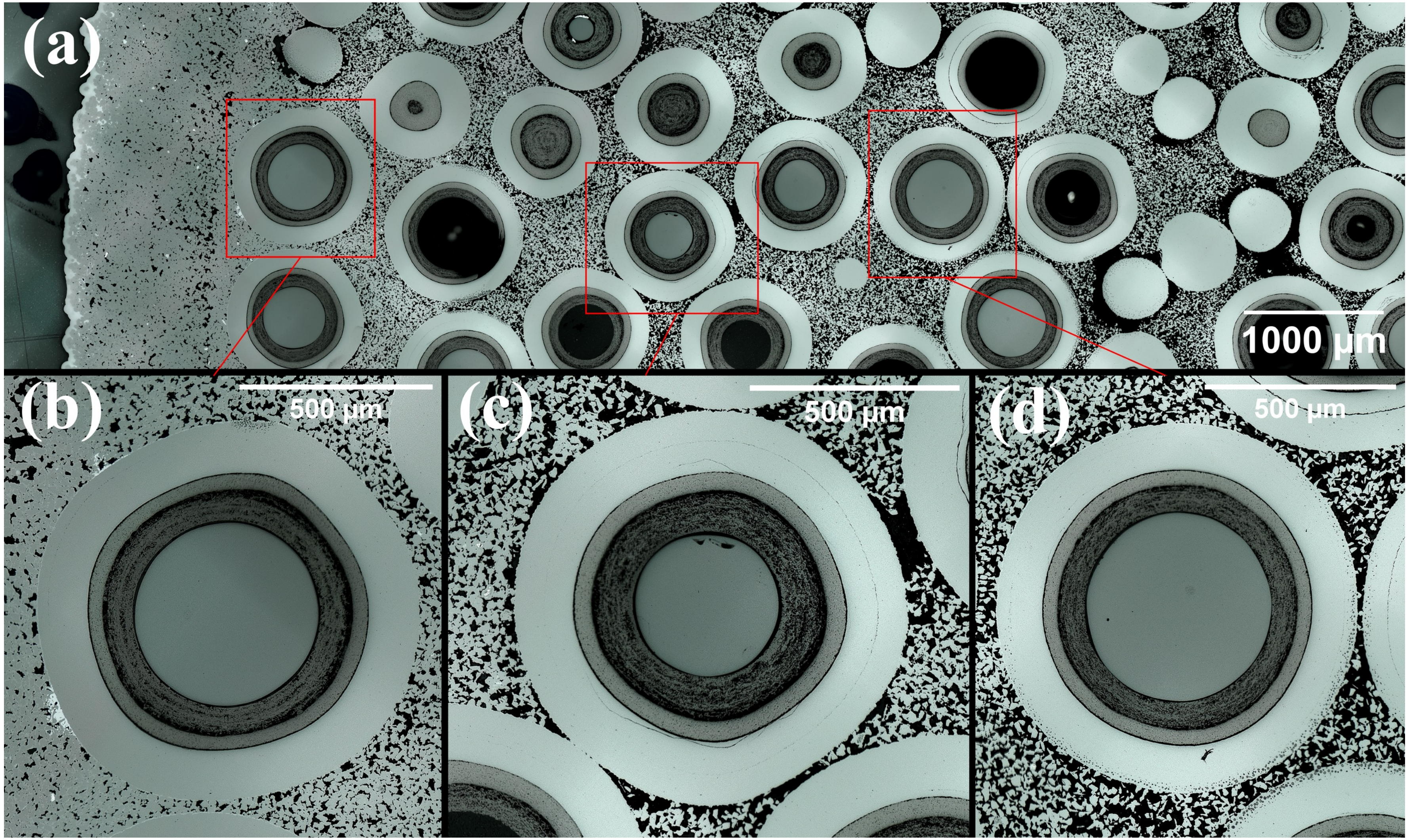




Higher magnification image showing crack propagation through compact C7

Implications

- **FGR was clearly a result of SiC matrix cracking that propagated through the TRISO coatings, which was not expected**
- The fact that the coating failures only occurred on the outer particle ring is consistent with higher matrix densities in this region



Optical images of transverse section of surrogate fuel compact

  - **Not observed previously when using graphite matrices or hot-pressed SiC matrices**
  - Suggests that strong particle/matrix interfaces may not be desirable
  - Future work will focus on process modifications to prevent crack propagation through the TRISO coatings

Summary and conclusions

- The SiC AM process developed under TCR has extraordinary potential
  - Highly complex geometries
  - High-purity crystalline SiC
  - Retains radiation resistance of traditional CVD SiC
  - Demonstrated potential for integrating fuel and sensors
- However, we need to continue to understand the limitations and potential failure modes
  - CVI has limitations in maximum component thickness but this could be mitigated through proper engineering design (i.e., channels to improve infiltration)
  - Matrix density and TRISO particle/matrix interface clearly has implications on TRISO particle failure modes, including fission gas retention
- Industry interest remains high as evidenced by USNC's licensing of TCR technology and BWXT's ARDP focusing specifically on the TCR fuel form

Questions?

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