GE Hitachi Nuclear Energy

Monte Carlo Simulation of Fuel Pellet Spills with Axial Inter-Pellet Moderation and Stochastic Geometry

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Data, Analysis, and Operations in Nuclear Criticality Safety - I

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Overview

• Introduction
• Methodology
• Results
• Summary and Conclusions
Introduction

- In LWR nuclear fuel manufacturing facilities, spills of UO$_2$ pellets are of concern to criticality safety.

- Occurrence of a criticality incident or accident depends on the mass, geometry and moderation involved in a pellet spill.

- Criticality safety assessment of pellet spills must be performed in accordance with the Double Contingency Principle.
Consider a spill of sintered UO$_2$ pellets involving:

- 5 wt% U-235 fuel enrichment
- Hemispherical spill geometry involving 37 kg (safe mass of pellets).
- 12” concrete floor
- 12” water reflection on hemispherical surface
- Pellets modeled as rods (no axial spacing) or volume-equivalent spheres

Analyzed with MCNP5 in KCODE mode with $10^6$ active histories and standard deviation of about 0.0007.
Introduction (cont)

A) Array of rods

B) Array of equivalent spheres

Hemispherical spill top and side cross-sectional views.
Introduction (cont...)

Investigate effect of modeling pellets explicitly with axial spacing to isolate effect from sphere approximation.
Methodology – Alternate arrangement of pellets in spills

**Stochastic rods:** Array of pellets arranged *nominally* as rods but each pellet located randomly in XY.

**Type I (axial spaced):** Array of pellets similar to the array of rods but adjacent pellets separated from each other in Z. Adjacent pellets are in-line in the Z direction.

**Type II (offset axial spaced):** Fully triangular-pitched array of pellets similar in arrangement to the array of spheres. Pellets are centered between three pellets in adjacent plane in Z.
Monte Carlo Simulation of Fuel Pellet Spills with Axial Inter-Pellet Moderation and Stochastic Geometry

Methodology - Stochastic geometry in MCNP

\[ \text{Unit cell (XY)} \]

<table>
<thead>
<tr>
<th></th>
<th>universe</th>
<th>( dx_{\text{max}} )</th>
<th>( dy_{\text{max}} )</th>
<th>( dz_{\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>URAN</td>
<td>1</td>
<td>0.6</td>
<td>1.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

One “rod” shown randomized.
Methodology – Fully triangular pitched arrays

- An individual fuel pellet surrounded by water (*Universe 1*) is placed in an hexagonal prism and specified as a hexagonal lattice (lat=2) (*Universe 2*).
- A second hexagonal prism lattice is created translated by \((x, x \tan 30, z)\) (*Universe 3*).
- *Universe 2* is used to fill an infinite region defined by Planes 1 and 2 creating an infinite planar array of triangular-pitched pellets. *Universe 3* is used to fill an infinite region defined by Planes 2 and 3. Together these two regions define *Universe 4*.
- *Universe 4* is used to fill the region defined by planes 1 and 3, but using the square lattice (lat=1) and results in *Universe 5*.
- *Universe 5*, is used to fill the fuel region resulting in an array of triangular pitched pellets.
Results
Monte Carlo Simulation of Fuel Pellet Spills with Axial Inter-Pellet Moderation and Stochastic Geometry

Results

![Graph showing results of Monte Carlo simulation](image)

- **Graph Title**: Water-to-Fuel Ratio vs. $K_{eff}$
- **X-axis**: Water-to-Fuel Ratio
- **Y-axis**: $K_{eff}$
- **Legend**:
  - Equivalent Spheres
  - Rods (Stochastic Pellets)
  - Rods

One "rod" shown randomized
Results

![Graph showing results of Monte Carlo Simulation of Fuel Pellet Spills with Axial Inter-Pellet Moderation and Stochastic Geometry](image)

The graph illustrates the relationship between Water-to-Fuel Ratio and $K_{eff}$ for different fuel configurations. The x-axis represents the Water-to-Fuel Ratio, while the y-axis shows $K_{eff}$. The lines and markers represent different fuel types:

- Equivalent Spheres (red diamonds)
- Type I (Axial Spaced) (blue squares)
- Rods (Stochastic Pellets) (green triangles)
- Rods (black circles)

The graph shows how $K_{eff}$ changes with varying Water-to-Fuel Ratio for each configuration.
Results

![Graph showing results of Monte Carlo Simulation of Fuel Pellet Spills with Axial Inter-Pellet Moderation and Stochastic Geometry. The graph plots $K_{eff}$ against Water-to-Fuel Ratio. The line types represent different geometries: Equivalent Spheres, Type II (Offset Axial Spaced), Rods (Stochastic Pellets), and Rods.](image_url)
## Results

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<tr>
<th>Model description</th>
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<th>Reactivity for low W/F ($k_{\text{eff}}$) $(W/F=0.577)$</th>
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<td>Array of rods (deterministic)</td>
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<td>Equivalent volume spheres</td>
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<td>n/a</td>
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<td>0.576</td>
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Results – Axial spacing

![Graph showing the relationship between Axial Spacing (per unit) and Peak $K_{eff}$ for Type I (axial spaced) Array of rods.](image)

- Axial spacing values: 0.9, 0.91, 0.92, 0.93, 0.94
- Y-axis: Peak $K_{eff}$
- X-axis: Axial Spacing (per unit)

Array of rods
Results – Axial spacing

Offset axial spaced pellets give an axial moderation effect even without axial spacing.

Array of Rods

Peak $K_{eff}$

Axial Spacing (per unit)

- Type II (offset axial spaced)
- Type I (axial spaced)
Results – Pellet aspect

![Pellet aspect ratio graph]

- Pellet aspect ratio (L/D) vs. Peak $K_{eff}$
- Graph shows a decreasing trend in $K_{eff}$ with increasing L/D ratio.
Summary and conclusions

Dry conditions

• For low moderation conditions axial spacing had no effect.

Moderated conditions

• Limited stochastic treatment of array of pellets as rods gives an axial moderation effect but below models with explicit axial spacing.

• Array of equivalent volume spheres, or pellets with axial spacing (Type I or II), gave similar results and were the most conservative models.

Application

• If axial spacing at optimum moderation is a credible condition, axial spacing can be significant to safe operation.

• However for typical applications both conditions wouldn’t exist simultaneously as pellets would be expected to spill into a relatively close-packed array resulting in low W/F. As the W/F effect is significantly greater than the axial spacing effect, the array of rods model remains conservative and considering axial spacing can be used for added conservatism.