Ceramic Composites for Next Step Nuclear Power Systems

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Generation IV
The Next Generation Nuclear Power Reactors

• Generation IV is a multinational collaboration for the research, development, and construction next generation pilot nuclear power plant by 2015.

• Several Options Being Studied Internationally:

  Very High Temperature Gas-Cooled Reactor
  Gas-Fast Reactor
  Molten Salt Reactor
  Super Critical Water Reactor
  Lead Fast Reactor
  Sodium Fast Reactor
The Competitors for VHTR in the United States

- The Gas Turbine, Modular High-Temperature Reactor (GT-MHR)
- The Pebble Bed Modular Reactor (PBMR)
# Comparison of Example VHTR Operating Conditions and Features with GT-MHR and Fort St. Vrain

<table>
<thead>
<tr>
<th>Condition or Feature</th>
<th>Fort St. Vrain HTGR</th>
<th>GT-MHR</th>
<th>VHTR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Output (MWt)</td>
<td>841</td>
<td>600</td>
<td>600 - 900</td>
</tr>
<tr>
<td>(Depends on core height)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average power density (w/cm^3)</td>
<td>6.3</td>
<td>6.5</td>
<td>4 - 6.5</td>
</tr>
<tr>
<td>Coolant and Pressure (MPa / psia)</td>
<td>Helium @ 4.83 / 700</td>
<td>Helium @ 7.12 / 1032</td>
<td>Helium @ 7.12 / 1032</td>
</tr>
<tr>
<td>Moderator</td>
<td>Graphite</td>
<td>Graphite</td>
<td>Graphite</td>
</tr>
<tr>
<td>Core Geometry</td>
<td>Cylindrical</td>
<td>Annular</td>
<td>Annular</td>
</tr>
<tr>
<td>Safety Design Philosophy</td>
<td>Active Safety Sys</td>
<td>Passive</td>
<td>Passive</td>
</tr>
<tr>
<td>Plant Design Life (yrs)</td>
<td>30</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Core outlet temp. (°C)</td>
<td>785</td>
<td>850</td>
<td>1000</td>
</tr>
<tr>
<td>Core inlet temp. (°C)</td>
<td>406</td>
<td>488</td>
<td>490 (Needs to be optimized)</td>
</tr>
<tr>
<td>Fuel – Coated Particle</td>
<td>HEU-PyC/SiC Th/93% 235 U</td>
<td>LEU-PyC/SiC</td>
<td>a) LEU-PyC/SiC</td>
</tr>
<tr>
<td>Fuel Max Temp – Normal Operation (°C)</td>
<td>1260</td>
<td>1250</td>
<td>a) ~1250 b) ~ 1400</td>
</tr>
</tbody>
</table>
GT-MHR Control Rod Concept

(Courtesy of General Atomics)
- Workhorse alloy: steam generator, control rod and plenum application
- Incoloy 800: Ni30-35, Cr(19-23), Fe(39.5 min), C(0.1max.), Ti+Al(0.3-1.2)
Composite -v- Monolithic Ceramics

Composite materials, whether platelet, chopped fiber, or continuous fiber reinforced are superior “engineering” materials to monolithics:

- generally higher strength, especially in tension
- higher Weibull modulus (more uniform failure)
- much higher damage tolerance (fracture toughness)
Composite -v- Monolithic Ceramics

<table>
<thead>
<tr>
<th>Material</th>
<th>Composite Strength (MPa)</th>
<th>Monolithic Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite</td>
<td>176 ± 20</td>
<td>107 ± 20</td>
</tr>
<tr>
<td>SiC</td>
<td>220 ± 20</td>
<td>100 ± 50</td>
</tr>
</tbody>
</table>

Toughness MPa/m$^{1/2}$

<table>
<thead>
<tr>
<th>Material</th>
<th>Toughness MPa/m$^{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steel</strong></td>
<td>&gt; 50</td>
</tr>
<tr>
<td><strong>Tungsten</strong></td>
<td>&lt; 20</td>
</tr>
<tr>
<td><strong>Monolithic Ceramic</strong></td>
<td>3</td>
</tr>
<tr>
<td><strong>Platelet Reinforced Ceramic</strong></td>
<td>6</td>
</tr>
<tr>
<td><strong>Chopped Fiber Reinforced</strong></td>
<td>10</td>
</tr>
<tr>
<td><strong>Continuous Fiber Reinforced</strong></td>
<td>25-30</td>
</tr>
</tbody>
</table>
Control Rod Tube Architecture
± 20° spiral weave

$\sigma_{\text{hoop}} = < 10 \text{ MPa}$
$\sigma_{\text{axial}} = 20-50 \text{ MPa}$

Composite Articulated Control Rod Segment

Gen IV Program
Fabrication C/C and SiC/SiC
Testing (including irradiation)
Scaling
ASTM Test Methods
QA
Operating Range, Highly Irradiated Structural Materials

- **C/C**
- **SiC/SiC**
- **Tungsten**
- **Molybdenum**
- **ODS Ferritic**
- **F/M Steel**
- **316 Stainless**
- **Alloy 718**

The chart shows the operating temperature range for different structural materials, categorized as either reasonable or questionable based on their performance under highly irradiated conditions.
Ceramic Structural Composites
For Nuclear Application

Carbon/Carbon Composites

- In widespread structural use
- Manufacturing and design methods understood
- Expensive...
Graphite Under Irradiation

Normalized Thermal Conductivity

Dose, $10^{22}$ n/cm$^2$ [E>50keV]

Normalized Thermal Conductivity, $K_{\text{irr}} / K_{\text{unir}}$

Dose, $10^{22}$ n/cm$^2$

H451 Graphite
CFC’s Under Irradiation

(HFIR, 600° C)

1-D Fiber Composite (UFC)

Dose (dpa)

Dimensional Change (%)

⊥ Fiber Axis

∥ Fiber Axis

3D Balanced Weave

Pitch Fibers

PAN Fibers

INTERPLANER VOIDS

GRAPHITIC PLANES

CORE–SHEATH MODEL
CFC’s Under Irradiation

Composite allows “engineering” of properties such as dimensional change.
Ceramic Structural Composites

SiC/SiC Composites

- Essentially no current structural application
- Manufacturing and design methods immature
Ceramic Structural Composites

SiC/SiC Composites Under Irradiation

- May survive for life of machine
- Thermal conductivity is likely less than assumed
- Electrical conductivity appears not to be a problem
• Irradiation-induced thermo-physical property changes (swelling, thermal conductivity, strength) saturate by a few dpa for $T<1000^\circ$ C. Driven by simple defect clusters.

• Irradiation performance for $T>1000^\circ$ C is not well understood.
SiC/SiC Composites: Strength and Stability

Bend strength of irradiated “advanced” composites show no degradation up to 10 dpa.

1st- and 2nd generation irradiated SiC/SiC composites show large strength loss after doses >1 dpa.
SiC/SiC Composites: Thermal Conductivity

CVD SiC

CVD SiC Irradiated

Temperature (°C)

Thermal Conductivity (W/m-K)
## Materials Comparison at 1000° C

<table>
<thead>
<tr>
<th>Material</th>
<th>Cost $/Kg</th>
<th>Life (dpa)</th>
<th>Volume</th>
<th>Strength (MPa)</th>
<th>Modulus</th>
<th>Thermal Conductivity W/m-K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superalloy</td>
<td>25</td>
<td>~5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CFC*</td>
<td>~200</td>
<td>10-15</td>
<td>-5%</td>
<td>150→250</td>
<td>+20%</td>
<td>250→180</td>
</tr>
<tr>
<td>SiC/SiC*</td>
<td>~400</td>
<td>&gt;50?</td>
<td>+1%</td>
<td>75→75</td>
<td>-10%</td>
<td>50→20</td>
</tr>
</tbody>
</table>

* does not include prototyping or NDE evaluation.

<table>
<thead>
<tr>
<th>NGNP</th>
<th>Operating Temp</th>
<th>Maximum Temp</th>
<th>Lifetime Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Rods &amp; Guide Tubes</td>
<td>1200° C</td>
<td>1600° C</td>
<td>25 dpa</td>
</tr>
<tr>
<td>Upper Plenum Shroud/Core Restraint</td>
<td>650° C</td>
<td>1300° C</td>
<td>0.05 dpa</td>
</tr>
<tr>
<td>Floor Blocks</td>
<td>600° C</td>
<td>600° C</td>
<td>&lt;0.05 dpa</td>
</tr>
<tr>
<td>Hot Duct Inner Shell</td>
<td>1000° C</td>
<td>1200° C</td>
<td>0.005 dpa</td>
</tr>
</tbody>
</table>
Concluding Remarks

• Both GFR and NGNP concepts will require composite materials to achieve design goals, most importantly core internal temperature.

• Presently, there are only two viable candidate composites are C/C and SiC/SiC.

• C/C composite are more mature and have clear advantages in cost, manufacturability and some thermomechanical properties (eg thermal conductivity.)

• SiC/SiC has a clear advantage on irradiation stability, specifically a lower level of swelling and retention of mechanical properties. Offers possibility lifetime component for control rod application to NGNP (C/C would require 2-3 replacements over life.)

• Ceramic composite will require substantial investment in ASTM development, NDE development, and must be handled by prototyping and proof testing. Substantial additional costs compared to more conventional alloys.
Questions ???
Yield Strength of Various Structural Materials

- Superalloy
- C/C Composite
- SiC/SiC
- Carbon Steel
- Zircaloy
- Stainless Steel
- Graphite