Advanced Fuel Technologies at General Atomics

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

- Zr + 2H₂O $\rightarrow$ ZrO₂ + 2H₂ + 595 kJ/g-mole
- SiC + 4H₂O $\rightarrow$ SiO₂ + CO₂ + 4H₂ + 264 kJ/g-mole

Eliminate hydrogen explosions
\(\beta\)-SiC Composite (SiC\(_{\beta}\)/SiC\(_{\beta}\)) Is an Attractive Material for Nuclear Applications

\(\beta\)-phase (diamond) compared to \(\alpha\)-phase (hexagonal) SiC

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

<table>
<thead>
<tr>
<th>Properties</th>
<th>Zircaloy-4(^{a,b})</th>
<th>SiC(<em>{\beta})/SiC(</em>{\beta})(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density @ 25°C, g/cc</td>
<td>6.56</td>
<td>2.8 – 3.0</td>
</tr>
<tr>
<td>Design tensile stress @316°C, MPa</td>
<td>~450</td>
<td>120-250</td>
</tr>
<tr>
<td>Usable tensile strength above 800°C, MPa</td>
<td>None</td>
<td>120-250*</td>
</tr>
<tr>
<td>Irradiated fracture toughness @316°C, Mpa-m(^{0.5})</td>
<td>&lt; 45</td>
<td>25-37</td>
</tr>
<tr>
<td>Reaction rate with air at 1200°C, mm/s(^{0.5})</td>
<td>0.45</td>
<td>0.0026</td>
</tr>
<tr>
<td>Reaction rate with H(_2)O at 1200°C, mm/s(^{0.5})</td>
<td>5.9</td>
<td>0.005</td>
</tr>
<tr>
<td>Thermal absorptions per source neutron, barns/n</td>
<td>7.21E-04</td>
<td>3.27E-04</td>
</tr>
<tr>
<td>DPA limit</td>
<td>~10</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>Unirradiated thermal cond. at 316°C, W/m-K</td>
<td>18</td>
<td>25</td>
</tr>
</tbody>
</table>

- F.Azzarto, JNM (1969)
- E.Ibrahim, JNM (1984)
- 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

Both Zircaloy and SiCβ/SiCβ meet design condition

SiC-SiC composites maintain mechanical properties at high temperatures
- Strength
- Stiffness
- Toughness

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$_{\beta}$/SiC$_{\beta}$)
- Developing SiC$_{\beta}$/SiC$_{\beta}$ clad fuel rod for a new reactor concept, EM$^2$
- Making substantial investment in people & equipment to develop SiC$_{\beta}$/SiC$_{\beta}$ fab processes
- Vested interest in LWR fuel supply – mining, $U_3O_8$ supply and UF$_6$ conversion

Rio Grande Resources  
U.S.A and Canada

Heathgate Resources  
Australia

Nuclear Fuel Services

EM$^2$ reactor

SiC/SiC fabrication development lab

TRISO fuel

EM$^2$ fuel

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

- Sol-gel column
- drying
- calcining
- sintering

Sol-Gel particles with carbon

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

UC kernels

UN kernels

UC pellets
GA SiC_β/SiC_β Development Addresses All Aspects of Fuel Cladding Fabrication

Infiltration

High strength joint is β-SiC

GA SiC lab

Composite tubes

End plug fabrication

Joint sample

Monolith fragment

Prototypes

OECD/NEA Workshop on ATF
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

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
- GA modeling capabilities accelerate process development

EM$^2$ reactor example

Vented endcap

Bundle assembly

Core

10um composite

200μm
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**

**Diagram:**
- Normalized mass and rate
- Start of Process
- End of Process
- Mass gain
- 30% fiber
- 35% fiber
- 200μm scale
- Start - Normalized Infiltration time → End
CylindricalPrototypes Have Been Infiltrated and Polished

Bi-axial braid

Fibers inside tow

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 $\beta$-SiC Material

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

XRD analysis and peak broadening evaluation

$$D = \lambda / (\beta \cos \theta)$$

- Control of crystal size
  - $\approx 10$ nm at $T_B$ to $\approx 100$ nm at $T_C$
- Tyranno SA3 SiC fibers
  - $D_{avg} \approx 100$-200 nm 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

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

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