Enclosure 1

Presentation Materials for the September 8, 2021 ACRS Meeting

(Non-Proprietary)
Topical Report Contents

• Introduction
• Fuel Behavior (including PIRT analysis)
• Fuel Modeling
• Verification and Validation / Uncertainty Quantification
• KP-BISON Code
• Fuel Performance Analysis Methodology
# UCO TRISO Fuel Behavior

- **Fuel Kernel (UCO)**: Swells outward, pushes buffer outward.
- **Porous Carbon Buffer**: Shrinks inward, pulls IPyC inward if not debonded.
- **Inner Pyrolytic Carbon (IPyC)**: Shrinks early during irradiation and then start swelling later in irradiation as fast neutron fluence accumulates. Dimensional changes are anisotropic.
- **Silicon Carbide (SiC)**: Elastic behavior. PyC shrinkage provides compressive stress. Fission gas pressure causes tensile stress.
- **Outer Pyrolytic Carbon (OPyC)**: Shrinks and creeps.

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### Table: Irradiation Behavior

<table>
<thead>
<tr>
<th>Coating Layer</th>
<th>Irradiation Behavior</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kernel</td>
<td>Swells outward</td>
<td>Pushes buffer outward</td>
</tr>
<tr>
<td>Buffer</td>
<td>Shrinks inward</td>
<td>Pulls IPyC inward if not debonded</td>
</tr>
<tr>
<td>IPyC / OPyC</td>
<td>Shrink early during irradiation and then start swelling later in irradiation as fast neutron fluence accumulates. Dimensional changes are anisotropic.</td>
<td>Swelling starts radially at moderate fast neutron fluence levels and tangentially at higher fast neutron fluence levels</td>
</tr>
<tr>
<td>SiC</td>
<td>Elastic behavior</td>
<td>PyC shrinkage provides compressive stress. Fission gas pressure causes tensile stress</td>
</tr>
</tbody>
</table>

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UCO TRISO Fuel Behavior — Failure Mechanisms

Key failure mechanisms identified in TRISO fuel
• Pressure vessel failure of spherical or aspherical particles resulting in the failure of all three coating layers
• Cracking of the IPyC layer leading to SiC failure
• Partial debonding of the IPyC from the SiC leading to SiC failure
• Kernel migration towards the SiC layer and its subsequent failure
• Chemical attack of the SiC layer by fission products or CO leading to its failure
• Thermal decomposition of the SiC layer at high temperatures
• Buffer fracture leading to cracking of undebonded IPyC

KP-BISON models failure mechanisms relevant to UCO fuel under KP-FHR irradiation conditions with the purpose of predicting the potential failure of the SiC layer and the release of fission products.
UCO TRISO Fuel Performance Modeling – KP-BISON

➢ Fluoride Salt-Cooled High Temperature Reactor (KP-FHR)
➢ UCO TRISO Fuel

Engineering-scale nuclear fuel performance code
➢ Finite-element modeling of LWR, TRISO, and metal fuels in 1D-spherical, 2D-axisymmetric, and 3D geometries
➢ Fully-coupled thermodynamics and species diffusion equations
➢ Steady and transient reactor operations
KP-BISON was chosen as Fuel Performance Code by Kairos Power

- Computational benefits from the MOOSE framework
- Leverage of extensive development effort by INL and NEAMS
- Level of development and maturity of BISON code
  - Co-development KP-INL
  - FOA award DE-NE0008854 *Modeling and Simulation Development Pathways to Accelerating KP-FHR Licensing*
- Efficient support from development and maintenance team (“BISON Team”) at INL
KP-BISON – Inputs & Outputs

Geometry
➢ radius, thickness, etc.

Fuel characteristics
➢ composition, densities, etc.

Variation in as-fabricated properties

Material properties implemented in KP-BISON

Irradiation conditions
➢ Fission rate density
➢ Fast fluence
➢ Coolant temperature

Fuel temperature, fission gas pressure, displacements, stress

Figures of Merit (FOMs)
Failure probability
Fission product release

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Leverage of extensive DOE effort in the development and qualification of UCO TRISO fuel (AGR Program)

KP-FHR UCO TRISO fuel is similar to AGR UCO TRISO fuels

• AGR-2 -> *UCO TRISO-Coated Particle Fuel Performance* - Topical Report EPRI-AR-1(NP)-A

• AGR-5/6/7 -> AGR Program’s UCO TRISO fuel qualification and margin tests
# KP-BISON – Material Properties & Physical Models

<table>
<thead>
<tr>
<th>TRISO Constituents</th>
<th>Material Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Swelling</td>
</tr>
<tr>
<td></td>
<td>Elastic modulus</td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td></td>
<td>Irradiation-induced creep</td>
</tr>
<tr>
<td></td>
<td>Poisson’s ratio in creep</td>
</tr>
<tr>
<td></td>
<td>Irradiation-induced dimensional changes</td>
</tr>
<tr>
<td></td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td></td>
<td>Specific heat capacity</td>
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<tr>
<td></td>
<td>Thermal expansion</td>
</tr>
<tr>
<td></td>
<td>Diffusion coefficients</td>
</tr>
</tbody>
</table>

Existing database of material properties and physical models suited to modeling of TRISO fuel behavior and performance

<table>
<thead>
<tr>
<th>Physical Models</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Equation</td>
<td>Thermal state of the particle and temperature profile across the kernel and coating layers</td>
</tr>
<tr>
<td>Fission yields</td>
<td>Generation of fission products</td>
</tr>
<tr>
<td>Fission gas release</td>
<td>Generation of internal pressure</td>
</tr>
<tr>
<td>Internal gas pressure</td>
<td>Stress state of the particle potentially leading to its failure</td>
</tr>
<tr>
<td>Palladium penetration</td>
<td>Corrosion of the SiC layer potentially leading to its failure</td>
</tr>
<tr>
<td>Release rate over birth rate (R/B) ratio</td>
<td>Indicator of TRISO failure</td>
</tr>
<tr>
<td>Fission product transport (Fickian diffusion)</td>
<td>Release of fission products to the coolant</td>
</tr>
</tbody>
</table>
Verification & Validation

**INL Benchmark International Data**
- Code-to-code comparison with PARFUME
  - Representative cases of KP-FHR
- AGR-1 and AGR-2 PIE and AGR-5/6/7 R/B data
  - Select data within KP-FHR envelope
  - Separate effects
- Additional PIE or R/B data
  - German, Chinese, etc.

**IAEA CRP-6 Benchmark**
- Fuel Performance Models During Normal Operation And Operational Transients
  - Verification: cases 1-13
- Fission Product Release Behavior Models Under Accident Conditions
  - Verification: cases 1-5
  - Validation: cases 6-11

**Gen-IV Benchmark**
- TRISO Fuel Performance Models Under Accident Conditions
  - Select AGR-1, AGR-2, and HFR-EU1bis safety tests
  - Includes code-to-code comparison during normal operation
For each TRISO particle
• Irradiation input parameters
• Thermo-mechanical analysis of the TRISO coating layers
• Evaluation of the failure probability (stress) and fission product release (diffusivities)
Particle-to-particle statistical variations in physical dimensions and fuel properties (layer thickness, density, etc.) that arise from the fuel fabrication process.

Particles in the tails of the statistical distributions are more prone to failure.

⇒ statistical treatment of a large population of particles to compute its overall failure probability.

⇒ Monte Carlo computation scheme implemented in KP-BISON

<table>
<thead>
<tr>
<th>Property</th>
<th>Specified Mean Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kernel diameter (µm)</td>
<td>425 ± 10</td>
</tr>
<tr>
<td>Buffer thickness (µm)</td>
<td>100 ± 15</td>
</tr>
<tr>
<td>PyC thickness (µm)</td>
<td>40 ± 4</td>
</tr>
<tr>
<td>SiC thickness (µm)</td>
<td>35 ± 3</td>
</tr>
<tr>
<td>Kernel density (g/cm³)</td>
<td>≥ 10.4</td>
</tr>
<tr>
<td>Buffer density (g/cm³)</td>
<td>1.05 ± 0.10</td>
</tr>
<tr>
<td>PyC density (g/cm³)</td>
<td>1.90 ± 0.05</td>
</tr>
<tr>
<td>SiC density (g/cm³)</td>
<td>≥ 3.19</td>
</tr>
<tr>
<td>C/U atomic ratio</td>
<td>0.40 ± 0.10</td>
</tr>
<tr>
<td>O/U atomic ratio</td>
<td>1.50 ± 0.20</td>
</tr>
<tr>
<td>PyC BAF</td>
<td>≤ 1.045</td>
</tr>
<tr>
<td>SiC aspect ratio</td>
<td>1.04</td>
</tr>
</tbody>
</table>
Monte Carlo Calculation Scheme

- Sampling loop
- Sampling Fuel Properties
- Fuel Performance Analysis of sampled particle
- Computation of statistics for all sampled particles
- Failure Probability Fission Product Release
Uncertainty Quantification

Uncertainty exists in:

- Operating conditions (i.e., fission rate density, neutron flux, temperature)
- Material properties that define the mechanical state of the TRISO particles and, ultimately, the integrity of the coating layers
- Physical models that determine some of the physical quantities affecting material properties and fission product transport
- Fuel properties (geometrical dimension, density, etc.) that are tailored by fuel fabrication to obtain TRISO particles that adequately perform under irradiation

⇒ sensitivity studies will be conducted to assess the quantitative impact of the variations of these input parameters to the probability of failure of the TRISO particles and subsequent release of fission products.
A proprietary methodology was developed to ensure that the probability of failure of the TRISO particles and subsequent release of fission products are calculated conservatively.

In particular, the methodology derives one-sided 95/95 tolerance limits on the two FOMs.