Metallic Nuclear Fuel Study at University of Central Florida (UCF)

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Outline

- Introduction
- Objective
- Experimental Details
- Results and Discussion
- Future Plan
- Sponsor, Partner and Group Members
Introduction: Metallic Fuel

Nuclear energy is very important:

Advantages:
• Safest
• Cheapest
• Clean
• High Efficiency

Use of nuclear power:
• 20% in USA
• 30% in EU
• 80% in France
• 30% in Japan

Major nuclear fuel types:
• Oxide
• Metallic
• Ceramics (carbide, nitride)

Metallic fuels[1]:
Advantages:
• high thermal conductivity
• passive safety
• ease of fabrication
• ease of recycling

Alloy elements are required, such as: Zr, Mo, Ti, Cr.

Introduction: U-Zr fuel

U-Zr fuel:
- developed for sodium fast reactor (SFR)
- encapsulated in stainless steel cladding

SFR[1]:
- generation IV nuclear reactor designs
- employs liquid sodium as coolant
- employs fast neutrons as source
- high efficiency of using nuclear fuels
- minimizes long-lived actinide waste production

FCI (Fuel Cladding Interaction)

U-23at.%Zr vs. Fe diffusion couple annealed at 923K [2].

Introduction: U-Mo fuel

U-Mo fuel:
- developed for the program of Reduced Enrichment for Research and Test Reactor (RERTR)
- dispersed or laminated in aluminum or Al alloy

RERTR [3]:
- to avoid nuclear proliferation
- convert research and test reactor from using HEU fuels to LEU fuels
- increase density of U isotopes in the fuel

**FCI (Fuel Cladding Interaction)**
- induced by interdiffusion.
- involves multiple-phases and multiple-components.

**Deleterious effects:**
- thins the cladding layer.
- produces phases with relative low melting point.

**Objective:**
to help understand the complex FCI.
to provide the experimental diffusion data to verify and improve FCI modeling.
to explore potential barrier layer materials to impede FCI.

**Experiments:**
Solid-to-solid isothermal diffusion studies were carried out.
Scanning Electron Microscopy (SEM) and Electron Probe Microanalysis (EPMA) and Transmission electron microscopy (TEM) were applied to analyze the microstructure, phase constituents and concentration profiles.
Experimental Details

Preparing alloy disks
- Sample cutting
- Sample polishing

Assembling & Capsuling

Annealing & Quenching

Characterization
- SEM
- EPMA
- XRD
- TEM
Diffusion Matrix

<table>
<thead>
<tr>
<th>U related diffusion</th>
<th>Cladding related diffusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>U vs. Fe</td>
<td>Fe vs. Mo</td>
</tr>
<tr>
<td>U vs. Fe-15Cr</td>
<td>Fe vs. Zr</td>
</tr>
<tr>
<td>U vs. Fe-15Cr-15Ni</td>
<td>Mo vs. Zr</td>
</tr>
<tr>
<td>U-Zr vs. Fe</td>
<td>Mo vs. Fe-15Cr</td>
</tr>
<tr>
<td>U-Zr vs. Fe-15Cr</td>
<td>Zr vs. Fe-15Cr</td>
</tr>
<tr>
<td>U-Zr vs. Fe-15Cr-15Ni</td>
<td>Mo vs. Fe-15Cr-15Ni</td>
</tr>
<tr>
<td>U vs. Mo</td>
<td>Zr vs. Fe-15Cr-15Ni</td>
</tr>
<tr>
<td>U-Mo vs. Al</td>
<td></td>
</tr>
<tr>
<td>U-Mo vs. Al-Si</td>
<td></td>
</tr>
</tbody>
</table>
U vs. Fe Diffusion Couples
SEM and EPMA concentration profiles of U vs. Fe at 923K for 4 days.

Thickness of $U_6Fe$ and $UFe_2$.

<table>
<thead>
<tr>
<th>Phase of U</th>
<th>T (K)</th>
<th>Annealing time (hours)</th>
<th>$\Delta x^{(U_6Fe)}$ (µm)</th>
<th>$\Delta x^{(UFe_2)}$ (µm)</th>
<th>$\Delta x^{(U_6Fe)} / \Delta x^{(UFe_2)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$-U (orthorhombic)</td>
<td>853</td>
<td>240</td>
<td>46.4±0.9</td>
<td>2.5±0.1</td>
<td>18.56</td>
</tr>
<tr>
<td></td>
<td>888</td>
<td>240</td>
<td>70.1±0.8</td>
<td>6.0±0.4</td>
<td>11.68</td>
</tr>
<tr>
<td></td>
<td>923</td>
<td>96</td>
<td>64.1±2.5</td>
<td>7.8±0.6</td>
<td>8.22</td>
</tr>
<tr>
<td>$\beta$-U (tetragonal)</td>
<td>953</td>
<td>96</td>
<td>78.4±2.0</td>
<td>8.4±0.3</td>
<td>9.33</td>
</tr>
<tr>
<td></td>
<td>973</td>
<td>96</td>
<td>90.3±2.1</td>
<td>12.1±0.5</td>
<td>7.46</td>
</tr>
</tbody>
</table>
• First kind (extrinsic) growth constant $K_I$ and second kind (intrinsic) growth constant $K_{II}$ were calculated according to Wagner [6] description.

• $K_{II}$ is a characteristic constant value for a phase, and the values of $K_I$ may be affected by other phases existing in the diffusion zone.

• The thick $U_6Fe$ impeded the growth of $UFe_2$ because $K_{I, UFe_2}$ was smaller than $K_{II, UFe_2}$. However, $UFe_2$ layer had a small influence on the growth of $U_6Fe$, since $UFe_2$ is very thin compared to $U_6Fe$.

**Intrinsic and Extrinsic Growth Constant**

First Kind of Diffusion couples ($N^{-\infty} = 0$ ; $N^{+\infty} = 1$)

“Extrinsic”

$$K_{I}^{(v)} = \left[ \frac{(\Delta x^{(v)})^2}{2t} \right]_{N_i^{-\infty} = 0, N_i^{+\infty} = 1}$$

Integrated Interdiffusion Coefficient:

$$\tilde{D}_i^{Int,(v)} = \int_{N_i^{(v)-}}^{N_i^{(v)+}} \tilde{D}dN_i = N_i^{(v)} \times (1 - N_i^{(v)})K_{I}^{(v)} + \frac{\Delta x^{(v)}}{2t} \left[ (1 - N_i^{(v)}) \times \int_{-\infty}^{x^{(v)-}} \frac{V^{(v)}}{V_m} N_i dx \
+ N_i^{(v)} \times \int_{x^{(v)+}}^{+\infty} \frac{V^{(v)}}{V_m} (1 - N_i^{(v)}) dx \right]_{N_i^{-\infty} = 0, N_i^{+\infty} = 1}$$

Second Kind of Diffusion couples ($N^{-\infty} = N^{(v-1)} ; N^{+\infty} = N^{(v+1)}$)

“Intrinsic”

$$\tilde{D}_i^{Int,(v)} = \frac{(N_i^{(v)} - N_i^{(v-1)+})(N_i^{(v+1)-} - N_i^{(v)})}{(N_i^{(v+1)-} - N_i^{(v-1)+})} \times \left[ K_{II}^{(v)} \right]_{N_i^{-\infty} = N_i^{(v-1)}, N_i^{+\infty} = N_i^{(v+1)}}$$
U-Zr vs. Fe Diffusion Couples
SEM of U10wt.%Zr vs. Fe at 650 °C for 4 days.

- Layer-A including reaction layers adjacent to Fe.
- Layer-B including layers with ε-phase and χ-phase.
- Layer-C including layer with λ-phase.
U-Zr vs. Fe: Growth Constant

Activation Energy
- Layer A: 393 kJ/mol
- Layer B: 363 kJ/mol
- Layer C: 224 kJ/mol
- Sum: 304 kJ/mol
U vs. Mo Diffusion Couples
U vs. Mo: SEM and EPMA

SEM image and concentration profiles of U vs. Mo at 1273K for 24 hours.

SEM image and concentration profiles of U vs. Mo at 973K for 360 hours.

- Phase Boundary
- Marker Plane
- U diffused faster than Mo
U vs. Mo: Interdiffusion

Interdiffusion coefficients of U-Mo alloy.

Temperature dependence of interdiffusion coefficients at $N_{\text{Mo}}=0.12, 0.18, 0.24$.

Composition dependence of activation energy of interdiffusion.