Reactor Physics Analysis of the VHTGR Core

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INTRODUCTION

As part of an I-NERI project to develop safety analysis codes and experimental validation for a Very-High Temperature Gas-Cooled Reactor (VHTGR), we have developed MCNP5 [1] models to represent material heterogeneities inherent in the microsphere fuel particles and fuel compacts for a GT-MHR design [2]. We have also performed preliminary coupled nuclear-thermal-hydraulic (NTH) analysis to obtain self-consistent global power and temperature distributions using a homogenized global model for MCNP5 and three-ring core model for the RELAP5-3D/ATHENA code [3]. We present a comparison of heterogeneous and homogeneous representations of the microsphere and fuel compact cells, establishing the impact of heterogeneities on the overall VHTGR neutronics analysis. We also discuss the importance of fuel temperature feedback on the global power distribution.

MCNP5 MODELING OF MICROSPHERES

As part of the effort to address the double heterogeneity inherent in the VHTGR fuel design, we have assumed the same microsphere geometry and densities as used in the NGNP Point Design [2], consisting of a 10.36% enriched uranium oxycarbide fuel kernel with layers of carbon buffer, pyrolytic carbon, and silicon carbide and a packing fraction of 0.289. Homogeneous and heterogeneous microspheres were simulated, both as standalone microsphere cells as well as a fuel compact cell consisting of microsphere cells contained within a hexagonal graphite block. We have performed MCNP5 simulations of:

- Microsphere centered within a graphite cube with reflecting boundary conditions on the cube surface, represented both as a homogeneous and heterogeneous cell.
- Hexagonal graphite block with a fuel compact consisting of either homogeneous or heterogeneous microsphere cells. There are reflecting boundary conditions on the outer hexagon surfaces and the top and bottom surfaces of the fuel compact.

The heterogeneous microsphere cell is illustrated together with the homogeneous and heterogeneous compact cells in Figure 1.

Figure 1. Heterogeneous microsphere and homogeneous and heterogeneous fuel compact cells for MCNP5 simulations
MCNP5 was used to analyze the microsphere cells, comprising either homogeneous or heterogeneous microspheres, with a graphite cube of edge 0.951 mm. In a related collaboration [4] with Forrest Brown at Los Alamos National Laboratory (LANL), MCNP5 simulations were performed for a 5x5x5 array of heterogeneous microsphere cells, with the microsphere centered in the graphite cube and randomly placed (wholly within) the graphite cube. As summarized in Table 1, the heterogeneous microsphere makes a substantial change to $k_{eff}$, increasing it by nearly 5%. In addition, a comparison of the two LANL calculations in Table 1 confirms that the placement of the microsphere within the graphite cube (centered versus random) has a negligible impact on the resultant $k_{eff}$, which has been reported previously in the literature [5].

### Table 1. MCNP5 Simulations of Microsphere Cells

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Kernel location</th>
<th>$k_{eff}$</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogeneous microsphere cell</td>
<td>---</td>
<td>1.1001</td>
<td>.0004</td>
</tr>
<tr>
<td>Heterogeneous microsphere cell</td>
<td>Centered</td>
<td>1.1533</td>
<td>.0003</td>
</tr>
<tr>
<td>Heterogeneous microsphere cell (LANL)</td>
<td>Centered</td>
<td>1.1531</td>
<td>.0004</td>
</tr>
<tr>
<td>Heterogeneous microsphere cell (LANL)</td>
<td>Random</td>
<td>1.1515</td>
<td>.0004</td>
</tr>
</tbody>
</table>

MCNP5 simulations of the fuel compact cells summarized in Table 2 show convincingly the importance of modeling the fuel microsphere regions, since there is an increase in $k_{eff}$ of nearly 0.06 with heterogeneous microspheres cells versus homogenous microsphere cells. The actual value of $k_{eff}$ is not important for this comparison because the fuel compact cell does not correspond to a physical configuration since the coolant holes and reflector regions are not included in this cell.

### Table 2. MCNP5 Simulations of Fuel Compact Cells

<table>
<thead>
<tr>
<th>Fuel Compact</th>
<th>$k_{eff}$</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogeneous microsphere cells</td>
<td>1.2885</td>
<td>.0004</td>
</tr>
<tr>
<td>Heterogeneous microsphere cells</td>
<td>1.3401</td>
<td>.0004</td>
</tr>
</tbody>
</table>

**COUPLED NUCLEAR-THERMAL-HYDRAULIC CALCULATIONS**

In parallel with the reactor physics analysis at the particle/compact level discussed above, we have also made initial effort to represent the effects of temperature feedback on global power distributions. For this coupled NTH analysis for the VHTGR core configuration, we have used a homogenized representation for each of 103 prismatic fuel assemblies and grouped the fuel assemblies into three rings: inner, middle and outer rings comprising 30, 37, and 36 assemblies each. The core, with a height of 7.93 m, is discretized axially into 12 equal segments. In order to represent distributed temperatures, we have devised a pseudo-material scheme in our MCNP5 runs, where cross section libraries at a few temperature points are mixed and interpolated to yield cross section libraries at the actual temperatures for each of the 36 core volumes.

Adapting an input deck obtained from Cliff Davis at INEEL, we have performed RELAP5/ATHENA calculations representing the homogenized three-ring model of the VHTR core and completed four iterations involving manual transfers of temperature and power distributions between MCNP5 and RELAP5/ATHENA. As illustrated in Figure 2, after four iterations, we have yet to achieve a satisfactory convergence on the axial power distributions within each of the three rings, although the fraction of the power summed over each ring is easily converged. This may be due to the large core height, which tends to make the core loosely coupled, thereby rendering the axial power distribution sensitive to axial imbalances in cross sections.

**CONCLUSIONS**

Our MCNP5 simulations of homogenous and heterogeneous microspheres have clearly indicated the importance of properly representing material heterogeneities within the microspheres. Additional MCNP5 calculations will be performed to represent the fuel compact with randomly distributed microspheres. We plan to study the difficulty encountered in attaining converged axial power distributions in coupled NTH
calculations and initiate effort to represent material heterogeneities in global MCNP calculations.

ACKNOWLEDGEMENTS

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REFERENCES


Figure 2. Axial power distribution in the middle core ring