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

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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

LWR
Adv. Reactors

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.
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

<table>
<thead>
<tr>
<th>Joint type</th>
<th>He Leak Rate (atm-cc/sec) @ 10 PSI He</th>
</tr>
</thead>
<tbody>
<tr>
<td>10x HSiC tubes</td>
<td>~6 x10^{-9}</td>
</tr>
<tr>
<td>4x CA tubes</td>
<td>~0.1 – 5 x10^{-8}</td>
</tr>
<tr>
<td>6x CA tubes</td>
<td>~6 x10^{-7} – 2 x10^{-4}</td>
</tr>
<tr>
<td>10x TEP tubes</td>
<td>&gt; 1 x10^{-2}</td>
</tr>
</tbody>
</table>

Target is 1x10^{-7} atm-cc/sec

### Endplug Pushout Joint Performance

<table>
<thead>
<tr>
<th>Joint type</th>
<th>Failure load (N)</th>
<th>Nominal Burst Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEP 20°</td>
<td>1450</td>
<td>35.6</td>
</tr>
<tr>
<td>HSiC 20°</td>
<td>1059</td>
<td>26.0</td>
</tr>
<tr>
<td>CA 20°</td>
<td>2365</td>
<td>58.1</td>
</tr>
</tbody>
</table>

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

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

Light Water Reactor
- Safety
- Higher burn-up
- Higher uprates
- Simpler design

Gas-cooled Fast Modular Reactor
- Safety
- Burn and produce much less waste
- Much higher burn-up and efficiency

Silicon Carbide Joining and Composites

High Temperature Gas-cooled Reactor
- Safety
- Cheaper Fuel
- Higher efficiency
- Higher burn-up

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

2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030

ATF Phase II: PWR cladding
Channel boxes for BWR
Cost Effective SiGA®
SiC cladding irradiation (NSUF)
SiC cladding irradiation in PWR
SiC Joint irradiation (NSUF)
SiC Joints

SiC cladding commercial reactor irradiation
Lead Test Irradiations
Phase III: Transition to Production (Manufacturing throughput)
Commercialization Phase

SiC Joining at TRL 4

Westinghouse
Framatome
Demonstrations, scale-up
Fabrication, performance
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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