INTRODUCTION

The HTR-10 is a small pebble-bed test reactor rated at a thermal power of 10 MWt intended as a stepping stone for the development of PBR technology in China. The HTR-10 reactor includes the design features of the modular High-Temperature Gas-cooled Reactor (HTGR), which is primarily characterized by inherent safety features. The reactor geometry is depicted in Fig. 1. In this work we present MAMMOTH results for the initial critical and the 17,000 pebble initial critical configurations specified in Ref. [1, 2].

Overall, the neutronically relevant core, reflector and shielding regions (everything inside of the boronated carbon bricks and carbon bricks in Fig. 1) are 6.1 meters tall and have a radius of 1.9 meters; the core containing the pebble bed is split into the upper part containing the cylindrical core and the upper cone and a lower part containing the lower cone and the discharge tube. The upper part of the core during the initial critical contains a mix of 16,890 fuel and "dummy" graphite pebbles with a ratio of 57 : 43, while the lower part of the core only contains dummy graphite pebbles. The benchmark report assumes a uniform packing fraction of 0.61 throughout the whole core. Control rod worth measurements were performed with a small excess reactivity that is introduced by dropping an additional 110 pebbles to the core; for convenience we refer to this configuration as initial critical 17k.

In this work, we report highly accurate results obtained with the MAMMOTH reactor physics application for the HTR-10 initial critical and initial critical 17k benchmark problem. MAMMOTH is a unique reactor physics code that is built on the MOOSE FEM framework and utilizes the Rattlesnake radiation transport code. Its design allows seamless coupling with MOOSE modules containing heat conduction and solid mechanics functionality and with the thermal fluids code Pronghorn. The presented results serve as the stepping stone for establishing the MAMMOTH reactor physics application as high-fidelity tool for multiphysics, transient pebble bed reactor analysis.

HTR-10 SERPENT AND MAMMOTH MODELS

The three-dimensional continuous-energy Monte Carlo reactor physics code Serpent [8] is used for providing multigroup cross sections and region integrated fluxes that are utilized by the superhomogenization method (SPH), implemented in MAMMOTH. It was selected as the main cross section preparation tool for this work because it offers 3-D spatial homogenization and group constant generation for deterministic reactor simulator calculations. At the same time, Serpent 2 provides a detailed reference calculation without energy, angular, or spatial discretization error. We utilize the Serpent’s unique capability to explicitly model the random TRIstructural-ISOtropic (TRISO) distribution inside the pebbles and the random distribution of pebbles in the reactor core. For this purpose, Serpent is provided with the pebbles’ center positions. Serpent represents the location of TRISO particles in the core without applying any homogenization.

The MAMMOTH reactor multiphysics analysis application developed at INL is used for computing the core multiplication factor and power distribution. In addition to implementing reactor physics specific capabilities such as depletion and equivalence methods, MAMMOTH seamlessly interfaces with several other MOOSE applications including Rattlesnake for radiation transport algorithms, MOOSE modules for heat transfer and solid mechanics, BISON for fuel performance modeling and Pronghorn for thermal fluids calculations. The Rattlesnake neutron transport solver incorporates a variety of spatial and angular discretization methods including diffusion, $P_N$ and $S_N$ (both 1st and 2nd order) formulations. In this work, we exclusively use the second order $P_N$ formulation discretized with continuous FEM and the continuous FEM diffusion solver. The computation of directional diffusion coefficients requires the solution of a neutron-transport like equation that is facilitated with the first order $S_N$ solver.

Between the top of the pebble bed core and the top reflector, HTR-10 contains a cavity region that is filled with ambient,
moist air. Neutronically, this region is optically transparent posing problems for obtaining physically meaningful diffusion coefficients. A variety of methods exists to meaningfully define diffusion coefficients in near-void regions, e.g. Morel’s non-local diffusion coefficients [13] that are successfully used by Trahan [14] for analysis of reactors with optically thin channels, Monte-Carlo methods have been equipped with tallies to compute diagonal tensor diffusion coefficients based on the cumulative migration method [15]. Serpent currently does not include the capability to generate anisotropic diffusion coefficients in extended geometries to allow better modeling of neutron streaming effects within the diffusion approximation and hence we resort to using Morel’s non-local diffusion coefficient in the top core cavity.

The computation of non-local diffusion tensors was implemented in the Rattlesnake transport solver [14][16] to address the streaming effects through the region above the pebble bed. In addition to computing tensor diffusion coefficients, an advanced implementation of the traditional equivalence procedure [17] developed at INL, the PIFJNK-SPH [9], is employed to ensure preservation of the reaction rates between the reference Monte Carlo model and the cross section set used in the MAMMOTH model. The data preparation sequence adopted within this work is described in detail in Ref. [16]. For the deterministic transport model, we do not explicitly model the location of all pebbles separately even though this capability is available in MAMMOTH through the pebble tracking transport algorithm implemented in Rattlesnake [18]. Instead, we homogenize the top core cavity and the upper cone between the lower onset of the top cone and the cone’s tip.

**COMPUTATIONAL RESULTS**

The eigenvalues obtained with Serpent and MAMMOTH for the initial critical core are included in Table I. First, we note that the Serpent calculation with ENDF/B-VI based data is consistent with the IRPhEP high fidelity MCNP benchmark results. The difference of 163 pcm can be attributed to the differences in the two models:

- the use of a random distribution of TRISO particles versus the original lattice constrained distribution in MCNP,
- the difference in the randomization of the fuel pebble assignment,
- approximating the KLAK (emergency reactivity control pebbles) channels as cylinders with an equivalent volume

- the use of air instead of Helium for all calculations, adopted from Ref. [2].

Serpent’s and MAMMOTH’s prediction of the eigenvalue in the critical configuration using ENDF/B-VII.f1 data matches the experimental value keff = 1 very well. For this calculation we have a critical core height of 144 cm measured from the bottom of the reactor barrel to the tip of the upper core conus or an equivalent surface plane of 123 cm. The Serpent model is 23 pcm above critical and the MAMMOTH SPH corrected model is 89 pcm above critical.

An additional validation step for the Serpent model was performed with the control rod worth measurement performed by INET. The rod measurement is reported in the IRPhEP benchmark [2] and was conducted with initial critical 17k. The rod worth measurement and model prediction are included in Table III. The calculated control rod worth is almost identical to the measured value.

In order to confirm the accuracy of the MAMMOTH results, the neutron production and absorption rates are compared to the Serpent computed values in the 1,443 distinct SPH equivalence regions of the active core and reflectors. It is worth noting that these Serpent reaction rates are computed from the homogenized cross sections for each region and the flux tallies used for the SPH data. However, we expect these derived reaction rates to match the direct tallies of the reaction rates from Serpent quite well. To facilitate a comparison between MAMMOTH and Serpent reaction rates, we define the RMS and max errors as:

\[
\text{RMS: } \epsilon_{\text{RMS}} = \sqrt{\frac{1}{N} \sum_{j=1}^{N} \left(1 - \frac{R_j}{L_j}\right)^2} \\
\text{max: } \epsilon_{\text{max}} = \max_{j=1,...,N} \left|1 - \frac{R_j}{L_j}\right|.
\]

where \(N\) is the number of equivalence regions, \(R_j\) and \(L_j\) are integral reaction rates (either absorption or fission neutron production) over equivalence region \(j\) computed with MAMMOTH and Serpent, respectively.

Table III shows that the results obtained with MAMMOTH’s diffusion solver employing the transport cross section calculated in Serpent for the void region above the core, but without applying the SPH equivalence correction are \(-2,500\) pcm high due to errors emerging from discretization, homogenization and the multi-group approximation. Similarly to the computed eigenvalue, the errors in the reaction rates, \(\epsilon_{\text{RMS}}\) and \(\epsilon_{\text{max}}\), are quite high. When Morel’s tensor diffusion coefficients are employed, the solution improves and better matches the P1 and P3 solutions also provided in Table III.

This leads us to conclude that the cross section homogenization carries a 4,000 pcm bias; the magnitude of the bias is consistent with the expected error originating from the control rod homogenization in the top reflector region. When the SPH equivalence correction is applied to the cross sections, we closely match the reference solution from Serpent. The error in the eigenvalue is less than 70 pcm and the reaction rates are within 0.4% of the Monte Carlo result. The use of TDC-SPH marginally improves the solution. A rendering of the flux solution obtained for the critical core is presented in Fig. 2. Three axial cuts through the core are displayed located at elevations near the lower conus, the upper end of the cylindrical core region and in the top core cavity. The maximum of the thermal scalar flux near the core reflector interfaces and the flat flux in the top core cavity are clearly visible for the thermal flux on the left of Fig. 2. The fast scalar flux is largest in the center of the core where fast neutrons are born; the top conus region with reduced density of fissionable material is clearly visible as well as the outline of the top core cavity in which the fast flux is, as expected, nearly constant.
TABLE I: Eigenvalues computed with different codes for the initial critical configuration.

<table>
<thead>
<tr>
<th>Code</th>
<th>keff</th>
<th>uncertainty rel. error [pcm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCNP (ENDFB-VI) [2]</td>
<td>1.01190</td>
<td>±21</td>
</tr>
<tr>
<td>Serpent (ENDFB-VI)</td>
<td>1.01025</td>
<td>±5.1</td>
</tr>
<tr>
<td>Serpent (ENDFB-VII.r1)</td>
<td>1.00023</td>
<td>±2.3</td>
</tr>
<tr>
<td>MAMMOTH TDC-SPH-Diffusion</td>
<td>1.00089</td>
<td>67.3</td>
</tr>
</tbody>
</table>

TABLE II: Single Control Rod Worth for the 17k initial critical core configuration.

<table>
<thead>
<tr>
<th>Code (case)</th>
<th>keff</th>
<th>Rod worth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>-</td>
<td>1.4693%</td>
</tr>
<tr>
<td>Serpent (ARO)</td>
<td>0.99102</td>
<td>-</td>
</tr>
<tr>
<td>Serpent (IR1)</td>
<td>0.97693</td>
<td>-</td>
</tr>
<tr>
<td>Serpent</td>
<td>-</td>
<td>1.4558%</td>
</tr>
</tbody>
</table>

CONCLUSIONS

We successfully developed high fidelity Monte Carlo Serpent models of the HTR-10 critical and full core configurations. The models include both a random discrete distribution of TRISO particles in the pebbles and a random pebble distribution in the pebble bed core. The Serpent results match very well the critical and control rod worth measurements provided in the International Reactor Physics Experiment Evaluation Project (IRPhEP) report with the ENDF/B-VII.r1 data-set.

We used the Serpent model to prepare 10 coarse energy group cross sections and flux tallies for the MAMMOTH Reactor Physics MOOSE application. The presented results show that MAMMOTH can reproduce the Monte Carlo solution obtained with Serpent for the HTR-10 reactor very accurately when using SPH correction. The MAMMOTH results are within 70 pcm of the Serpent Monte Carlo reference calculation. The maximum errors in neutron absorption and generation rates are within 0.4% and 0.059% from the Serpent Monte Carlo reference calculation, respectively.

DISCLAIMER

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TABLE III: Relative differences of eigenvalues (pcm) and reaction rates (%) between MAMMOTH and the Serpent model for the initial critical core.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Eigenvalue keff</th>
<th>Absorption RMS</th>
<th>Absorption max</th>
<th>Generation RMS</th>
<th>Generation max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffusion</td>
<td>1.02544</td>
<td>21.5</td>
<td>2520.8</td>
<td>153</td>
<td>41.1</td>
</tr>
<tr>
<td>TDC-Diffusion</td>
<td>1.03475</td>
<td>17.4</td>
<td>3451.3</td>
<td>117.9</td>
<td>41.7</td>
</tr>
<tr>
<td>P1</td>
<td>1.03706</td>
<td>20.7</td>
<td>3682.3</td>
<td>144.6</td>
<td>6.53</td>
</tr>
<tr>
<td>P3</td>
<td>1.04053</td>
<td>19.6</td>
<td>4029.0</td>
<td>134.7</td>
<td>7.12</td>
</tr>
<tr>
<td>SPH-Diffusion</td>
<td>1.00090</td>
<td>0.16</td>
<td>67.3</td>
<td>0.4</td>
<td>0.062</td>
</tr>
<tr>
<td>TDC-SPH-Diffusion</td>
<td>1.00089</td>
<td>0.16</td>
<td>66.1</td>
<td>0.4</td>
<td>0.059</td>
</tr>
</tbody>
</table>

Fig. 2: Flux Distribution in the critical core for the most thermal ($g = 10$) and fastest ($g = 1$) energy groups.
REFERENCES


