Fuel Behavior in Severe Accidents and Potential Accident Tolerance Fuel Designs

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EPRI Breakthrough Fuel Technology Program

- EPRI started evaluation of BFT for enhancing fuel reliability, efficiency, and safety in late 2010
- Utility executive committee approved two tasks (post- Fukushima)
  - Accident tolerant fuel cladding
  - SiC channel (led by Ken Yueh)

- Objectives:
  - Develop technical needs and basis from utility/fuel user perspectives
  - Supplement efforts undertaken by DOE and fuel vendors, as needed

- Science Advisory Panel (SAP) established to guide BFT efforts
  - TVA, Dominion Generation, Exelon Generation, Constellation Energy, Duke Energy, PPL
  - EDF, KKL
Outline

• Behavior of fuel rods during a severe accident
• Key parameters controlling fuel degradation and possible improvements
• Candidate materials for accident tolerant fuel (ATF) cladding
• Novel cladding designs based on molybdenum alloys
  – feasibility studies
• SiC channel
• Summary
Fuel in Severe Accidents

- **TMI-2 accident in 1979**
  - Fuel failure detected ~2.7 hr after loss of coolant flow
  - 50% core melted in 7 hours
  - Small hydrogen explosion in ~10 hrs, no RPV breach

- **Fukushima Daichi Units 1-3 Station Blackout (SBO)**
  - Some passive cooling after tsunami
  - Hydrogen explosion and RPV breach
    - Unit 1 in <1 day
    - Unit 3 in ~2 days
    - Unit 2 in ~3 days

Fuel exposed to high temperature, high pressure steam, leading to rapid oxidation of Zr-alloys and generation of heat and hydrogen
Behavior of Fuel/Core Materials in Severe Accidents
- Zr-alloys, Fe-based, Ni-based Alloys and UO$_2$

Zr Exothermic Reaction
Hydrogen Generation
Cladding Embrittlement

Core Melt

Control Rod/Blade Collapse

290-345°C

Great for Normal Operations

Zr Cladding Balloon & Burst

Pressure effect
eutectic

2200-2800°C

Eutectic

UO$_2$ Melting

Zr-alloy Melting?

2000°C

Stainless Steel/Ni-alloy Melting Point

1400-1500°C

Rapid Zr Cladding Oxidation

1000-1200°C

1850°C

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Fuel Cladding Temperature in a Simulated Station Blackout (SBO) Accident – EPRI MAAP Code Analysis

Fuel rod surface “dryout” leads to rapid cladding temperature rises

Some low power rods peak temperature may be <~2000°C
Passive Cooling Capability is Most Important Parameter

- Increasing passive cooling capability from 2 to 24 hrs can:
  - decrease decay heat by ~43%
  - Increase time to initiation of fuel melting from ~3 to ~10 hrs (Zircaloy cladding)

<table>
<thead>
<tr>
<th>Battery-Assisted Passive Cooling, hrs</th>
<th>Decay Heat, %Pre-scram Power</th>
<th>Time to Fuel Melt after Flow Stops, hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>~1.18</td>
<td>~3</td>
</tr>
<tr>
<td>24</td>
<td>~0.67</td>
<td>~10</td>
</tr>
<tr>
<td>72</td>
<td>~0.58</td>
<td>~11</td>
</tr>
</tbody>
</table>
Reducing Cladding Steam Reaction Rate can Delay Fuel/Core Melting

- All 3 “hypothetical” improved-cladding cases stabilize at ~1500°C for ~10 hrs longer than Zr cladding

- “Improved cladding” requires material other than Zr-based alloys

(Assume 72 hr passive cooling)
Requirements for Accident Tolerant Fuel Cladding

• Good high temperature properties:
  – high melting temperature
  – resistance to steam (+hydrogen) corrosion at 1200-1500°C
  – adequate cladding tensile & creep strength at 1200-1500°C

• Viable economics
  – acceptable neutronic absorption cross sections
  – material availability at reasonable costs

• Fabricable into full length cladding tubes
  – can be hermetically sealed

• Compatible with current LWR designs and coolants

• Good fuel reliability under normal operation

• No fuel storage and disposal issues
Candidate Advanced Cladding Materials:
- Ceramics, Refractory Metals, Fe-based Alloys

<table>
<thead>
<tr>
<th>Material</th>
<th>Melting Temp (°C)</th>
<th>Thermal Neutron Absorption, barns</th>
<th>Thermal Conductivity, W/m-K</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zr alloys</td>
<td>~1800</td>
<td>~0.19</td>
<td>22</td>
<td>Weakens at ~750-800°C</td>
</tr>
<tr>
<td>Stainless Steels</td>
<td>~1400-1500</td>
<td>~2.6-2.8</td>
<td>16</td>
<td>Fe-B eutectic melting at 1161°C; with Al addition resists steam to 1350°C due to formation of Al₂O₃</td>
</tr>
<tr>
<td>Inconel/Ni alloy</td>
<td>~1400</td>
<td>~4.0-4.2</td>
<td></td>
<td>Produce Co-58 isotope</td>
</tr>
<tr>
<td>SiC</td>
<td>(2600)*</td>
<td>0.09</td>
<td>20 (composite)</td>
<td>*sublimation; ceramic, brittle</td>
</tr>
<tr>
<td>Mo</td>
<td>2623</td>
<td>2.6</td>
<td>138</td>
<td>Vaporize as MoO₃ in oxidizing condition; stable in reducing condition to 2000°C</td>
</tr>
<tr>
<td>Nb</td>
<td>2477</td>
<td>1.15</td>
<td>53</td>
<td>Limited supply; hydriding</td>
</tr>
<tr>
<td>ZrO₂</td>
<td>2715</td>
<td></td>
<td>2</td>
<td>Stable in steam to 1900°C</td>
</tr>
</tbody>
</table>

Candidate materials limited; SiC, Mo, stainless steel; and naturally forming surface protective coating: Al₂O₃, ZrO₂, SiO₂ and Cr₂O₃
High Temperature Mechanical Properties of ATF Cladding Material Candidates

<table>
<thead>
<tr>
<th>Material</th>
<th>300°C</th>
<th>1000°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zircaloy-4*</td>
<td>270</td>
<td>nil</td>
</tr>
<tr>
<td>Stainless Steel 304**</td>
<td>475</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Ferritic Martensitic Steel</td>
<td>480</td>
<td>&lt;10</td>
</tr>
<tr>
<td>SiC/SiC Composite</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Molybdenum alloys</td>
<td>400-570</td>
<td>200-300</td>
</tr>
</tbody>
</table>

*Phase transition of Zr at ~800°C
**Phase transition of Fe at ~900°C
Molybdenum Alloy Cladding Design Concepts

• Utilizing Mo alloys’ unique properties:
  – Tensile and creep strength at 1000-1800°C
  – High stability in reducing and inert environments to ~2000°C
  – Fabricability into long, thin wall tubes
  – Can be welded to end caps

• Challenges for LWR fuel applications:
  – Reacts with oxygen/steam; needs improvement/protection
  – Higher neutron absorption cross sections than Zr; cladding wall thickness needs to be reduced (<0.25 mm or 10 mils)
  – Irradiation embrittlement is known and needs further evaluation
  – Industry infrastructure for Mo cladding not well established
Mo-Alloy Based Cladding for LWR Accident Tolerant Fuel Designs

- Thin-wall Mo alloy tube protected by Zr alloy (ZrO$_2$), or advanced steel (Al$_2$O$_3$) on the OD surface (duplex)
- Mo inner surface protected by a soft Zr alloy or others as an option (triplex)
- May achieve
  - Accident tolerance to 1200-1500$^\circ$C
  - Eliminate design base LOCA issues
- Monolithic Mo alloy cladding?
  - Need focused R&D on alloy development to bring to LWR applications
  - Mo is compatible with GEN-IV reactor coolants: He, liquid metal, or molten salts
Fabrication of Mo Alloy, Duplex and Triplex Cladding – EPRI Feasibility Studies

• Making thin wall Mo cladding
  – 0.37 mm (14.7 mil) wall Mo (M) and Mo+La₂O₃ (ML)
  – 0.20 mm (8 mil) M and ML tubes (2 meter -6 ft tubes)

• Fabricating duplex and triplex tubes
  – Coating technologies
    • Plasma spray (air or vacuum), HVOF (high velocity oxi-field), physical vapor deposition (PVD), and CVD
    • Feasibility demonstrated
  – Mechanical forming
    • Co-extrusion/rolling/drawing
    • Plans developed

• Developing and testing new Mo alloys
  – Better corrosion resistance, ductility/formability
  – Mo material vendors, UC Berkeley, ORNL…..
Some Duplex Cladding by Coating Technologies

Plasma Spray Coating in Air: Zry-2 on Mo

Zry2 Coating by CA-PVD on Mo (GEGRC)

FeCrAIY Coating by HVOF on Mo (GEGRC)
Testing of ATF Cladding

• **Material properties:**
  – Corrosion resistance at operation temperatures (3 autoclaves)
  – Layer bonding strength, durability and chemical stability
  – Resistance to steam and steam + hydrogen reaction at 1000°C
  – Microstructures

• **Optimizing fabrication process**
  – Vacuum plasma spray
  – HVOF, PVD, and CVD coating
  – Co-rolling/extrusion
  – Making tubes with new Mo alloys

• **Irradiation**
SiC BWR Channel Application Background

- Silicon carbide used in multiple applications
- Recent years considered for LWR fuel applications
- Rationale for BWR channel development
  - Existing zirconium channels are susceptible to channel bow
  - High temperature steam environment stability desired for accident scenarios (~40% of total Zr loading in BWRs)
  - Much simplified requirements compared to cladding
  - Could provide information for cladding development
EPRI SiC BWR Channel Program

• **Initial feasibility evaluation performed**
  – In-core functional requirements
    • Initial volumetric swelling may be an issue, but limited to few positions
    – Lower neutron capture cross-section, ~$3.1M in fuel savings/reload
    – Impacts tests showed prototype is resistance to fragmentation

• **Irradiation program planned at ORNL and MIT research reactors**
  – Irradiation swelling, creep and corrosion
  – Small scale demonstration
  – Project co-funded by DOE NEET program

• **Characterization of mechanical and thermal properties**

• **Full scale commercial demonstration may be possible around 2019 time frame**
Summary

- Maintaining passive cooling is utmost important for avoiding fuel/core damage in severe accidents
- Safety margins of Zr alloys over ~800°C may be small
- Cladding materials with lower steam reaction rate in combination with higher tensile/creep strength to maintain fuel integrity and coolability may increase tolerance to accidents
  - Candidate cladding materials for LWR is limited
  - Mo-alloy and SiC/SiC composite are being considered; both have attractive features and technical challenges
- A novel ATF design based on Mo-alloys (metallic) is proposed and is under feasibility evaluation
- EPRI effort is intended for industry/laboratory collaboration and eventual implementation
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