AGR-2 and AGR-3/4 Heating Tests

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Outline

• AGR-2 reirradiation testing
  - Purpose
  - FACS description
  - Sample preparation
  - Results

• AGR-3/4 heating test results
  - Fission product releases
  - Release rates
AGR-2 Reirradiation Heating Testing

• Goal: measure short-lived fission products release (e.g., I-131 and Xe-133) from irradiated TRISO particles

• Execution:
  - Select deconsolidated particles from AGR-2 Compacts 6-4-1 and 5-4-2
  - Crack particles to remove TRISO coatings (6-4-1) or crack while retaining TRISO coatings (5-4-2)
  - Reirradiate kernels in NRAD to produce I-131 ($t_{1/2} = 8.02$ d) and Xe-133 ($t_{1/2} = 5.2$ d)
  - Retrieve kernels and transfer them to Fuel Accident Condition Simulator (FACS) furnace
  - FACS fission gas monitoring system (FGMS) measures Xe-133 during test, FACS condensation plates collect I-131
Reirradiation Test 1 – Deconsolidated AGR-2 Compact 6-4-1 Particles

- Particles cracked to remove TRISO layers leaving bare kernels
- Four kernels loaded into individual containers and gamma counted
- Individual containers loaded into aluminum container for reirradiation

<table>
<thead>
<tr>
<th>Compact</th>
<th>Average Burnup (% FIMA)</th>
<th>Average Fast Fluence $\times 10^{25}$ (n/m$^2$)</th>
<th>Irradiation Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-4-1</td>
<td>9.24</td>
<td>2.20</td>
<td>1081</td>
</tr>
</tbody>
</table>

Loading into holders for heating testing and reirradiation
Reirradiation Test 1 in Neutron Radiography Reactor (NRAD)

- Aluminum capsule with kernels inserted in C4SW position
- Reirradiation was for 4 days at 8 hours per day
- Calculated I-131 prior to FACS testing: 8.64 µCi/particle
- Calculated Xe-133 prior to FACS testing: 25.1 µCi/particle
- Kernels gamma counted after NRAD before FACS
Releases from 1600°C Test of Reirradiated AGR-2 6-4-1 Kernels

- I-131 and Xe-133: Releases similar; Supports assumption that I-131 behaves like Xe-133
- Kr-85: releases under-measured; some lost when TRISO coating removed; indicates most Kr-85 is in kernel when TRISO coatings intact
- Eu-154: ~20% retention in kernel

Fractions based on measured/calculated ratio.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Total Fraction Released</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs-134</td>
<td>0.8524</td>
</tr>
<tr>
<td>Eu-154</td>
<td>0.7950</td>
</tr>
<tr>
<td>I-131</td>
<td>0.9997</td>
</tr>
<tr>
<td>Kr-85</td>
<td>0.6705</td>
</tr>
<tr>
<td>Xe-133</td>
<td>0.8428</td>
</tr>
</tbody>
</table>
Reirradiation Tests 2 and 3: AGR-2 Compact 5-4-2 Particles

<table>
<thead>
<tr>
<th>Compact</th>
<th>Average Burnup (% FIMA)</th>
<th>Average Fast Fluence $\times 10^{25}$ (n/m$^2$)</th>
<th>Irradiation Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-4-2</td>
<td>12.03</td>
<td>3.14</td>
<td>1071</td>
</tr>
</tbody>
</table>

- Bare kernels not representative of failed TRISO particle
- New samples prepared with small through-TRISO cracks
- ORNL: Particles mounted in epoxy in individual IG-110 holders
- ORNL: Impact cracked after mounting, imaged with X-ray CT
- INL: Gamma counted cracked particles before reirradiation
Test 2: 5-4-2 Cracked Particles Inspected by XRCT

- X-ray CT images from ORNL
- Success criteria:
  - Cracking extends through OPyC, SiC, and IPyC
  - Avoid significant SiC shearing
  - Avoid SiC cracks at bottom of hemisphere
Test 3: Second Set of AGR-2 5-4-2 Particles

- X-ray CT images from ORNL
- Arrows highlight induced through-TRISO cracks
Test 2 Summary: cracked 5-4-2 particles heated at 1600°C

- This test ~ 4 times longer than Test 1 with 6-4-1 bare kernels. At longer time, shows additional Eu-154 release compared to short test.
- I-131 and Kr-85 releases within 10%

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Total Fraction Released</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs-134</td>
<td>1.03</td>
</tr>
<tr>
<td>Eu-154</td>
<td>0.964</td>
</tr>
<tr>
<td>I-131</td>
<td>0.996</td>
</tr>
<tr>
<td>Kr-85</td>
<td>0.898</td>
</tr>
<tr>
<td>Xe-133</td>
<td>0.720</td>
</tr>
</tbody>
</table>

Fractions based on measured/calculated ratio.
Test 3 Summary: cracked 5-4-2 particles heated at 1400°C

- Kr-85 and Xe-133 releases similar to prior 1600°C tests
- Cs-134 and Eu-154 releases similar to 5-4-2 1600°C test

Challenges:
- Sample handling:
  - Difficulty separating particles from holders and counting each separately
  - Difficulties not encountered in prior tests
- Sample handling and isotope detection limits:
  - Calculating new FACS condensation plate collection efficiencies
  - Correcting for holdup in the graphite holder

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Total Fraction Released</th>
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<tbody>
<tr>
<td>Cs-134</td>
<td>0.994</td>
</tr>
<tr>
<td>Eu-154</td>
<td>0.982</td>
</tr>
<tr>
<td>I-131</td>
<td>0.975</td>
</tr>
<tr>
<td>Kr-85</td>
<td>0.884</td>
</tr>
<tr>
<td>Xe-133</td>
<td>0.793</td>
</tr>
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</table>

- Fractions based on measured/calculated ratio.
- Cs-134 and I-131 “old” used original FACS 1600°C efficiencies. Others used efficiencies calculated for this particular test.
Comparison I-131

- Releases range ~97-100%
- New efficiencies were calculated for both 1400 and 1600°C
- Additional efficiencies are needed at lower temps and for other isotopes
Comparison Xe-133

- Release range 73-84%
- Errors overlap
Comparison Kr-85

- The 1400 and 1600°C tests show release range 88-90%
- Some overlap between Kr-85 and Xe-133 releases
- Kr-85 releases might be slightly higher than Xe-133
- Total 6-4-1 Kr-85 releases appear lower than reality due to cracking off coatings prior to test
Status of AGR-2 Particle Reirradiation Heating Tests

- Tests serve two purposes:
  - Determine I-131 and Xe-133 retention in exposed kernels to address sparsity of data
  - Provide FACS condensation plate collection efficiencies for temperatures other than 1600°C
    - Needed for AGR-3/4 testing and upcoming AGR-5/6/7 testing
    - Challenge: Ag-110m in AGR-2 fuel has already decayed through ~10 half-lives.

<table>
<thead>
<tr>
<th>Compact</th>
<th>FACS Testing Temperature (°C)</th>
<th>Completed</th>
<th>Planned</th>
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<tbody>
<tr>
<td>6-4-1</td>
<td>1600</td>
<td>FY18</td>
<td></td>
</tr>
<tr>
<td>5-4-2</td>
<td>1600</td>
<td>FY18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1400</td>
<td>FY19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1200</td>
<td>FY19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td></td>
<td>FY20</td>
</tr>
<tr>
<td></td>
<td>Repeat 1400</td>
<td></td>
<td>FY20</td>
</tr>
<tr>
<td></td>
<td>(Optional) repeat 1200</td>
<td></td>
<td>FY20</td>
</tr>
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</table>
AGR-3/4 Compact Heating Tests
Completed AGR-3/4 Compact Heating Tests

<table>
<thead>
<tr>
<th>Compact ID</th>
<th>Burnup (% FIMA)</th>
<th>Fast Fluence (n/m², E &gt; 0.18 MeV)</th>
<th>TAVA Irradiation Temp (°C)</th>
<th>Heating Test Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-2</td>
<td>12.5</td>
<td>4.17E+25</td>
<td>1196</td>
<td>1600/1700</td>
</tr>
<tr>
<td>8-2</td>
<td>14.6</td>
<td>5.11E+25</td>
<td>1213</td>
<td>1400</td>
</tr>
<tr>
<td>10-2</td>
<td>12.0</td>
<td>4.01E+25</td>
<td>1213</td>
<td>1200</td>
</tr>
<tr>
<td>10-4</td>
<td>11.4</td>
<td>3.75E+25</td>
<td>1168</td>
<td>1400</td>
</tr>
</tbody>
</table>

FIMA: fissions per initial metal atom
TAVA: time-averaged, volume-averaged

Symbols show time and temp of condensation plate changes
Compact 8-2: 1400°C Test

Note:
- Fractions based on measured/calculated ratio
- 1 particle equates to a compact fraction of 5.29E-4
Ag-110m Comparison

- AGR-3/4 1400 and 1600°C tests rates comparable to AGR-1 1600°C tests
- AGR-3/4 1200°C test had highest rates: $t > 24$ hrs, rate $3 \times 10^{-5}$ to $8 \times 10^{-5}$ hr$^{-1}$
- At 1150°C, AGR-1 Compact 4-2-2 Ag-110m release rate was $3.9 \times 10^{-5}$ hr$^{-1}$

Note: 1 particle equates to a compact fraction of $5.29 \times 10^{-4}$
Cs-134 Comparison

- Compact 3-2 rate increases when temperature raised to 1700°C, rate decreases after ~ 30 hrs at 1700°C, indicates depletion
- Mass balance indicates little Cs remains in DTF after irradiation. Heating tests support this.

Note: 1 particle equates to a compact fraction of 5.29E-4
Eu-154 and Sr-90

- Eu-154 and Sr-90 similar at each temperature. Releases and rates increase with temperature.
- Higher burnup 8-2 has slightly higher releases than 10-4.
- DTF contribution to rate most obvious in AGR-3/4 Compact 3-2 1600/1700°C test.
- Preliminary: for T ≤ 1400°C ~ 75-87% of DTF inventory remains in compact after irradiation AND heating (FACS efficiencies may change).

Notes:
- 1 particle equates to a compact fraction of 5.29E-4
- “high estimate” includes values determined from minimum detectable activities (MDA)
- “low estimate” takes MDAs to be zero
**Kr-85 Comparisons**

- Release rates generally higher than AGR-1
- Releases 5 to 200x higher than typical AGR-1 1600°C test, but still low:
  - Highest total release was 0.4 of 1 particle
  - Lowest total release was 0.05 of 1 particle
- Appears majority of Kr-85 released in-pile
- A small amount (~2%) is retained in DTF kernels after irradiation

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**Table:**

<table>
<thead>
<tr>
<th>Rates</th>
<th>Temp (°C)</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-2</td>
<td>1200</td>
<td>2.43E-6</td>
<td>1.59E-8</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
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<tr>
<td>10-4</td>
<td>1400</td>
<td>4.90E-6</td>
<td>4.36E-7</td>
<td>1.93E-7</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>8-2</td>
<td>1400</td>
<td>1.56E-6</td>
<td>3.59E-7</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
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<tr>
<td>3-2</td>
<td>1600/1700</td>
<td>1.25E-5</td>
<td>3.09E-7</td>
<td>1.10E-7</td>
<td>1.51E-6</td>
<td>3.07E-7</td>
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<tr>
<td>AGR-1</td>
<td>1600</td>
<td>1E-9</td>
<td>(typical, with no TRISO failures)</td>
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<td></td>
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<tr>
<td>AGR-1</td>
<td>1700</td>
<td>4E-8</td>
<td>(typical, with no TRISO failures)</td>
<td></td>
<td></td>
<td></td>
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</table>
Must complete 2 Compact Reirradiations in NRAD and subsequent FACS heating testing for Level 2 milestone in FY19.

Purpose of these tests:
- Compare to AGR-2 loose kernel/particle tests
- AGR-3/4 = most prototypic test for Xe-133 and I-131 behavior in exposed kernels
- Calculate effective diffusivity (kernel & compact matrix) for Xe-133 and I-131

### AGR-3/4 Completed and Planned Heating Tests

<table>
<thead>
<tr>
<th>Capsule</th>
<th>Compact</th>
<th>Test Temp (°C)</th>
<th>Completed</th>
<th>Planned</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2</td>
<td>1600</td>
<td>FY17</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>1400</td>
<td>FY18</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>1200</td>
<td>FY18</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>1400</td>
<td>FY18</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1600</td>
<td></td>
<td>FY19 – reirradiation test</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>1200</td>
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<td>FY19 – reirradiation test</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>1400</td>
<td></td>
<td>FY20 – reirradiation test</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1400</td>
<td></td>
<td>FY20 – reirradiation test</td>
</tr>
</tbody>
</table>
Conclusions from Completed AGR-3/4 Heating Tests

- Tests demonstrate releases from exposed kernels during a core-conduction cooldown event at end of life (EOL)
- At similar or lower test temperatures, exposed kernels → higher Cs, Eu, Sr, and Kr-85 releases than intact fuel
- Tests show that EOL releases from exposed kernels are small compared to sudden release from failure of a particle that was intact all the way through the irradiation
  - Cesium
    - 0.2% to 4.5% of the exposed kernel fraction
  - Europium and strontium:
    - $1200 \leq T \leq 1400^\circ C$: 0.02% to 0.5%
    - $T \geq 1600^\circ C$: 50% (includes intact fuel contribution)
  - Kr-85
    - 0.25% to 2%
- Certain fission products (i.e., Cs and Kr-85) would be outside of the fuel already and either cleaned out of the coolant or deposited in cooler places throughout the core/reactor system
- It is estimated that exposed kernels retain 2% of their Kr-85 at the end of irradiation
- Ag-110m behavior dictated by intact fuel
## Questions and Discussion

<table>
<thead>
<tr>
<th>John Stempien</th>
<th>AGR PIE Technical Lead</th>
</tr>
</thead>
<tbody>
<tr>
<td><a href="mailto:John.Stempien@inl.gov">John.Stempien@inl.gov</a></td>
<td>Phone (208) 526-8410</td>
</tr>
</tbody>
</table>
AGR-2 Reirradiation Testing I-131, Xe-133, and Kr-85 summary
AGR-2 Reirradiation/Heating Test Sequence

1. Cracked particles: Each particle was gamma counted prior to cracking.

2. Cracked particles loaded into individual graphite holders

3. Each of the four graphite holders should be gamma counted separately on the HOG after loading to get a final pre-test fission product inventory.

4. All four graphite holders are loaded into aluminum capsule.

5. Capsule inserted in NRAD, and particles reirradiated

6. After re-irradiation, capsule unloaded from NRAD.

7. Graphite holders removed from re-irradiation capsule and placed individually into four clean aluminum holders. Repackaging after re-irradiation is required due to Na-24 produced in the Al holder.

8. Each of the four aluminum holders is gamma counted individually on the HOG.

9. After the post-re-irradiation gamma count in the HOG, graphite sample holders are removed from the Al holders.

10. Each graphite holder is loaded into the FACS furnace for heating.

11. FACS condensation plates packaged into Al containers and gamma counted on the HOG.

12. Graphite holders unloaded from the FACS furnace

13. Graphite holders loaded into Al holders

14. Each Al holder gamma counted individually on the HOG.

15. Each graphite holder removed from each Al holder. Graphite holders opened and particle/cup removed.

16. Separately count each particle/cup and graphite holder on HOG