



DEC 2 – 3, 2020

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

*Award Number: DE-NE0008720*

*Project Number: 17-12573*

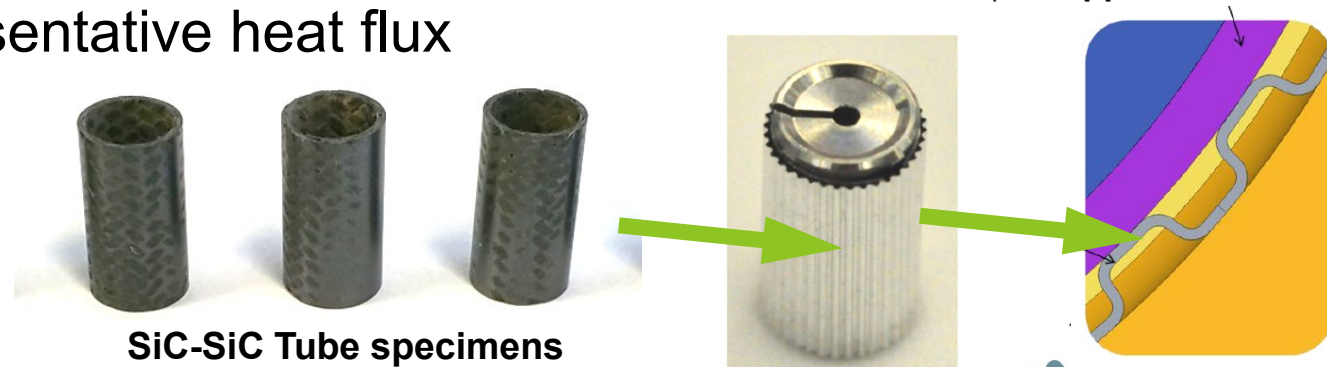
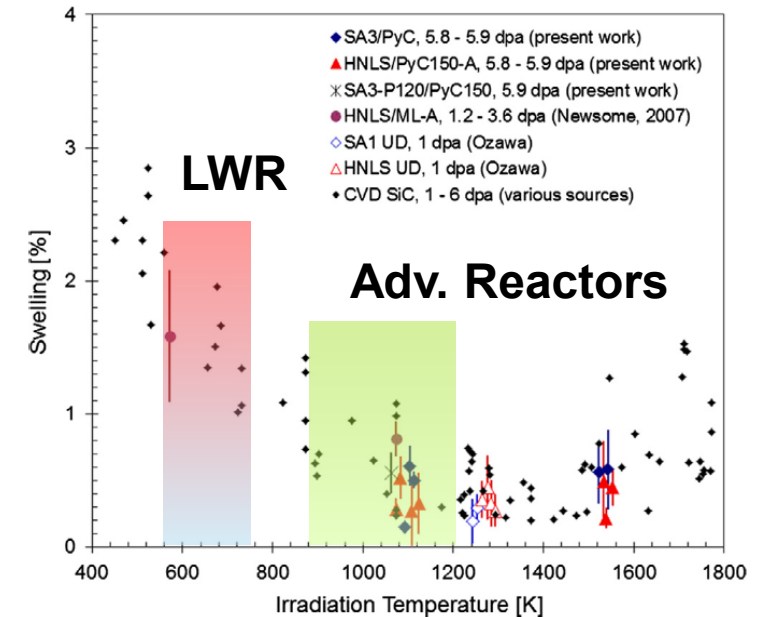
*Award Dates: 10/2017 to 9/2021*

*PI: Christian Deck (General Atomics)*

*Team Members: Takaaki Koyanagi (Oak Ridge National Laboratory)*

# SiC-SiC Cladding Undergoes Temperature-Dependent Swelling Under Irradiation

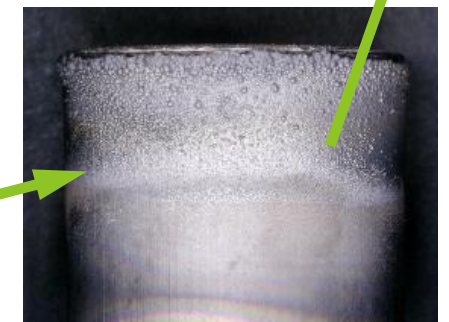
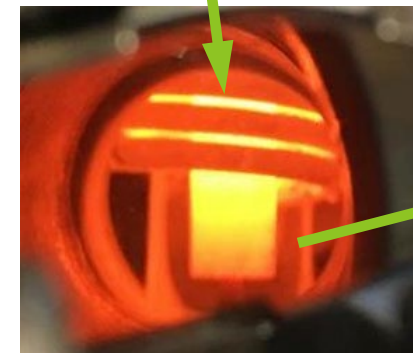
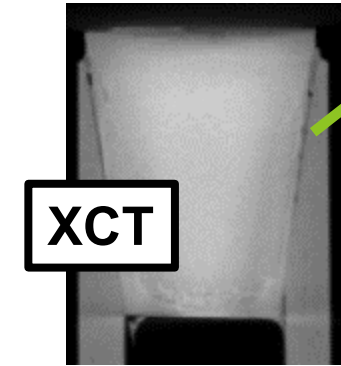
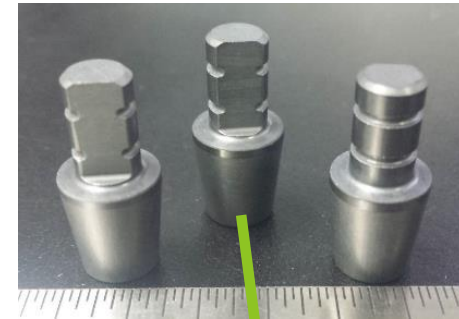
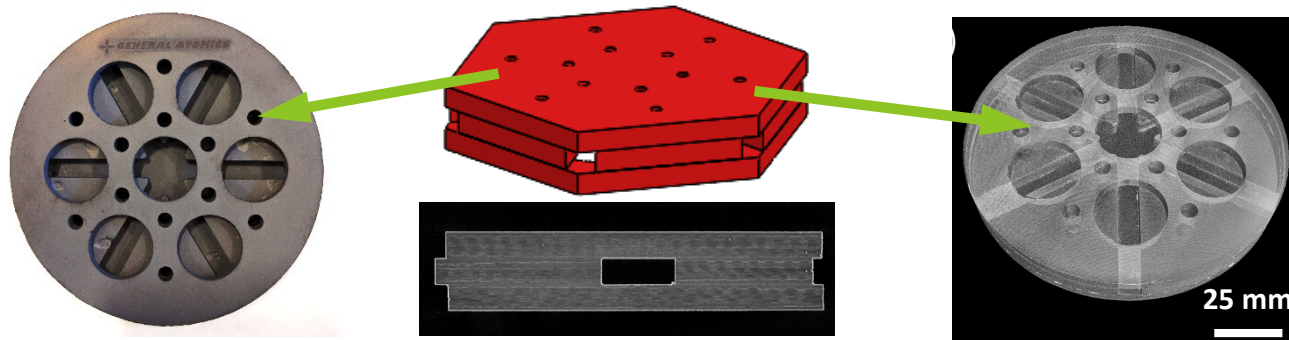
- SiC irradiation-induced swelling stabilizes at ~1-2 dpa
  - Temperature dependent (higher at lower temps)
  - Inverse relationship with thermal conductivity
  - Highly dependent on purity
- Previous ORNL NSUF project to observe effects of temperature gradient irradiations
  - Thermal expansion and 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

# 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

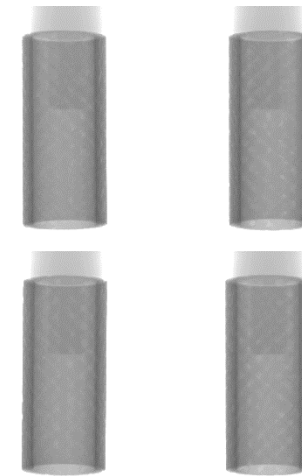
## *Project Objectives:*

- *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

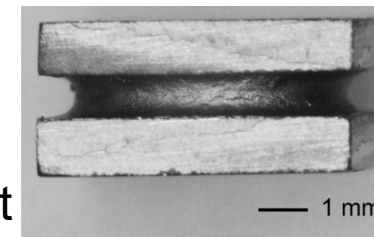
- Three SiC joint formulations
  - Transient Eutectic Phase (TEP) joint
  - Oxide-based SiC joint (CA: Calcia-Alumina)
  - Hybrid (HSiC) joint (pre-ceramic polymer+CVD)
- Three tests for temperature and irradiation effects
  - Double-notch shear for high temp strength
  - Tube-endplug and torsion for irradiation
- Irradiation at two temperatures:
  - Prototypic LWR (~350°C)
  - Prototypic Advanced Reactor (~750°C) GFR, HTGR, molten salt, etc.



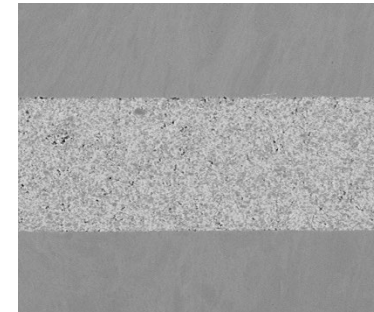
Tube-Endplug



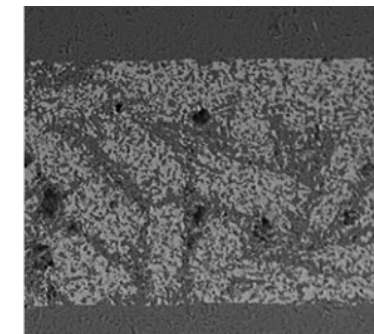
Double-Notch Shear



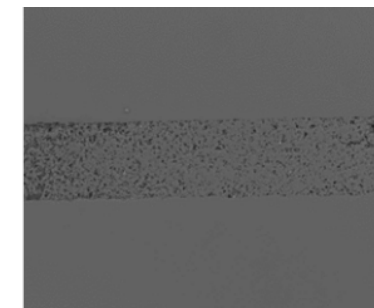
Torsion Joint



TEP SiC Joint



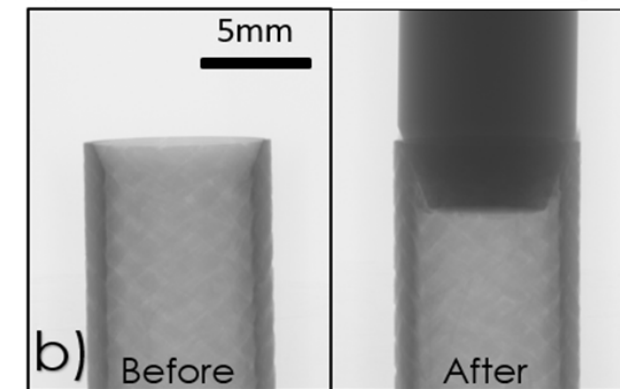
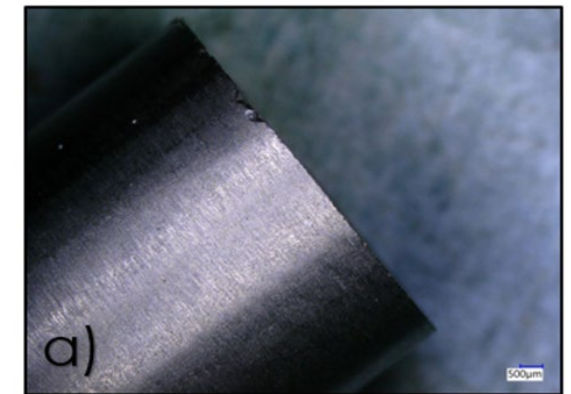
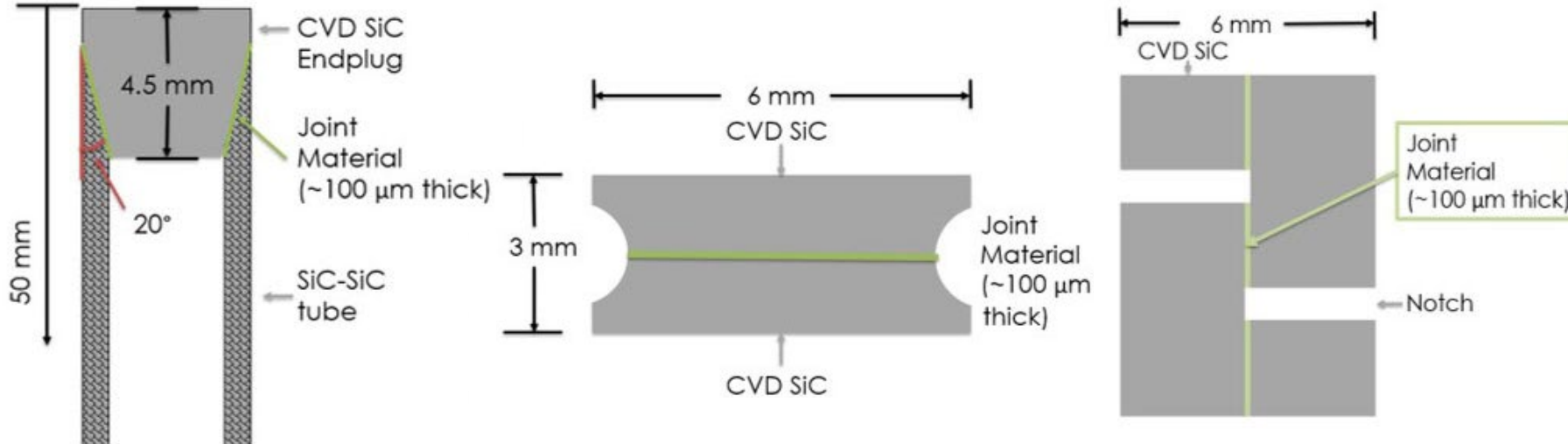
Oxide SiC Joint



Hybrid SiC Joint

# Technical Progress: Sample Fabrication

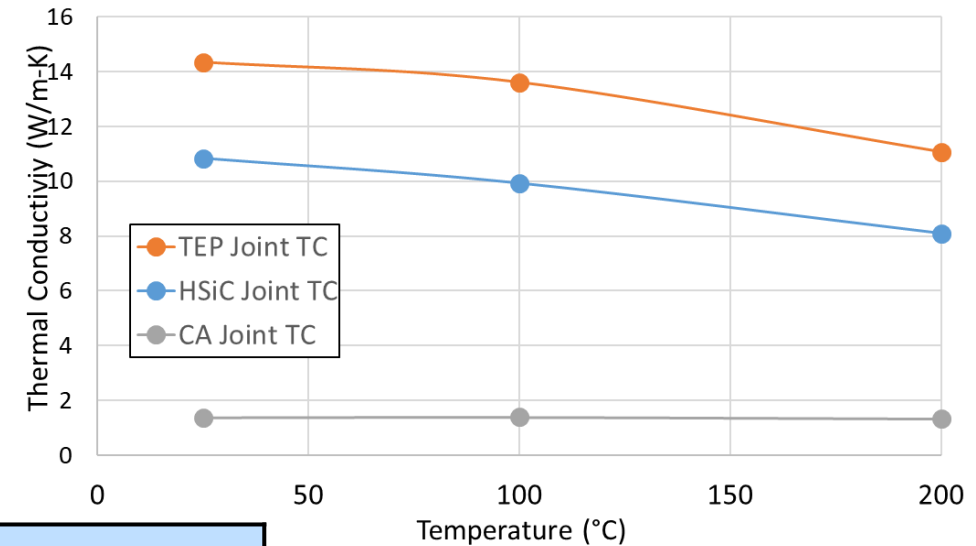
- Scarf joint balances joint area and processing considerations
  - Smaller endplug angle gives larger contact area and a stronger joint
    - HSiC and Oxide (CA) joints are essentially pressureless
  - TEP joining requires pressure ( $\geq 10$  MPa) to form good joint
    - Applied pressure causes tube 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 750°C
- 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	~6 x10 <sup>-9</sup>
4x CA tubes	~0.1 – 5 x10 <sup>-8</sup>
6x CA tubes	~6 x10 <sup>-7</sup> – 2 x10 <sup>-4</sup>
10x TEP tubes	> 1 x10 <sup>-2</sup>

Target is 1x10<sup>-7</sup> 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

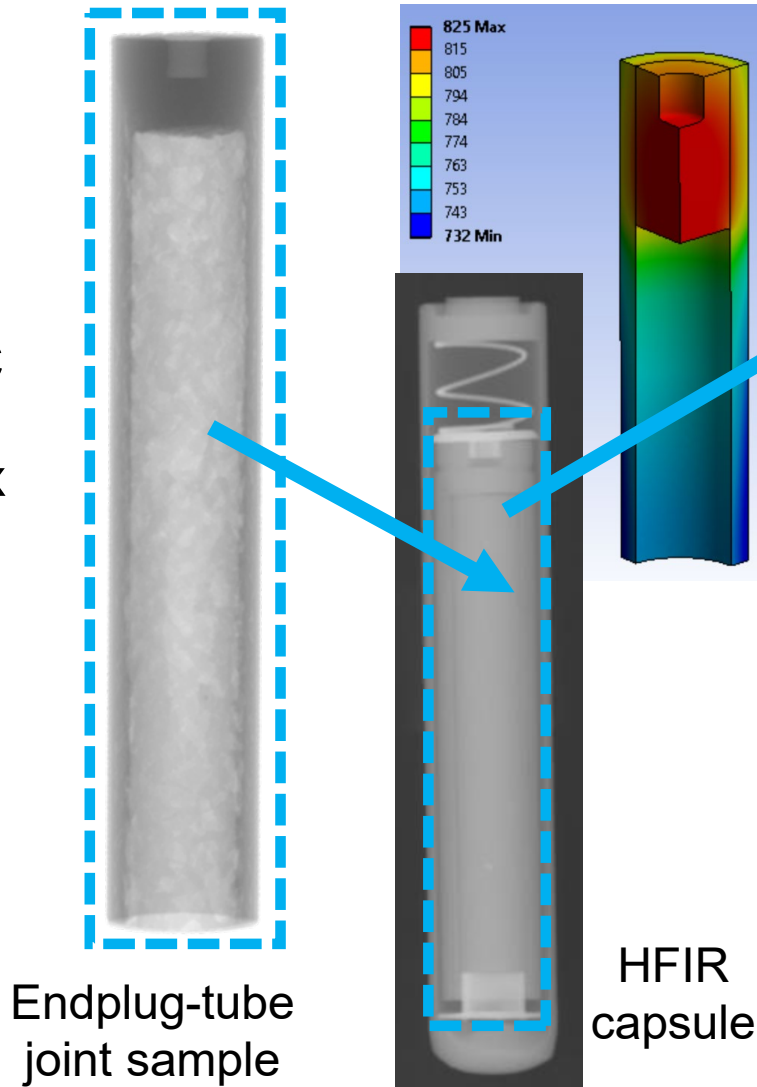
Testing Per ASTM Standard C1862-17

**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 ~350°C and ~750°C target irradiation temperatures using fill gas mix
- Samples retrieved and being decontaminated in LAMDA
  - PIE to start 12/2020

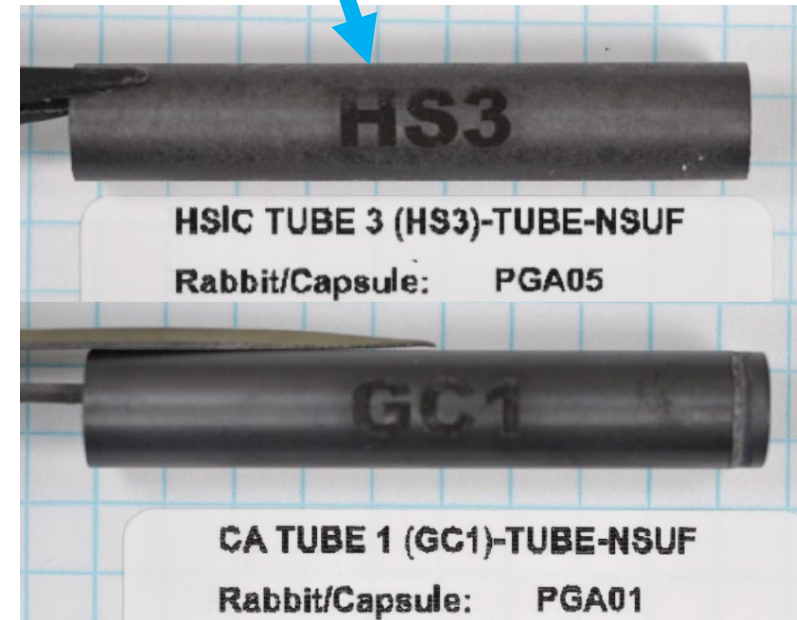
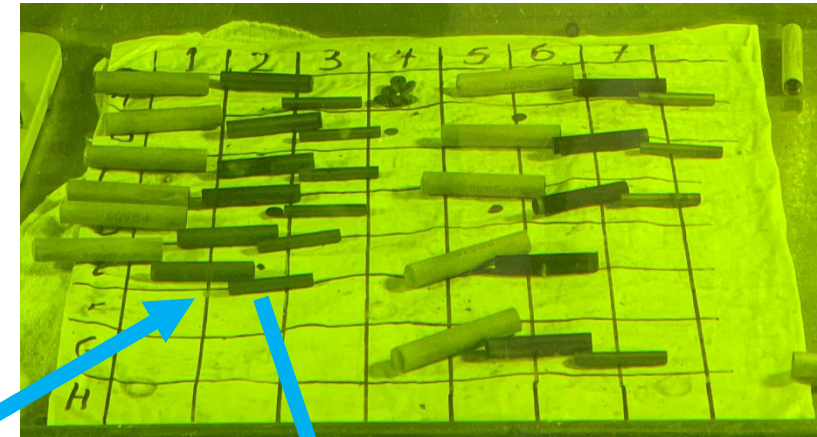
**All HSiC, CA Joints Intact After Irradiation**



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

Mechanical and hermetic performance of SiC-SiC joints in representative cladding geometries  
 E. Song<sup>1</sup>, S. Gonderman<sup>1</sup>, K. Shapovalov<sup>1</sup>, G. Jacobsen<sup>1</sup>, H. Khalifa<sup>1</sup>, T. Koyanagi<sup>2</sup>, C. Petrie<sup>2</sup>, C. Deck<sup>1</sup>

<sup>1</sup>General Atomics, San Diego, CA USA  
<sup>2</sup>Oak Ridge National Laboratory, Oak Ridge, TN, USA

Abstract:

SiC matrix composites (SiC-SiC) offer strength at high temperature during irradiation, and are being developed by General Atomics (ATF) applications and advanced reactor concepts. As part of these applications, SiC cladding tubes must be joined to a CVD SiC endplug to which must be able to withstand irradiation and thermal stresses throughout a full fuel cycle, and oxide, trans-eutectic phase (TEP), and strength resilience under irradiation in planar geometries. This report details joint performance in representative fuel rod geometries by mechanical and hermeticity before and after irradiation in the High Flux

ORNL/SPR-2019/1392  
**Assembly of Capsules for Irradiation of Silicon Carbide Joint Specimens in the High Flux Isotope Reactor**

GA-C28761  
**TECHNICAL REPORT ON SPECIMEN GEOMETRIES SELECTED FOR CHARACTERIZATION AND IRRADIATION DESIGN NEEDS**

Performance of SiC-SiC Cladding and Endplug Joint Under Neutron Irradiation with a Thermal Gradient  
 Technical Report  
 (January 2018 – June 2018)

By  
 S. Gonderman

GA-C28761  
**TECHNICAL REPORT ON OUT-OF-PILE MECHANICAL, THERMAL, AND MICROSTRUCTURAL CHARACTERIZATION**

Performance of SiC-SiC Cladding and Endplug Joint Under Neutron Irradiation with a Thermal Gradient  
 Technical Report  
 (January 2019 – December 2019)

By  
 Project Staff  
 General Atomics

Prepared for the  
 U.S. Department of Energy  
 under Grant No. DE-NE0008720

ORNL/TM-2018/940  
**Design and Thermal Analysis for Irradiation of Silicon Carbide Joint Specimens in the High Flux Isotope Reactor**

Assessment of Pre-irradiation SiC CMC Joint Performance in Representative Cladding Geometries

S. Gonderman<sup>1</sup>, G. Jacobsen<sup>1</sup>, T. Koyanagi<sup>2</sup>, C. Petrie<sup>2</sup>, C. Deck<sup>1</sup>

<sup>1</sup>General Atomics, San Diego, CA USA  
<sup>2</sup>Oak Ridge National Laboratory, Oak Ridge, TN, USA

SiC fiber reinforced, SiC matrix composites (SiC-SiC) offer strength at high temperatures, corrosion resistance, and stability during irradiation, and are being developed by General Atomics as cladding for accident tolerant fuel (ATF) applications and advanced reactor concepts. Advanced joining techniques capable of withstanding harsh reactor environments are key to enable GA's SIGA™ SiC-SiC composite. The objective of this work

pre-irradiation thermal testing has been completed to establish a baseline for comparison after irradiation. Subsequent irradiation of these joints types in HFIR will provide further detail on joint material properties and their appropriateness for nuclear applications.

I. INTRODUCTION

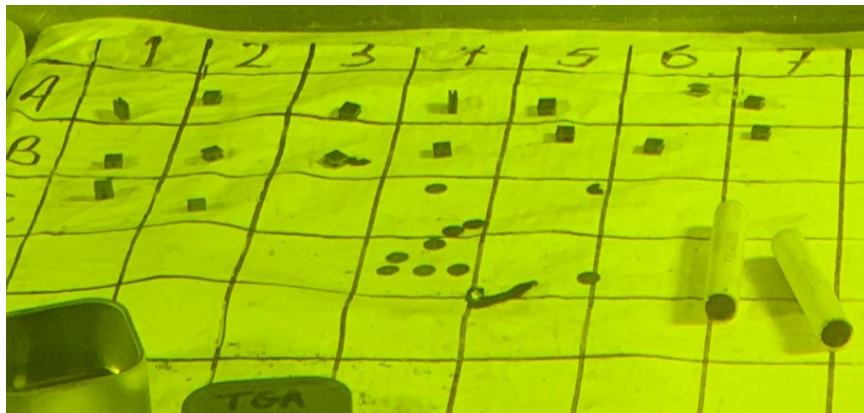


Christian M. Petrie  
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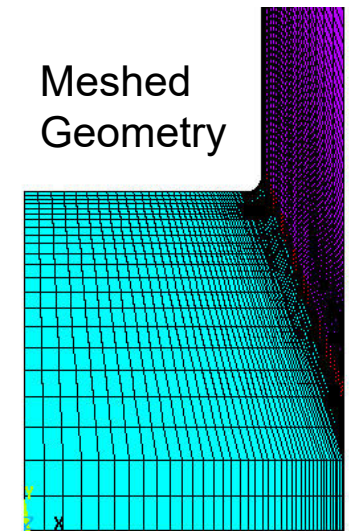
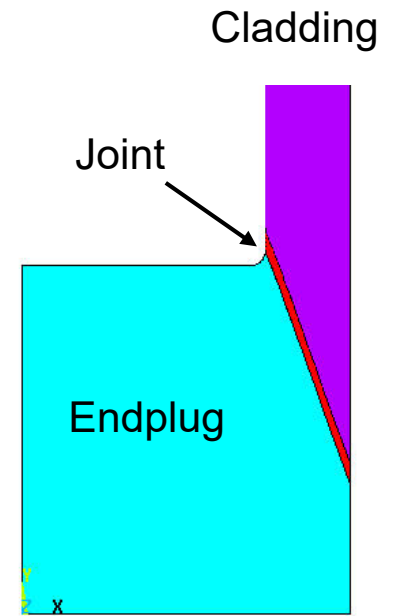
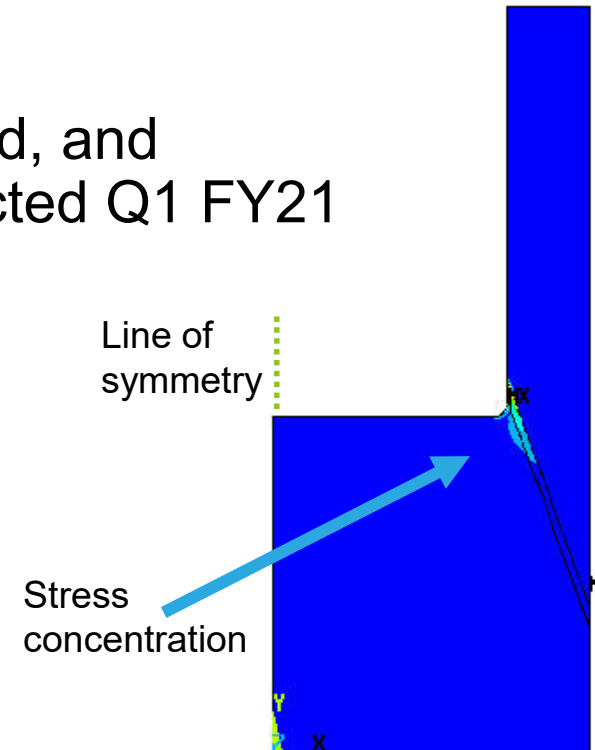
Approved for public release.  
 Distribution is unlimited.

# 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

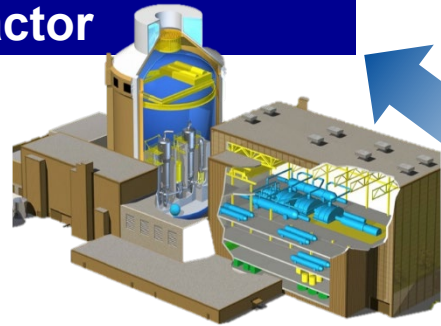
PIE Test Category	PIE Test Type	Material Property (Post Irradiation)	Number of Tests	
			Tube-Endplug	Torsion
Non-destructive testing	Dimensional measurement	Irradiation Induced Swelling	Each specimen	Each specimen
	Photography	Bulk Material Changes	Each specimen	Each specimen
	XCT	Dimensions, microstructure	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

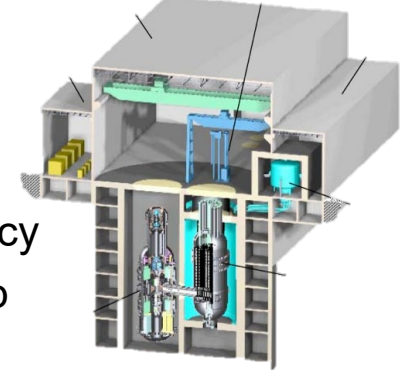
- Safety
- Higher burn-up
- Higher uprates
- Simpler design



## High Temperature Gas-cooled Reactor

### HTGR

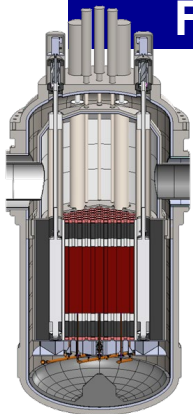
- Safety
- Cheaper Fuel
- Higher efficiency
- Higher burn-up



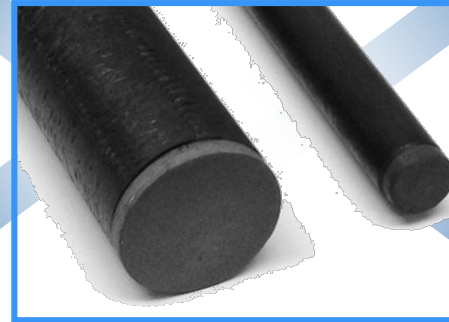
## Gas-cooled Fast Modular Reactor

### FMR, EM<sup>2</sup>

- Safety
- Burn and produce much less waste
- Much higher burn-up and efficiency



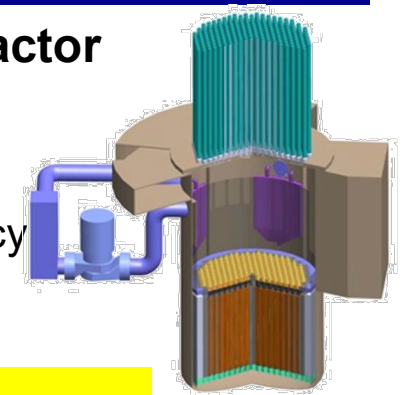
## Silicon Carbide Joining and Composites



## Molten Salt Reactor

### Molten Salt Reactor

- Safety
- Anti-corrosion
- Higher efficiency
- Higher burn-up



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

# SiC Joining is Critical to DOE's ATF Program



SiC Joints

← SiC Joint irradiation (NSUF)

ATF Phase II: PWR cladding

Channel boxes for BWR



Westinghouse

← Demonstrations, scale-up

framatome

← Fabrication, performance

Cost Effective SiGA<sup>®</sup>

← 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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