Advanced Methods for Manufacturing

DEC 2 – 3, 2020

Performance of SiC-SiC Cladding and Endplug Joints under Neutron Irradiation with a Thermal Gradient

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Project Number: 17-12573
Award Dates: 10/2017 to 9/2021

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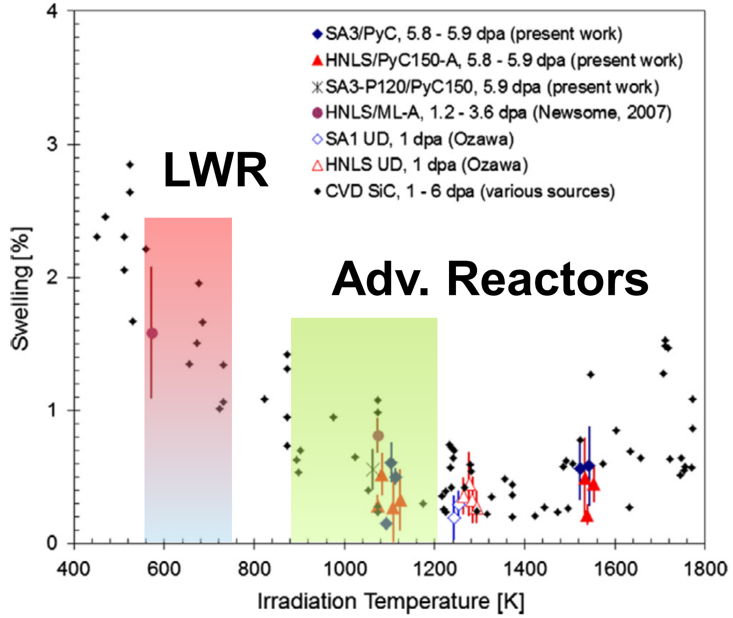
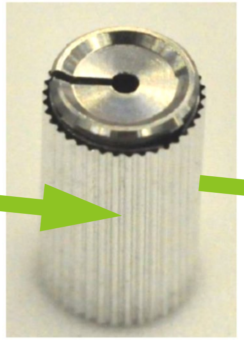
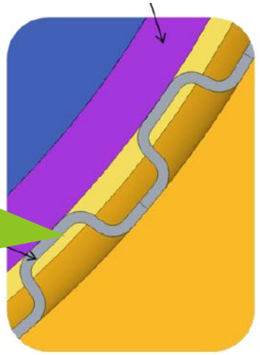
SiC-SiC Cladding Undergoes Temperature-Dependent Swelling Under Irradiation

- SiC irradiation-induced swelling stabilizes at ~1-2 dpa
  - Temperature dependent (higher at lower temps)
  - Inverse relationship with thermal conductivity
  - Highly dependent on purity
- Previous ORNL NSUF project to observe effects of temperature gradient irradiations
  - Thermal expansion and irradiation induced-swelling
  - Internal Mo-heater to obtain representative heat flux
- ORNL PIE measurements of residual stresses, swelling, mechanical and thermal properties



SiC-SiC Tube specimens

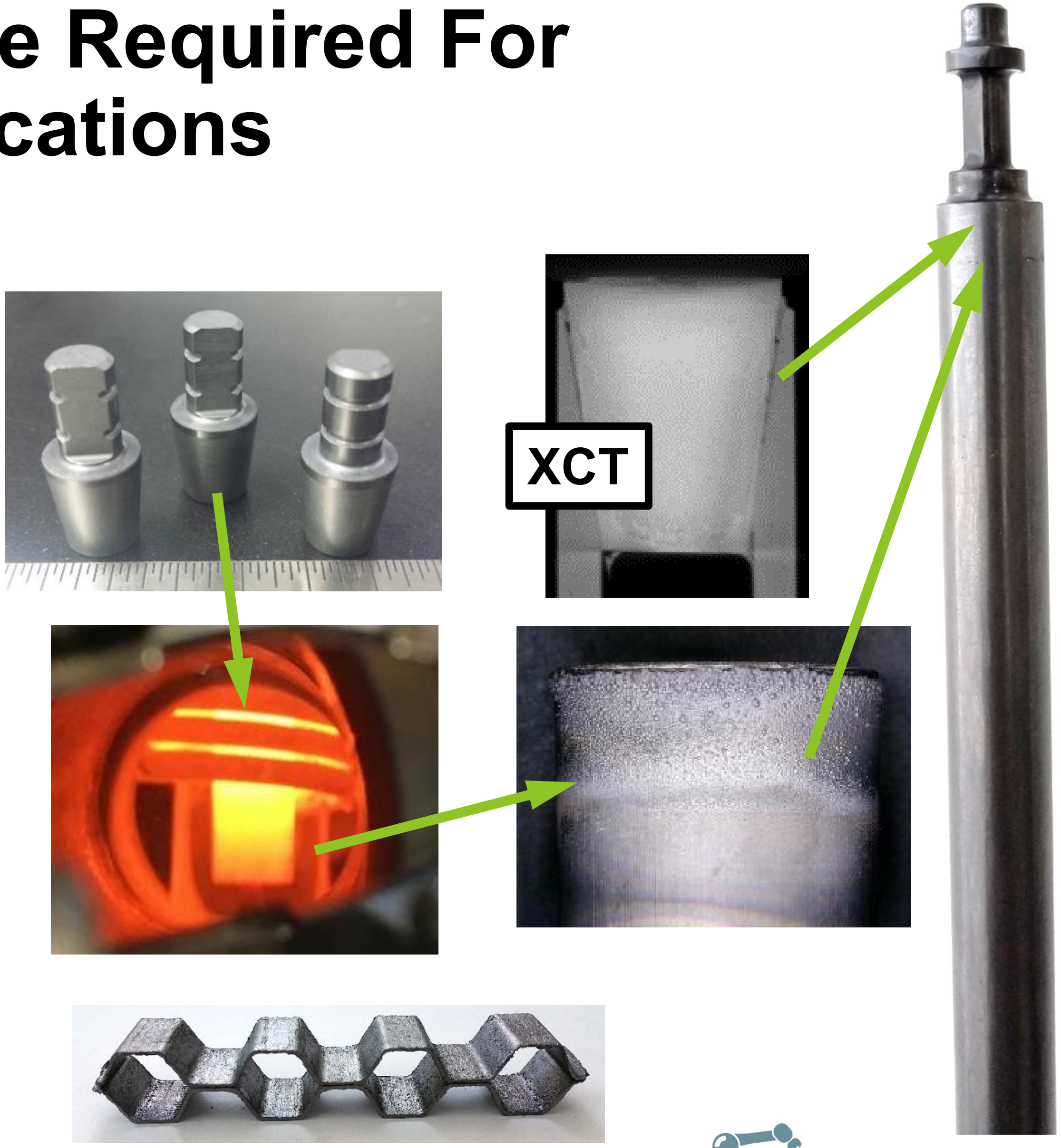


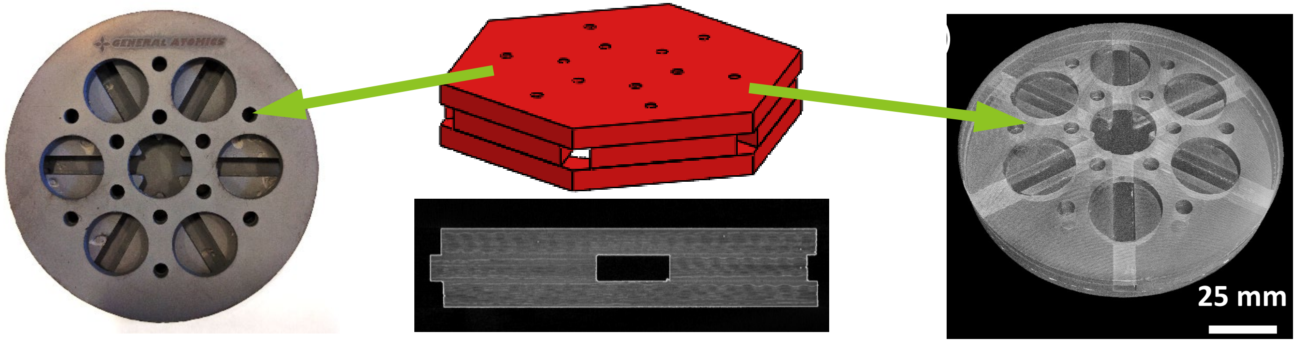


Y. Katoh et al. / Journal of Nuclear Materials 448 (2014) 448–476

Irradiation-Resistant Joints Are Required For Cladding And Structural Applications

- SiC joining methods are required for many SiC applications
  - Cladding endplugs must be sealed
  - Accident tolerant spacer grids
  - Attachments for control rods, etc.
  - Manifold structures, heat exchangers, etc.





Project Objectives

- A bonding material for SiC joints must be:
  - Irradiation and corrosion resistant
  - Retain strength and hermeticity to high temperatures
  - Withstand thermal gradients through joint
  - Processing compatible with joint geometry

Project Objectives:

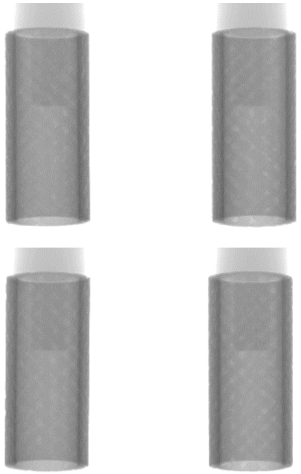
- *Obtain critical performance data for SiC joints:*
  - *Under irradiation,*
  - *In representative thermal conditions,*
  - *In representative joint geometries*
- *Provide material property data to enable more accurate modeling of joints in SiC-based components*

Joint Test Matrix Investigates Promising Joint Formulations In Representative Conditions

- Three SiC joint formulations
  - Transient Eutectic Phase (TEP) joint
  - Oxide-based SiC joint (CA: Calcia-Alumina)
  - Hybrid (HSiC) joint (pre-ceramic polymer+CVD)

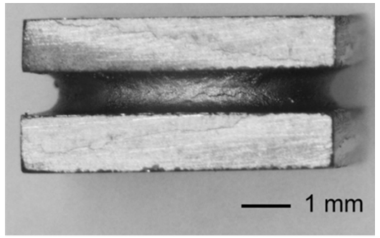
- Three tests for temperature and irradiation effects
  - Double-notch shear for high temp strength
  - Tube-endplug and torsion for irradiation

- Irradiation at two temperatures:
  - Prototypic LWR (~350ºC)
  - Prototypic Advanced Reactor (~750ºC) GFR, HTGR, molten salt, etc.

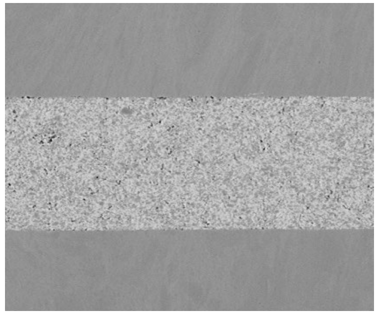


Tube-Endplug

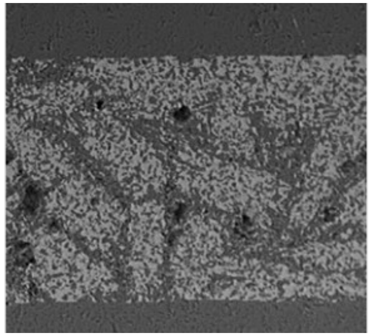
Double-Notch Shear



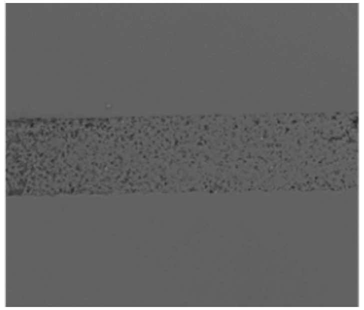
Torsion Joint



TEP SiC Joint



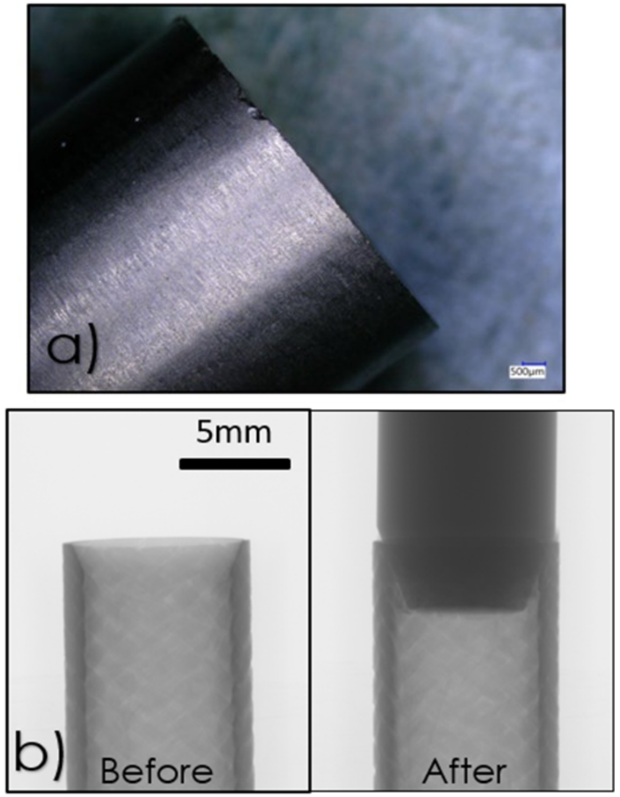
Oxide SiC Joint

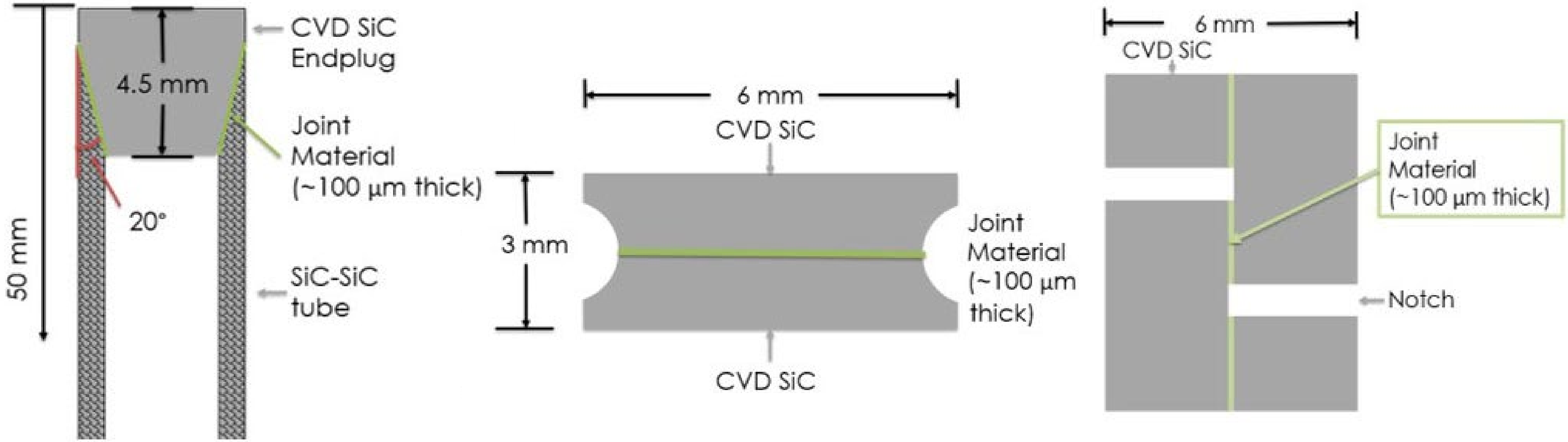


Hybrid SiC Joint

Technical Progress: Sample Fabrication

- Scarf joint balances joint area and processing considerations
  - Smaller endplug angle gives larger contact area and a stronger joint
    - HSiC and Oxide (CA) joints are essentially pressureless
  - TEP joining requires pressure (≥ 10 MPa) to form good joint
    - Applied pressure causes tube stress and damage with small angles
  - 20 degree joint angle balances strength, manufacturability

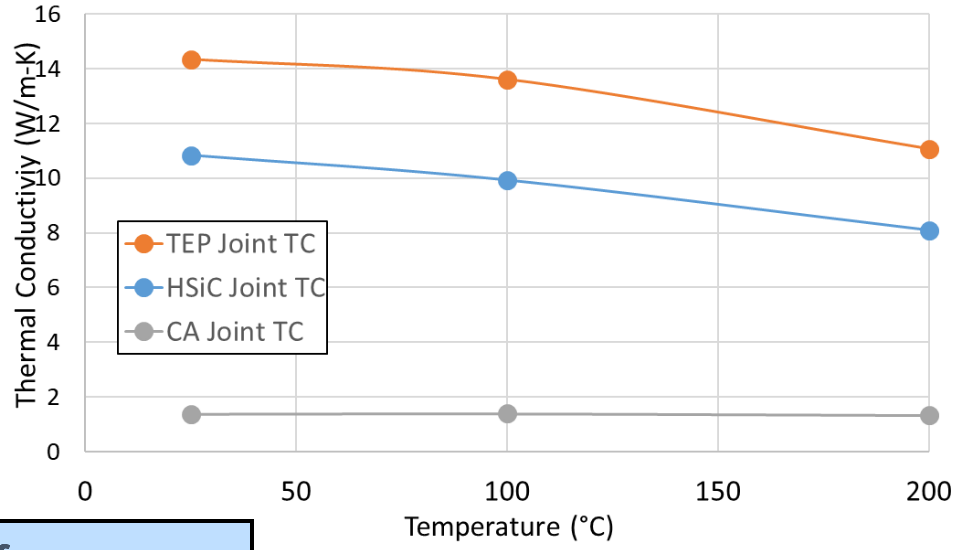




Joint Manufacturability Must Be Considered!

Technical Progress: Out-of-Pile Testing

- HSiC joints were the only joint formulation to consistently pass leak test
- All joints provided sufficient strength and retained strength at 750ºC
- First-of-a-kind thermal measurement from torsion sample; CA joint thermal conductivity was low



He Leak Measurements of Tube-Endplug Joints	
Joint type	**He Leak Rate (atm-cc/sec) @ 10 PSI He**
10x HSiC tubes	**$\sim 6 \times 10^{-9}$**
4x CA tubes	**$\sim 0.1 - 5 \times 10^{-8}$**
6x CA tubes	**$\sim 6 \times 10^{-7} - 2 \times 10^{-4}$**
10x TEP tubes	**$> 1 \times 10^{-2}$**

Target is 1×10^{-7} atm-cc/sec

Endplug Pushout Joint Performance		
Joint type	**Failure load (N)**	**Nominal Burst Pressure (MPa)**
TEP 20°	1450	35.6
HSiC 20°	1059	26.0
CA 20°	2365	58.1

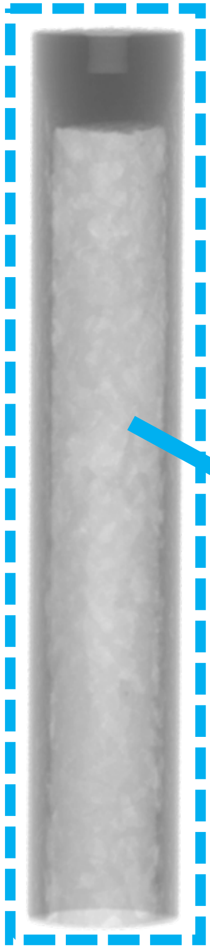
Testing Per ASTM Standard C1862-17

HSiC Joint provided best balance of strength, hermeticity, and thermal performance

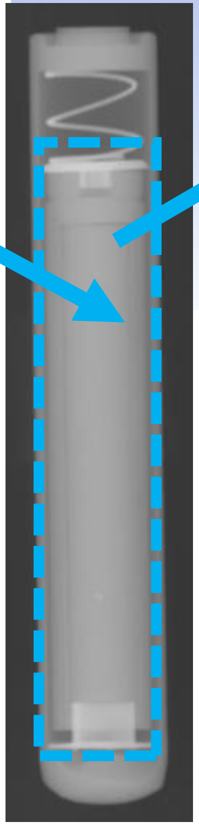
Technical Progress: HFIR Irradiation

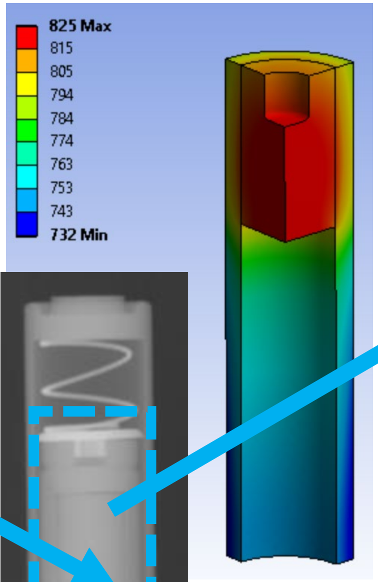
- 43 Joint specimens irradiated in HFIR to saturation (~2 dpa)
  - Tube-endplug & torsion
- Capsule designs to hit ~350ºC and ~750ºC target irradiation temperatures using fill gas mix
- Samples retrieved and being decontaminated in LAMDA
  - PIE to start 12/2020

All HSiC, CA Joints Intact After Irradiation



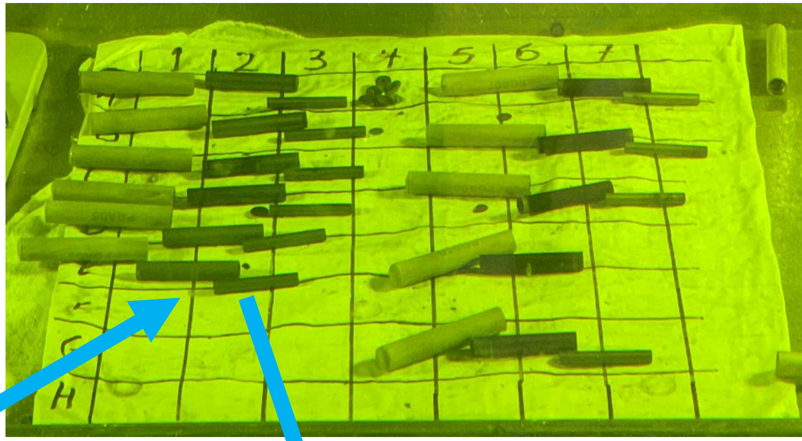
Endplug-tube joint sample

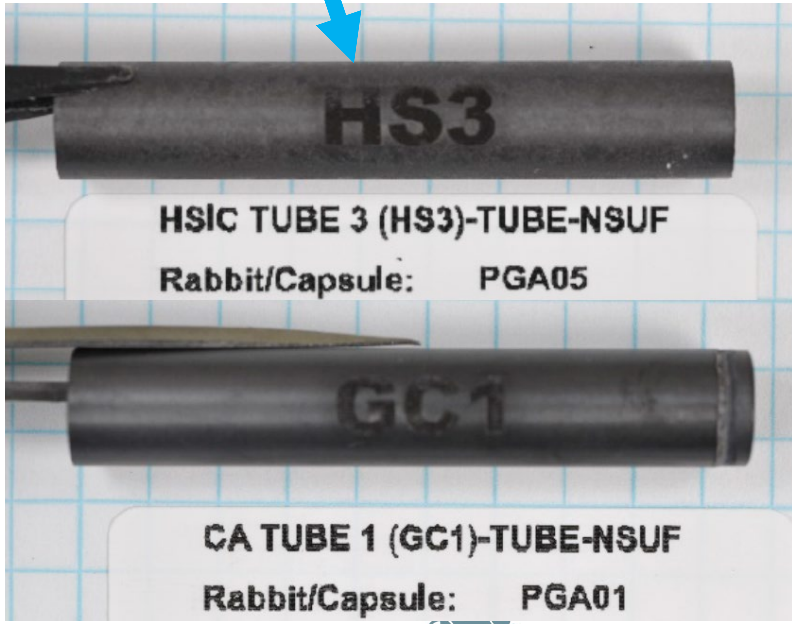




HFIR capsule

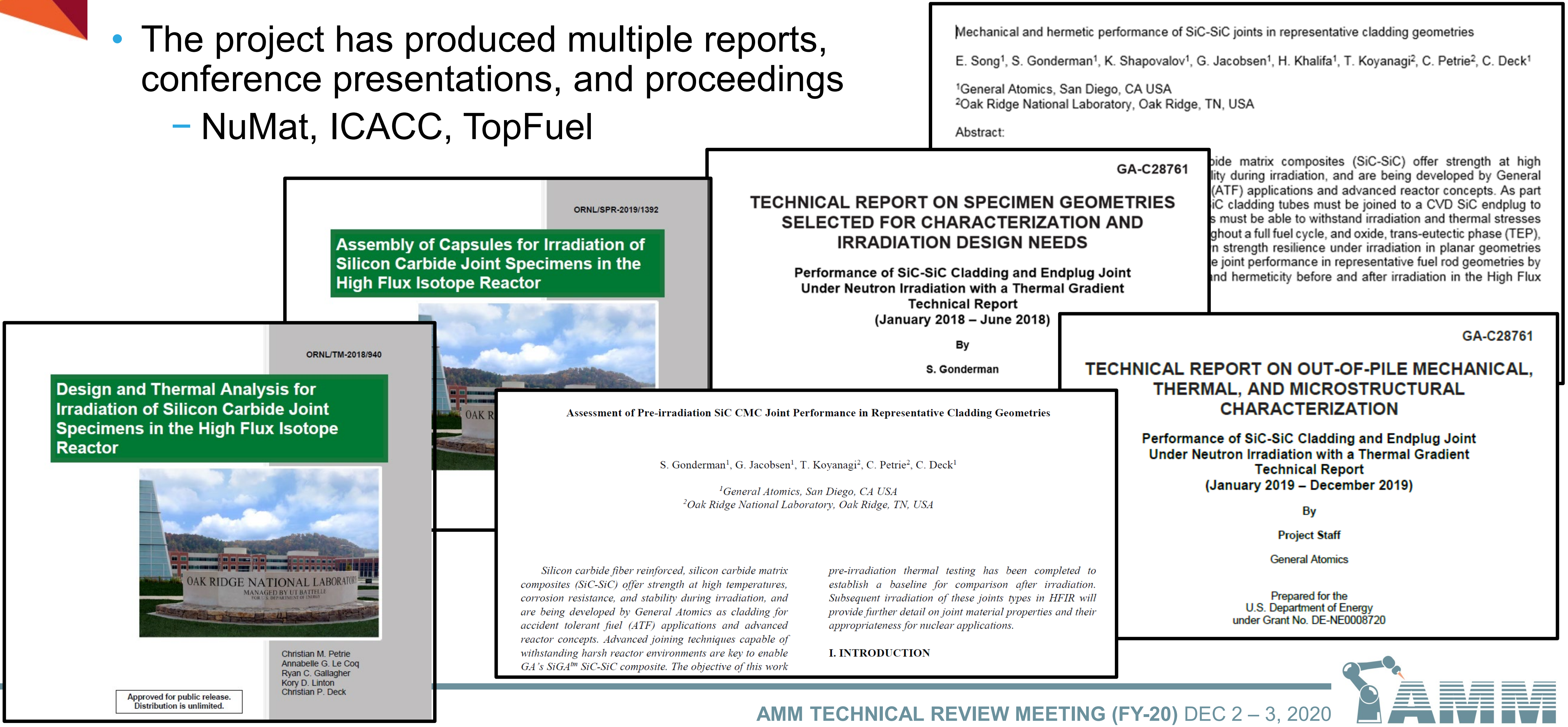
Tube-endplug samples in hot cell





Project-Related Presentations & Publications

- The project has produced multiple reports, conference presentations, and proceedings
  - NuMat, ICACC, TopFuel



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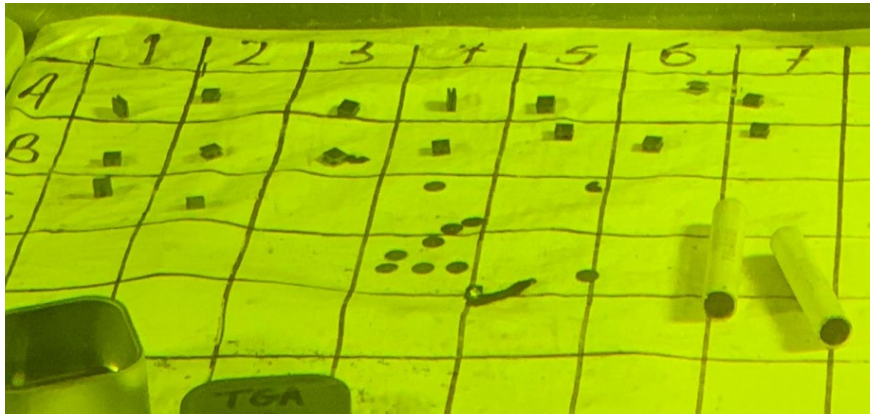
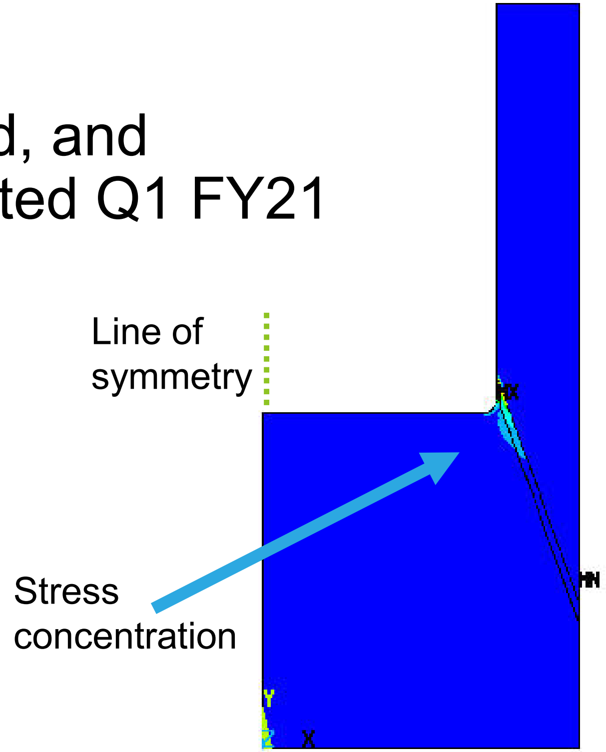
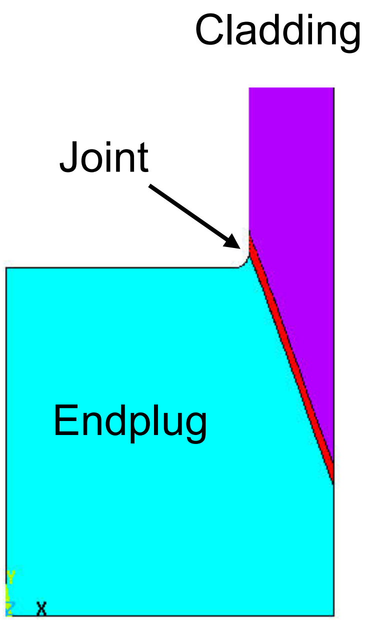
Milestones and Deliverables for FY-20

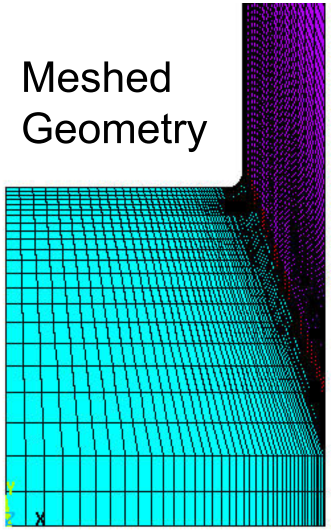
- Major milestone for FY20 completed:
  - Joint samples inserted into HFIR
  - Completed irradiation
  - Disassembled in hot cell
  - Transferred to LAMDA facility
- Joint material property database assembled, and modeling underway. Modeling report expected Q1 FY21



Torsion joint samples in hot cell







Issues and Concerns, Remaining Project Risks

- Delay in start of irradiation due to unplanned HFIR outage in 2019
- 12-month no-cost extension granted 4/2020; new project end date: 9/2021

- Two identified risk remaining:
- Risk of handling damage to irradiated samples leads to loss of data
  - Extra samples have already been made and delivered to provide initial handling and practice to perform needed tests
  - Initial testing has already been performed
  - There are already back-up samples built into in the irradiation test matrix

- Risk of ongoing ORNL COVID-related impacts delays PIE results
  - Tracking ORNL activity with monthly updates

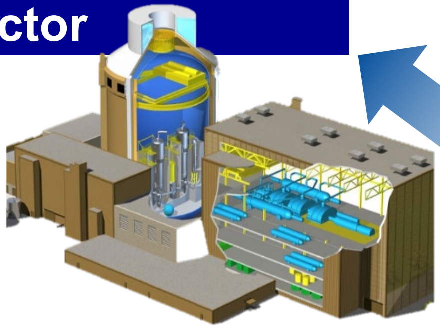
Milestones and Deliverables for FY-21

- ORNL: PIE report
- GA: Final joint material property and modeling report; Final project report

PIE Test Category	PIE Test Type	Material Property (Post Irradiation)	Number of Tests	
			Tube-Endplug	Torsion
Non-destructive testing	Dimensional measurement	Irradiation Induced Swelling	Each specimen	Each specimen
	Photography	Bulk Material Changes	Each specimen	Each specimen
	XCT	Dimensions, microstructure	Each specimen	Each specimen
	He leak testing	Permeability retention	Each specimen	N/A
	Laser Flash Analysis	Thermal diffusivity	N/A	Each specimen
	SiC thermometry	Irradiation temperature	One per capsule	
Destructive testing	EPPO	Apparent burst strength	Each specimen	N/A
	Torsion shear	Joint shear strength	N/A	Each specimen
Post-test Examination	SEM	Fracture Microstructure	Each specimen	Each specimen
	SiC thermometry	Irradiation Temp and gradient	Up to 4 per group	1 per group

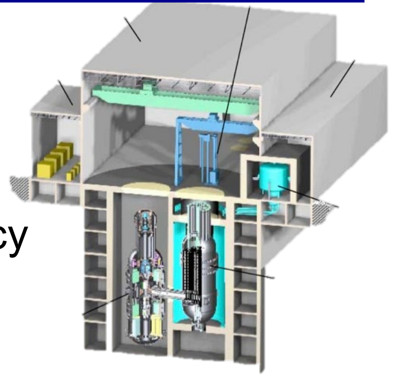
SiC Joining is Required for Nuclear Components

Light Water Reactor

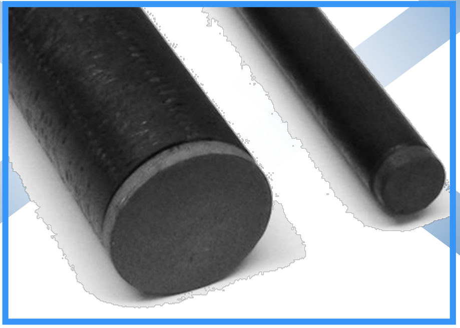


LWR
- Safety
- Higher burn-up
- Higher uprates
- Simpler design

High Temperature Gas-cooled Reactor

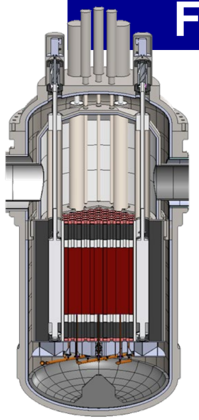


HTGR
- Safety
- Cheaper Fuel
- Higher efficiency
- Higher burn-up



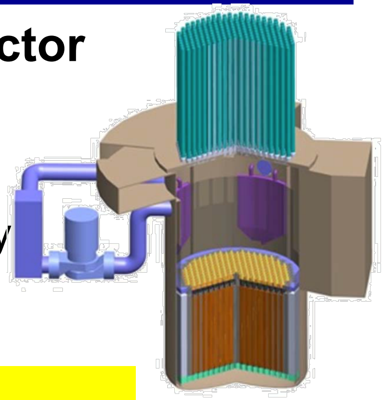
Silicon Carbide Joining and Composites

Gas-cooled Fast Modular Reactor



FMR, EM^2
- Safety
- Burn and produce much less waste
- Much higher burn-up and efficiency

Molten Salt Reactor



Molten Salt Reactor
- Safety
- Anti-corrosion
- Higher efficiency
- Higher burn-up

While requirements differ, irradiation-stable joining materials are cross cutting

Advanced Methods for Manufacturing

SiC Joining is Critical to DOE's ATF Program

2021	2022	2023	2024	2025	2026	2027	2028	2029	2030

SiC Joints ← **SiC Joint irradiation (NSUF)**

ATF Phase II: PWR cladding — Westinghouse ← **Demonstrations, scale-up**

Channel boxes for BWR — framatome ← **Fabrication, performance**

Cost Effective SiGA® ← **Cost Effective Fabrication**

SiC cladding irrad. design, fab | SiC cladding irrad. in PWR ← **SiC cladding commercial reactor irradiation**

Lead Test Irradiations

Phase III: Transition to Production (Manufacturing throughput)

Commercialization Phase

SiC Joining at TRL 4

Performance of SiC Joints: Conclusions

- Manufacturability of SiC joints is critical and must be assessed
- HSiC joints provide the best combination of manufacturability, strength, hermeticity, and thermal performance
- First-of-a-kind thermal measurement from torsion sample expands data obtained
- Completed irradiation of 43 joint specimens in HFIR at representative LWR and advanced reactor temperatures
- Visual examination of irradiated samples shows all HSiC and CA joints intact
- SiC materials are cross-cutting with current and advanced nuclear applications
- Hermetic, irradiation-stable joints are required for nuclear applications

Contact Information and Questions

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