Accident Tolerant Fuel (ATF) Development: KAERI’s R&D Status

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Hydrogen Explosion

• Huge amount of hydrogen is formed: $\text{Zr} + 2\text{H}_2\text{O} \rightarrow \text{ZrO}_2 + 2\text{H}_2$

• $\text{H}_2$ explodes when its fraction in the steam is higher than $\sim 10\%$

• Hydrogen explosion: Important in terms of radioactivity release
KAERI’s Approach to ATF Cladding

• To reduce $H_2$ production during accident conditions than current Zr cladding
• KAERI’s approach: 1) **Surface modification**, 2) **Metal-ceramic hybrid**

**Mid-term**
- Surface Modified Zr Cladding
  - Zr alloys
  - Surface modification

**Long-term**
- Metal-Ceramic Hybrid Cladding
  - Zr alloys
  - Ceramic composite
  - Surface coating

**Major Points Considered**
- Oxidation resistance
- Thermal conductivity
- Thermal expansion coefficient
- Phase stability up to high temp.
- Adhesion to the matrix
- Neutron economy
- Irradiation susceptibility
- Tube fabricability

- Material properties, neutron economy, fabricability, irradiation susceptibility
1-1. Zr Surface Modification by Coating

- Surface coating of Zr cladding with Cr powder to enhance corrosion resistance at high temperature

- Cr coating: Oxide thickness ($H_2$ generation) is reduced by $1/30$ of that in Zry-4 at 1200°C/2000 sec
1-1. Zr Surface Modification by Coating

- **Adhesion of coating** is important to prevent the damage of coated layer during normal/accident conditions

- Ring test shows **good adhesion** of Cr coated layer
  - Cracks were initiated only when strain was higher than 3%
1-2. Zr Surface Modification by ODS Alloying

- ODS alloying to increase mechanical strength: Enhanced deformation resistance → **Reduced ballooning & rupture** during accident

- **Y$_2$O$_3$** particles alloying: Mechanical strength is increased **2 times** at 500°C
1-2. Zr Surface Modification by ODS Alloying

- $Y_2O_3$ particles alloying on cladding tube: Test samples are made using laser beam scanning. $Y_2O_3$ particles are uniformly dispersed in cladding surface

- The thickness of $Y_2O_3$ dispersed layer and the density of $Y_2O_3$ particles: easily controlled by the conditions for laser beam scanning
2. Metal-Ceramic Hybrid Cladding

• Combination of advantages of both metal and ceramic
  - Inner layer: **Zr liner** for ductility and fission gas retention
  - Mid layer: **Ceramic composite (SiC$_f$/SiC)** for high strength and reduced H$_2$ generation
  - Outer layer: **ZrO$_2$ coating** to prevent ceramic composite from being dissolved to coolant

**Ceramic Composite (SiC$_f$/SiC)**
- Accident Tolerant
  - High temperature strength
  - Low reactivity with water
  - Suppressed hydrogen production
- Strengthening
  - Improved mechanical property

**Metal Liner (Zr)**
- Proven Performance
  - Ductility
  - Fission gas retention
  - End cap welding

**Corrosion resistance, High T oxidation**
2. Metal-Ceramic Hybrid Cladding

- Important factors in fabricating: Fabric winding, Impregnation, Surface coating, Mechanical strength
- Mockup samples of 20cm in length are made based on parametric studies
Radioactivity Release and Transportation

- **Xe & Kr**: All the inventory of units 1-3 was released into the atmosphere.
- **Cs & I**: Less than 10% of the inventory.


- Once **Xe, Kr, Cs, and I** are released, they can be **easily transported** around the world together with wind.
KAERI’s Approach to ATF Pellet

• **Mid-term: Micro-cell UO\(_2\) pellets**
  - To **enhance retention capability** of volatile fission products (Cs, I) → Reduced radioactivity release to the environment
  - To **use existing infrastructure**, experience and expertise to the maximum extent possible → Implemented in the near future

• **Long-term: Uranium nitride (UN) composite pellets**
  - To develop innovative fuel pellets with **uranium nitride composite**
  - To **increase thermal conductivity & uranium density** → Reduced fuel temperature (safety) and increased discharge burnup (economy)
1. Micro-cell UO$_2$ Pellet

- To **enhance the retention capability** of volatile fission products (Cs, I) during accident and normal conditions
- To provide many **chemical traps** and/or **physical barriers** within UO$_2$ pellet that prevents volatile fission products from being released to pellet outside
- Cell wall material: Ceramic / metallic micro-cell pellet
1-1. Ceramic Micro-cell UO$_2$ pellet

- **Si containing mixed oxide** for cell-wall: Si reacts with Cs and form metastable phase. Micro-cell concept was implemented successfully

**Pellet fabrication**

<table>
<thead>
<tr>
<th></th>
<th>Wall volume</th>
<th>Grain size</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si-Ti-O (CM-1)</td>
<td>~3%</td>
<td>~80μm</td>
<td>10.6g/cm$^3$</td>
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<tr>
<td>Si-Ti-Al-O (CM-2)</td>
<td>~3%</td>
<td>~85μm</td>
<td>10.6g/cm$^3$</td>
</tr>
<tr>
<td>Si-Cr-O</td>
<td>~3%</td>
<td>~65μm</td>
<td>10.7g/cm$^3$</td>
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</tbody>
</table>

**Thermal diffusivity**

- **Thermal diffusivity**: Ceramic micro-cell pellets have almost the same value as that of pure UO$_2$
1-1. Ceramic Micro-cell UO$_2$ pellet

- **Cs capture test:** Cs element mapping by EDS shows high Cs concentration (yellow spots) along cell walls → Cs reacts preferentially with cell wall material

- **Creep deformation test:** Ceramic cell pellets deform more easily than pure UO$_2$ due to soft cell-wall
1-1. Ceramic Micro-cell UO$_2$ pellet

• To test the behavior of ceramic micro-cell pellet under accident condition and normal operation, test equipment is being installed:
  - Thermal stability test under LOCA simulating heating conditions
1-1. Ceramic Micro-cell UO$_2$ pellet

- To test the behavior of ceramic micro-cell pellet under accident condition and normal operation, test equipment is being installed:
  - High temperature steam oxidation test (1700$^\circ$C, 3 bar of H$_2$O)
  - Water corrosion test in autoclave under normal operating condition
1-2. Metallic Micro-cell UO$_2$ pellet

- **Mo and Cr**: Selected as metallic cell-wall material
- Microstructure shows that metallic cell wall was formed along grain boundaries

<table>
<thead>
<tr>
<th>Element</th>
<th>$T_{\text{melting}}$ (°C)</th>
<th>$k$ (W/mK)</th>
<th>$\sigma_a$ (barn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo</td>
<td>2623</td>
<td>139</td>
<td>2.48</td>
</tr>
</tbody>
</table>

- Main advantage: Enhanced thermal conductivity & retention capability
- Thermal diffusivity: increased **1.5~2 times** compared to UO$_2$
2. Uranium Nitride Composite

**UN’s advantage:** High uranium density & high thermal conductivity

<table>
<thead>
<tr>
<th></th>
<th>UO₂</th>
<th>UN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical density (g/cm³)</td>
<td>10.96</td>
<td>14.32</td>
</tr>
<tr>
<td>Uranium density (U-g/cm³)</td>
<td>9.7</td>
<td>13.5</td>
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<tr>
<td>Melting point (°C)</td>
<td>2,865</td>
<td>2,597</td>
</tr>
</tbody>
</table>

- UN’s disadvantage: **Violent reaction with water**
- To enhance corrosion resistance: 1) modifying atomic structure of UN with minor alloying elements, 2) providing multiple protective layers
# 2. Uranium Nitride Composite

- **Nitride alloy powders**

<table>
<thead>
<tr>
<th></th>
<th>XRD</th>
<th>Raw (×200)</th>
<th>Nitrating (×200)</th>
<th>N-Milling (×1000)</th>
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</thead>
<tbody>
<tr>
<td>U</td>
<td><img src="image" alt="U XRD" /></td>
<td><img src="image" alt="U Raw" /></td>
<td><img src="image" alt="U Nitrating" /></td>
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<td><img src="image" alt="U-Zr N-Milling" /></td>
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<tr>
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<td><img src="image" alt="U₃Si₂ Raw" /></td>
<td><img src="image" alt="U₃Si₂ Nitrating" /></td>
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- **Sintered composite pellet**

  - **Microstructure**

    - ![Microstructure Image](image)
    - **Nitrides**
    - **Oxides**

- **XRD**

  ![XRD Chart](image)
3. Summary

- Cladding material: **Surface modified clad & Metal-ceramic hybrid clad**
- Pellet material: **Micro-cell pellet & UN composite pellet**
Thank you for your attention.