Developing a Benchmark Evaluation from the Experiments Performed on the Space Nuclear Thermal Propulsion Zero-Power Critical Assembly (SNTP-CX)

PRESENTED BY:

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SAND No 2021-1788 PE
The SNTP Program: 1987-1994

Purpose: To develop a new rocket capable of twice the performance of a standard chemical rocket using nuclear technologies.

Designed as Three Phase Effort
- Phase I: Proof of concept of particle bed reactor engine.
- Phase II: Perform ground test of the particle bed reactor engine.
- Phase III: Perform flight test of the particle bed reactor engine.
- Program terminated in 1994 before phase III began.

Diagram:
- Phase I: $53 M
  - Comp't Test
  - Prel Design
  - Site Selection
  - Ground Flight Test
- Phase II: $954 M
  - Reactor Neutronics Validation
  - EIS Record of Decision
  - Engine Dem/Val
- Phase III: Flight Exp't

Timeline:
- 1988
  - VX
  - Vehicle PDR
- 1989
  - Engine PDR
- 1990
  - PIPET PDR
- 1991
  - NET 1.2
- 1992
  - NET 3.4
- 1993
  - PIPET CDR
- 1994
  - PIPET GTA-1
- 1995
  - CX1
- 1996
  - CX2
- 1997
  - GTA-1 Competition
- 1998
- 1999
- 2000
Decided a zero power critical assembly was needed

Designed by SNL and B&W

Installed and operated at SNL

142 runs performed for various experiments from 1989 to 1992

19 fuel stalks on a 9.4 cm triangular pitch

Fuel annulus is a multi-particle type packed bed
The Particle Bed

3 Particle Types

- Fuel particle
  - UC kernel (93 w/o U-235 nominal enrichment)
  - Carbon graphite shell
- Carbon particle
  - Versar CARBOSPHERE Type S220
  - 6.2 w/o Sulfur impurity
- Zircaloy-4 particle
Particle Bed Information

What we have

Particle bulk densities
Material compositions
Total particle mass loaded/stalk
Particle size
Packing fraction of 0.64 [3]

Particle | Bulk Density (g/cc) [2] | Diameter (µm) [3] | Uncertainty (µm) [3] |
---------|------------------------|-------------------|---------------------|
Fuel Kernel | 5.47 | 275 | ±25 |
Carbon Shell (Thickness)* | - | 15 | ±5 |
Zircaloy-4 | 4.256 | 231 | ±19 |
Carbon | 1.269 | 231 | ±19 |

<table>
<thead>
<tr>
<th>Stalk ID</th>
<th>Particle Masses, Grams</th>
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<td>S890714</td>
<td>1331.450</td>
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<td>S890717</td>
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<td>AVG</td>
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<td>STD DEV</td>
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<tr>
<td>STD DEVI/AVG</td>
<td>0.025</td>
</tr>
</tbody>
</table>

[2]
General Approach to Modeling

1. **Estimate particle fractions**
2. **Choose lattice type and size**
   ◦ Size referring to number of particles per lattice element
3. **Ensure total masses are correct by:**
   ◦ Using iterative process to:
     ◦ Adjust Carbon and Zircaloy-4 particle radii
     ◦ Adjust UC\(_{1.7}\) kernel and C shell material densities

Dark Grey = Carbon Particle
Light Grey = Fuel Particle
Silver = Zircaloy-4 Particle
Estimating Particle Fractions

Assumptions
- Particles were of nominal radii
- Material densities were all equal to the bulk density/packing fraction

Calculate mass of each particle type

Divide total mass by particle mass

<table>
<thead>
<tr>
<th>Particle</th>
<th>Estimated # of Particles</th>
<th>Particle Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>1.41E+07</td>
<td>0.185</td>
</tr>
<tr>
<td>ZR-4</td>
<td>3.28E+07</td>
<td>0.430</td>
</tr>
<tr>
<td>C</td>
<td>2.94E+07</td>
<td>0.385</td>
</tr>
<tr>
<td>Totals</td>
<td>7.63E+07</td>
<td>1.000</td>
</tr>
</tbody>
</table>
Choosing a lattice type

Desirable traits

Packing fraction of at least 0.64

High particles/unit cell
  ◦ Allows to get closer to estimated particle fractions

Lower modeling difficulty preferred

Face Centered Cubic (FCC)

Max packing fraction of 0.72

4 particles per unit cell

Easily expandable
  ◦ Allows for more particles per lattice cell
  ◦ 1 lattice cell = 2x2x2 unit cells = 32 total particles
    ◦ 6 fuel, 12 carbon, 14 zircaloy-4

Easily modeled
  ◦ MCNP square lattice (type 1)
  ◦ Particle positions in the lattice cell can be defined as a function of side length
Lattice Side Length, Particle Sizes and Material Densities

Iterative process choosing values to ensure total stalk mass for each particle type is conserved.

Initial conditions
- 6 Fuel, 12 Carbon, 14 Zircaloy-4
- UC kernel radius = 125 µm
- C shell thickness = 15 µm
- Carbon density = bulk density/packing fraction = $\frac{1.269}{0.64} = 1.983$ g/cc
- Zircaloy-4 density = bulk density/packing fraction = $\frac{4.256}{0.64} = 6.650$ g/cc

Iterated values
- UC kernel and C shell density
- Carbon and Zircaloy-4 particle radius
- Lattice cell side length
Final Lattice

Lattice side length = 762.7583 µm
Fuel particle lattice positions fixed
Filler particle lattice positions randomized

<table>
<thead>
<tr>
<th>Particle</th>
<th># per lattice element</th>
<th>thickness/radius (µm)</th>
<th>density (g/cc)</th>
<th>Stalk Mass Delta (g)</th>
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<tbody>
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<td>Fuel Kernel</td>
<td>6</td>
<td>125</td>
<td>11.201</td>
<td>9.90E-03</td>
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<tr>
<td>Fuel Shell</td>
<td></td>
<td>15</td>
<td>1.827</td>
<td>-4.15E-05</td>
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<tr>
<td>Carbon</td>
<td>12</td>
<td>126.4</td>
<td>1.983</td>
<td>-8.61E-04</td>
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<tr>
<td>Zircaloy-4</td>
<td>14</td>
<td>124.6</td>
<td>6.650</td>
<td>1.34E-04</td>
</tr>
</tbody>
</table>

Purple/Blue = Fuel Particle
Orange = Carbon Particle
Pink = Zircaloy-4 Particle
View 1: YZ – Center Plane

Purple/Blue = Fuel Particle
Orange = Carbon Particle
Pink = Zircaloy-4 Particle
View 2: YZ – Mid Plane

Purple/Blue = Fuel Particle
Orange = Carbon Particle
Pink = Zircaloy-4 Particle
View 3: YZ – Face Plane

Purple/Blue = Fuel Particle
Orange = Carbon Particle
Pink = Zircaloy-4 Particle
Particle Boundary Truncation Analysis

The effects of the particle truncation at the fuel annulus boundaries were looked at.

- Tested in both radial and axial directions
- Particle bed shifted in increments of 1/10 the lattice cell side length
- No correlation made
Base Model Results

Model is representative of a critical experiment ($k_{\text{eff}} = 1.0$)
- Using case 1 critical parameters

Discrete particle modeling brings model closer to critical

Utilizing the “average stalk” results in slightly lower reactivity

<table>
<thead>
<tr>
<th>Model</th>
<th>k-eff</th>
<th>std. dev.</th>
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<tbody>
<tr>
<td>Individual Detailed</td>
<td>1.00151</td>
<td>0.00005</td>
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<tr>
<td>Average Detailed</td>
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<tr>
<td>Individual Smeared</td>
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<tr>
<td>Average Smeared</td>
<td>1.00293</td>
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Boron Worth Experiments

Experiment series was conducted to measure the boron reactivity worth in the moderator.

- 10 different boron concentrations tested
- Moderator height used as approach to critical parameter
- Control and safety blades fully withdrawn
- 19 runs performed
  - 10 Critical water height measurements (yellow)
  - 9 Reactivity measurements at the previous boron concentrations critical water height (blue)

<table>
<thead>
<tr>
<th>Case</th>
<th>B PPM</th>
<th>Water Height (mm)</th>
<th>Reactivity (Cents)</th>
<th>B Worth (Cents/PPM)</th>
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<tbody>
<tr>
<td>1</td>
<td>68.89</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>2</td>
<td>61.66</td>
<td>542.5</td>
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<tr>
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Modeling the Boron Worth Experiments

- Model created using methods described above
- 19 models are identical varying only in boron concentration and water height
- Boron worth calculated from the model is within 1 standard deviation of the experimentally measured values
- Model is behaving as expected

<table>
<thead>
<tr>
<th>Case</th>
<th>B PPM</th>
<th>Water Height (mm)</th>
<th>Reactivity (Cents)</th>
<th>B Worth (Cents/PPM)</th>
<th>Std. Dev. (Cents)</th>
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Future Work

• Determine causes for consistently increased multiplication factor in the model compared to the experiments
• Continue to close information gap
• Complete uncertainty analysis
• Finalize simplified model

Acknowledgements

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REFERENCES


2. G.S. Hoovler, “As-Built Description and Excess Reactivity of Reference CX Core 94WS100,” Babcock & Wilcox 1994