MCNP Simulations of Various Pebble Models for Pebble Bed Gas Cooled Reactors

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INTRODUCTION

Pebble Bed Reactors (PBRs) are high-temperature gas-cooled (or molten salt-cooled) reactors. Thousands of pebbles cycle through the nuclear reactor, at a relatively slow speed, to fuel the reactor. These pebbles are spherical and vary from a golf ball to tennis ball in size, depending on the reactor design. Contained within these pebbles are thousands of TRISO particles. These reactors claim to have high efficiency (40-50%) and claim that the pebbles cannot melt. Accurate data is needed to ensure the safety and security of PBRs. This includes, for example, waste management, nuclear safeguards, nonproliferation, and reactor criticality safety. Reactor criticality safety is of the upmost importance to avoid accident chain reactions, such as the demon core accidents that occurred in the mid-1940s.

The goal of this research is to create a pebble bed library that will contain useful information such as the burnup of spent fuel in the pebbles, isotope signatures such as gamma ray energies and neutron flux from spent fuel, the isotopic composition of the pebbles, the k-effective of spent fuel at different burnups, and the amount of fissile material in the spent fuel. Much of this work will be simulated using the MCNP (Monte Carlo N- Particle) software.

MODEL SPECIFICATIONS

TRISO Particle Specification

- 19,000 TRISO particles per pebble [2]
- 5 Spherical Layers
- Fuel kernel of UCO
- Porous Carbon Layer
- Inner Pyrolytic Carbon Layer
- Silicon Carbide Layer
- Outer Pyrolytic Layer
- Fuel enrichment is between 15 and 20 wt.% ^{235}U

Pebble Specification

- Carbon Matrix Density of 1.75 g/cm^3 [1]
- Outer Pebble Diameter of 6 cm [3]
- Outer pebble Carbon Layer Thickness of 0.5 cm [3]

METHODOLOGY AND MODELLING

Homogeneous Pebble, Heterogeneous (Clipped) Pebble, and Heterogeneous (Unclipped) Pebble

- Homogeneous Pebble contains the mass of all constituents of the heterogeneous pebble, but uniformly combined
- Heterogeneous Pebble contains TRISO particles in a uniform arrangement within the pebble
- Heterogeneous (Clipped Pebble) contains TRISO particles which were clipped at the boundary of the pebble
- Heterogeneous (Unclipped Pebble) does not contain TRISO particles that were clipped at the boundary of the pebble

Heterogeneous Unclipped Pebble with Helium

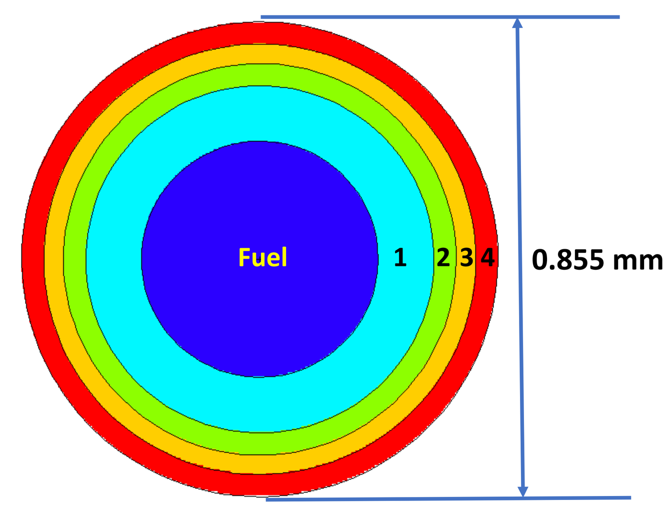
- Helium is placed outside the pebble and within a 6 x 6 x 6 cm^3 cube

FCC Homogeneous & Heterogeneous Pebble with Helium

- Homogeneous and Heterogeneous Models
- Face Centered Cubic (FCC) Structure Unit Cell
- 6 half pebble and 8 one-eighth pebbles
- Packing Factor of 0.7402
- Helium Matrix Between Pebbles to Correspond to Coolant in PBR

FCC Heterogeneous Semi-Unclipped Pebble with Helium

- Unclipped (Full) TRISO Particles Except for Those at the Boundary of Unit Cell
- Half Pebbles and one-eighth pebbles at the edges of the unit cell sphere reconnect to similar pebbles when FCC unit cells are placed in sequence



Layer	Material	Thickness (µm)
4	Outer Pyrolytic Carbon	40
3	Silicon Carbide	35
2	Inner Pyrolytic Carbon	40
1	Porous Carbon Buffer	100
Fuel Kernel	UCO	425

Figure 1. The 2-D view and layer properties of the TRISO fuel particle in the Xe-100 reactor. From inside to out the layers are: fuel kernel (blue), porous carbon buffer (cyan), inner pyrolytic carbon (green), silicon carbide (orange), and outer pyrolytic carbon (red).

RESULTS AND DISCUSSION

The k-infinity values of each of these models, shown in Tables I & II, were simulated for various boundary conditions. The values from these simulations provide validation that the models are correct (k-infinity values must be greater than 1) and identify what modeling assumptions create a statistical difference in the pebble's criticality.

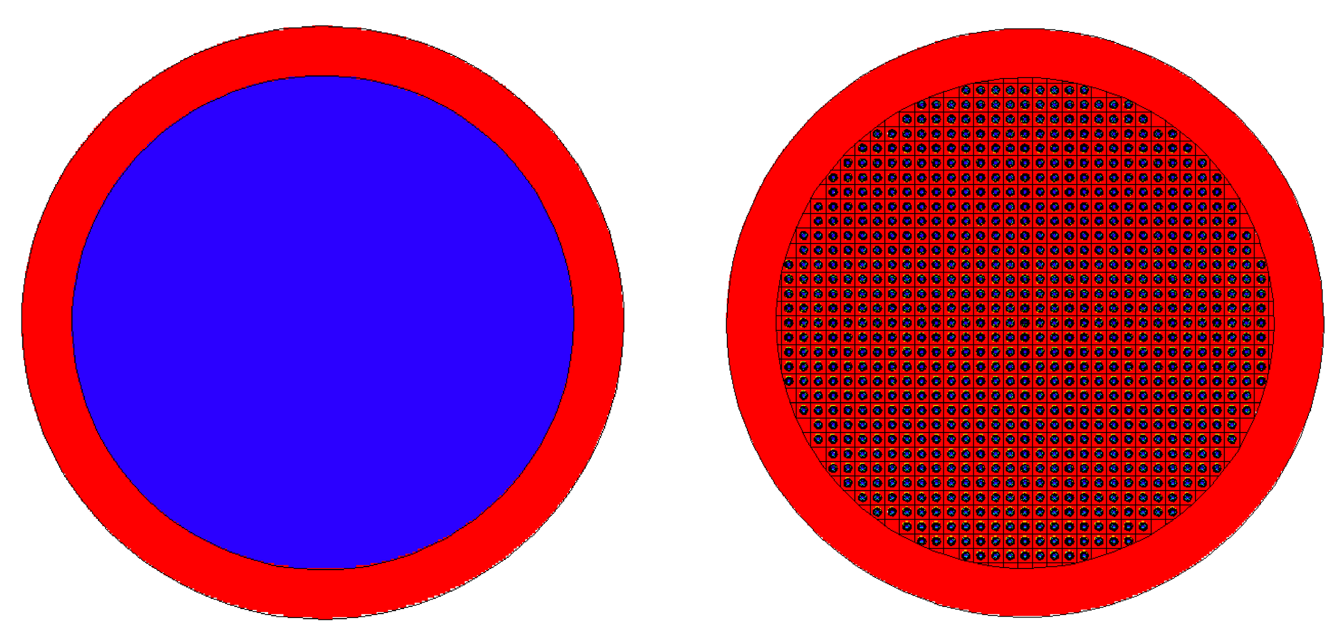


Figure 2. The 2-D view of the homogeneous (left) and unclipped heterogeneous (right) fuel pebble in the Xe-100 reactor. For the homogenous model, from inside to out the layers are: homogenized TRISO particle carbon matrix material (blue), outer carbon layer (red); for the heterogeneous model, the carbon matrix material is shown in red and heterogeneous TRISO particles are shown as small blue spheres.

Table I. k-infinity values of homogeneous and heterogeneous pebble models with different boundary conditions (B.C.) and environments.

Pebble Model	k-infinity (white B.C.)	k-infinity (Mirror B.C.)
Homogeneous	1.39962 ± 0.00063	1.41510 ± 0.00055
Clipped Heterogeneous	1.50473 ± 0.00077	1.51247 ± 0.00063
Unclipped Heterogeneous	1.50631 ± 0.00068	1.51638 ± 0.00054
Unclipped Heterogeneous w/ Helium	1.50816 ± 0.00062	1.50822 ± 0.00063

Note: White B.C. means the angle data is lost and the neutrons are reflected into the pebble with angles of equal probability. Mirror B.C. means that the angles in which the neutrons hit the reflective surface matter: these neutrons are reflected based on the physics of the angle in which they originated.

Table II. k-infinity values of the FCC homogeneous and heterogeneous pebble models with helium and different boundary conditions.

FCC Homogeneous w/ Helium	1.40165 ± 0.00078	1.39875 ± 0.00063
FCC Heterogeneous w/ Helium	1.49654 ± 0.00077	1.49598 ± 0.00071
FCC Heterogeneous Semi-Unclipped	1.51061 ± 0.00069	1.50827 ± 0.00056

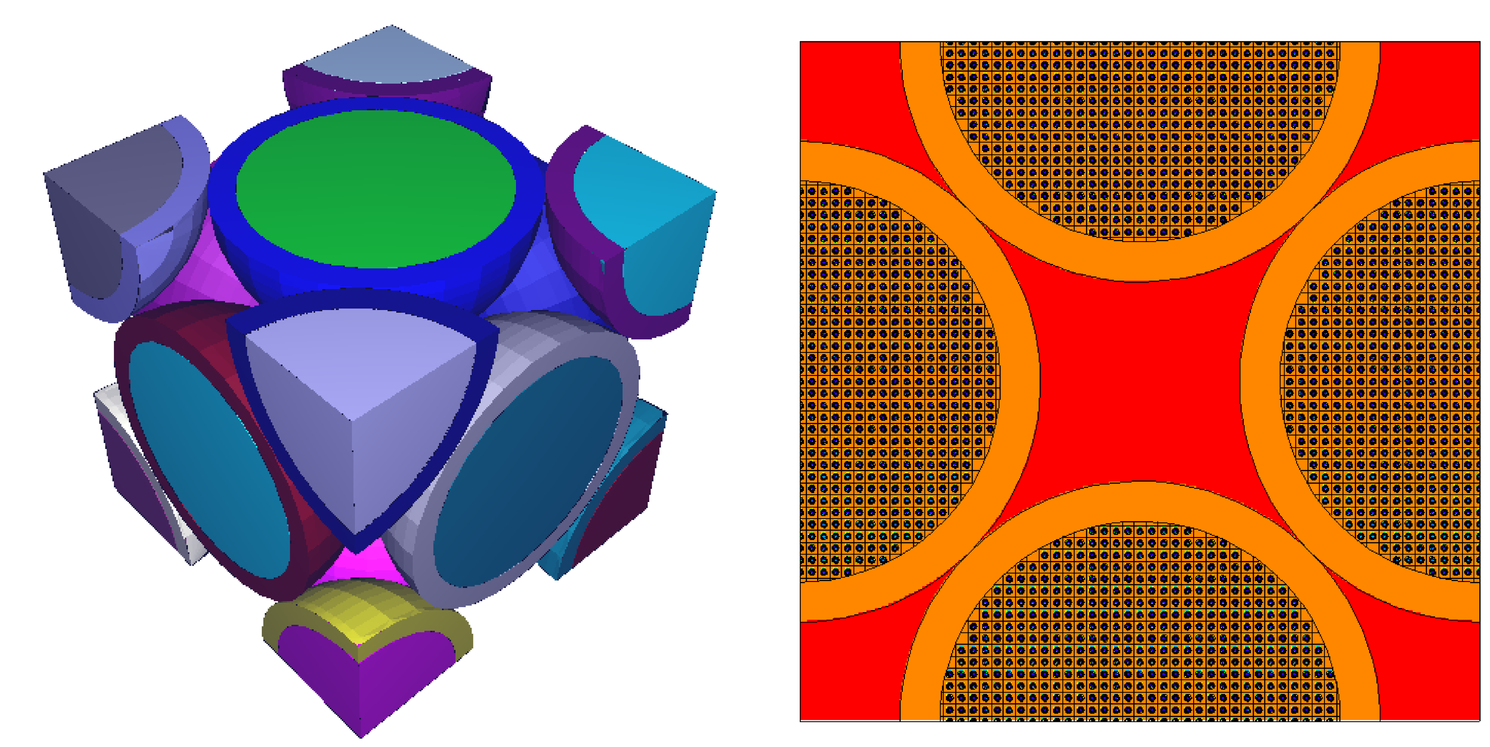


Figure 3. The 3-D (left) and 2-D (right) view of the FCC homogeneous pebble model with helium (red) and graphite (orange) in the Xe-100 reactor.

CONCLUSIONS

- Homogeneous Pebbles have a considerably lower statistical k-infinity value than Heterogeneous Pebbles because ^{235}U is completely diluted
- Clipped Heterogeneous Pebbles and Unclipped Heterogeneous Pebbles have very close statistical k-infinity value because ^{235}U is equal in mass and geometry
- White B.C. and Mirror B.C. have very small statistical difference in k-infinity values when modelling a spherical geometry, but the same k-infinity values when modelling a cubical geometry
- Helium that is added to the pebble's environment has a very small statistical difference in the pebbles k-infinity value
- Single Pebbles have a slight statistical difference in k-infinity values than their FCC model counterparts

FUTURE WORK

Future work will consist of MCNP modelling of the whole Xe-100 nuclear reactor including thousands of pebbles and nuclear reactor materials including reflectors. Simulations of the burnup of the pebbles will provide information about the isotopic composition of the pebbles as well as the gamma ray energies and neutron flux.

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Acknowledgement of funding statement, This work is performed with the support of U.S. Department of Energy's Nuclear Energy University Program (NEUP) with the Award No. DE-NE0009304.