Status of AGR-5/6/7 Fuel Fabrication

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Outline

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• TRISO Particle Fabrication
  – Challenges Overcome
  – Selection of TRISO Particle Batches
  – TRISO Particle Lot Characterization
• AGR-5/6/7 Fuel Compact Fabrication
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  – Characterization Data
    • Dimensional
    • Defect Fractions
• What We Have Learned
Advanced Gas Reactor Program Overview

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<td>Laboratory</td>
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<td>Engineering</td>
<td>Laboratory</td>
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<td>AGR-5/6/7</td>
<td>Fuel qualification and fuel performance margin testing experiments</td>
<td>Engineering</td>
<td>Engineering</td>
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## Fuel Fabrication Overview (cont.)

<table>
<thead>
<tr>
<th>AGR-5/6/7 Material</th>
<th>Produced</th>
<th>Used</th>
<th>Residue</th>
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<tbody>
<tr>
<td><strong>Certified LEUCO kernels</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J52R-16-69317</td>
<td>19.0 kg</td>
<td>18 kg</td>
<td>~1 kg</td>
</tr>
<tr>
<td>J52R-16-69318</td>
<td>5.1 kg</td>
<td>---</td>
<td>5.1 kg</td>
</tr>
<tr>
<td><strong>TRISO particles</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lot 98005</td>
<td>11.6 kg</td>
<td>6.1 kg</td>
<td>5.5 kg</td>
</tr>
<tr>
<td>Spares (93172, 93173)</td>
<td>~ 6 kg</td>
<td>---</td>
<td>~ 6 kg</td>
</tr>
<tr>
<td><strong>Overcoated particles</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25% PF</td>
<td>3.68 kg</td>
<td>3.46 kg</td>
<td>0.22 kg</td>
</tr>
<tr>
<td>40% PF</td>
<td>7.82 kg</td>
<td>7.08 kg</td>
<td>0.74 kg</td>
</tr>
<tr>
<td><strong>Compacts</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25% PF</td>
<td>684</td>
<td>147 + 80</td>
<td>457</td>
</tr>
<tr>
<td>40% PF</td>
<td>948</td>
<td>95 + 114</td>
<td>739</td>
</tr>
</tbody>
</table>
TRISO Particle Fabrication

• Restart challenges
  – Furnace maintenance
  – Operator experience
    • Infrequent operation
    • Turnover and reassignment
  – Equipment issues resulting in coating interruptions
  – Upgrading issues
    • Unexpected retention of undersized particles and fragments
    • Determined sieve shaker intensity was less than adequate
    • Re-sieved all of the product with revised parameters
    • Realized impressive reductions in the exposed kernel defect and missing-buffer fractions
TRISO Particle Lot Characterization

- Schedule Recovery Strategy:
  - Use certified kernels for 3x pre-production runs and ≤ 5 production runs
  - Use 3 – 5 TRISO particle batches for the certified TRISO particle lot

<table>
<thead>
<tr>
<th>Batch/Lot Layer Thicknesses (µm)</th>
<th>Buffer 100 ± 15</th>
<th>IPyC 40 ± 4</th>
<th>SiC 35 ± 3</th>
<th>OPyC 40 ± 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>JF2O-16-93165</td>
<td>104.5</td>
<td>40.7</td>
<td>36.6</td>
<td>30.3</td>
</tr>
<tr>
<td>JF2O-16-93168</td>
<td>96.6</td>
<td>39.1</td>
<td>35.7</td>
<td>38.5</td>
</tr>
<tr>
<td>JF2O-16-93169</td>
<td>98.7</td>
<td>38.9</td>
<td>35.8</td>
<td>36.0</td>
</tr>
<tr>
<td>JF2O-16-93170</td>
<td>101.5</td>
<td>38.2</td>
<td>36.5</td>
<td>35.6</td>
</tr>
<tr>
<td>JF2O-16-93172</td>
<td>100.7</td>
<td>38.0</td>
<td>36.5</td>
<td>38.7</td>
</tr>
<tr>
<td>JF2O-16-93173</td>
<td>100.7</td>
<td>38.4</td>
<td>35.1</td>
<td>39.7</td>
</tr>
<tr>
<td>J52R-16-98005 (lot)</td>
<td>100.4</td>
<td>39.2</td>
<td>36.1</td>
<td>35.0</td>
</tr>
</tbody>
</table>

Note: J52R-16-93166, 93167, and 93171 were excluded due to process interruptions.
TRISO Particle Lot Characterization (cont.)

- SiC aspect ratio passes the fuel specification
- Missing OPyC defect passes
- 11.6 kg of TRISO particles in the lot

<table>
<thead>
<tr>
<th>Batch/Lot Layer Density and BAF&lt;sub&gt;O&lt;/sub&gt;</th>
<th>Buffer $\rho_B$</th>
<th>IPyC $\rho_I$</th>
<th>BAF&lt;sub&gt;O&lt;/sub&gt;</th>
<th>SiC $\rho_S$</th>
<th>OPyC $\rho_O$</th>
<th>BAF&lt;sub&gt;O&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.05 ± 0.10</td>
<td>1.90 ± 0.05</td>
<td>≤ 1.045</td>
<td>≥ 3.19</td>
<td>1.90 ± 0.05</td>
<td>≤ 1.035</td>
</tr>
<tr>
<td>JF2O-16-93165</td>
<td>1.04</td>
<td>1.895</td>
<td>1.042</td>
<td>3.195</td>
<td>1.894</td>
<td>1.030</td>
</tr>
<tr>
<td>JF2O-16-93168</td>
<td>1.05</td>
<td>1.899</td>
<td>1.041</td>
<td>3.194</td>
<td>1.901</td>
<td>1.030</td>
</tr>
<tr>
<td>JF2O-16-93169</td>
<td>1.00</td>
<td>1.898</td>
<td>1.039</td>
<td>3.196</td>
<td>1.900</td>
<td>1.028</td>
</tr>
<tr>
<td>JF2O-16-93170</td>
<td>1.03</td>
<td>1.897</td>
<td>1.042</td>
<td>3.194</td>
<td>1.895</td>
<td>1.032</td>
</tr>
<tr>
<td>JF2O-16-93172</td>
<td>1.02</td>
<td>1.900</td>
<td>1.040</td>
<td>3.190</td>
<td>1.888</td>
<td>1.030</td>
</tr>
<tr>
<td>JF2O-16-93173</td>
<td>1.04</td>
<td>1.896</td>
<td>---</td>
<td>3.190</td>
<td>1.893</td>
<td>---</td>
</tr>
<tr>
<td>J52R-16-98005</td>
<td>1.03</td>
<td>1.897</td>
<td>1.041</td>
<td>3.195</td>
<td>1.897</td>
<td>1.030</td>
</tr>
</tbody>
</table>
Material Flow Chart

TRISO Coating

93165B

Lot J52R-16-98005

93166B

93169B

93170B

Overcoating

11034

11035

11036

11037

40% PF

25% PF

Compacting

13144

13145

13146

13147

Firing

14154

14155

14156

14157
**AGR-5/6/7 Fuel Compacts**

- Overcoat of resinated graphite applied in a mechanically fluidized bed
- Use of alcohol as a resin solvent eliminated
- Mass of resinated graphite overcoat calculated and applied
- Bulk density varies with packing fraction and from run-to-run
- Volumetric feeder insert chosen to give desired compact length
- BWXT delivered fuel compacts 3-weeks ahead of the milestone date
AGR-5/6/7 Fuel Compacts (cont.)

- Warm pressing used to reduce stresses on TRISO particles
  - A3-27 based matrix (novolac resin with HMTA, no alcohol)
  - Die body temperature ~ 165ºC
  - Punch hold with partial compression for better heating to soften the resin
  - Hold at force; 4.5 kN (9.3 MPa) to 5.0 kN (10.4 MPa) for partial cure

- Thermal treatment (firing) of compacts
  - Cure, carbonization, and final heat soak without unloading the furnace
  - Cure and carbonization at ~ 680 torr in an argon atmosphere
  - Final heat treatment under sub-millitorr vacuum
  - Temperature ramp rate
    - Varied temperature ramp rates from resin cure through carbonization
    - DSC/TGA data used for setting temperature schedule

- Dimensional measurements on “green” and “fired” compacts to monitor changes
Resinated Graphite DSC-TGA Scan

- At low temperatures:
  - lower MW gases/high specific volume
  - low matrix porosity
  - low matrix stiffness
  - highest susceptibility for deformation

- At high temperatures:
  - higher MW gases/low specific volume
  - high matrix porosity
  - rigid matrix

- A more linear mass loss rate thought preferable
Temperature Ramp Rates for Carbonization

- **Blue bars** show temperature ramp rate for a linearly increasing mass loss rate.

- **Red bars** show programmed temperature ramp rates.
Furnace Temperature Profile

- Temperature soak holds were eliminated, except at the final carbonization temperature.
# AGR-5/6/7 Compact Characterization

<table>
<thead>
<tr>
<th>Compact Batch</th>
<th>Diameter (mm)</th>
<th>Length (mm)</th>
<th>Mass (g)</th>
<th>$\rho_{\text{Matrix}}$ (g/cm³)</th>
<th>U loading (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J52R-16-14154A</td>
<td>12.293</td>
<td>25.094</td>
<td>6.729</td>
<td>1.74</td>
<td>1.428</td>
</tr>
<tr>
<td>J52R-16-14155A</td>
<td>12.291</td>
<td>24.692</td>
<td>6.607</td>
<td>1.73</td>
<td>1.388</td>
</tr>
<tr>
<td>J52R-16-14156A</td>
<td>12.237</td>
<td>24.996</td>
<td>6.182</td>
<td>1.76</td>
<td>0.923</td>
</tr>
<tr>
<td>J52R-16-14157A</td>
<td>12.260</td>
<td>24.752</td>
<td>6.093</td>
<td>1.74</td>
<td>0.914</td>
</tr>
</tbody>
</table>

![25% PF Compact Dimensions](image1.png) ![40% PF Compact Dimensions](image2.png)
Compact Photos

25% PF Compacts

40% PF Compacts
LANL Proton CT showing localized axial particle density, which is higher on the compact end faces of a development compact, but homogenous in the interior
INL X-ray CT showing radial particle distribution in a 25% PF AGR-5/6 compact.
AGR-5/6/7 Fuel Compacts (cont.)

- Significant damage can be done to TRISO particles
  - 25% PF compacts show no net increase in U contamination
  - 40% PF compacts show high U contamination; failing the fuel specification
- Source of damage is being investigated
What We Have Learned

• TRISO Particle Coating
  – “Like kind” or “like-for-like” parts replacement
  – “Operational Rhythm” impacts quality and production schedule

• Overcoating
  – Highly uniform product – no upgrading is required
  – Alcohol as solvent and wetting agent is not necessary
  – Batch-to-batch overcoat density variability (product bulk density) was noted

• Compacting and Firing
  – Mold release lubricant – flush capability needed
  – Holding at partial compression to warm the particles is beneficial
  – Firing schedule based on DSC/TGA data is beneficial
  – TRISO particles are concentrated near the compact surfaces

• Yet to be learned
  – Source of damage to TRISO particles during overcoating and/or compacting