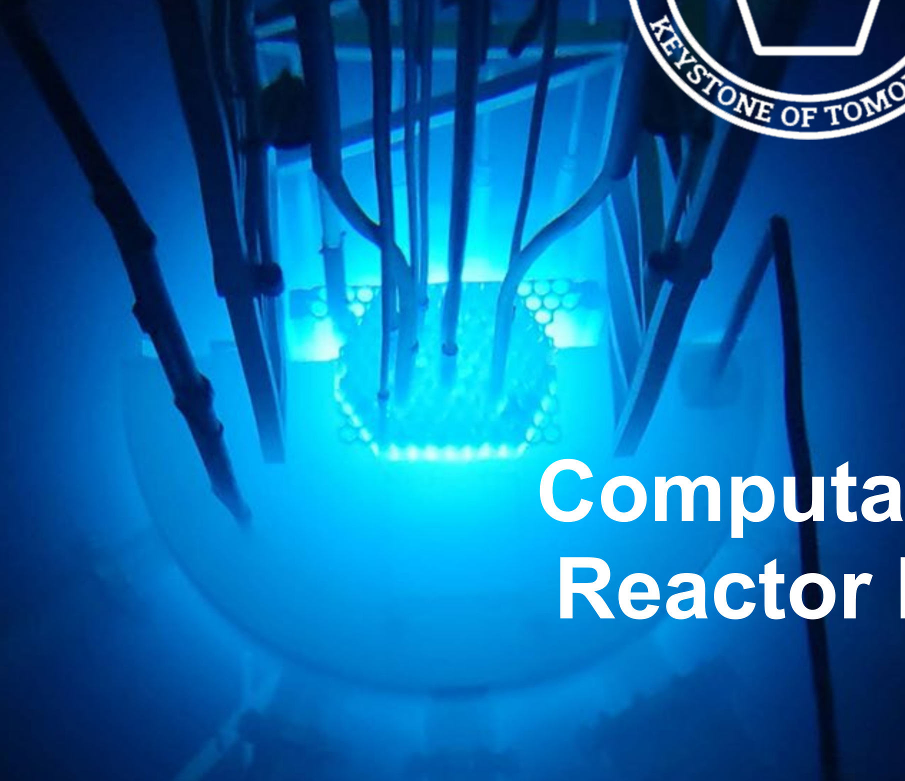

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A High-Fidelity Multiphysics Computational Model for Pebble Bed Gas Reactor based on Open-Source Software

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Background

Source-Wikipedia

- **First pebble bed reactor** –AVR reactor
- **West Germany-** Jülich Research Centre
- **Operated**- 1967-1988
- **Power** – 46MWt (15MWe)

Source-World Nuclear News

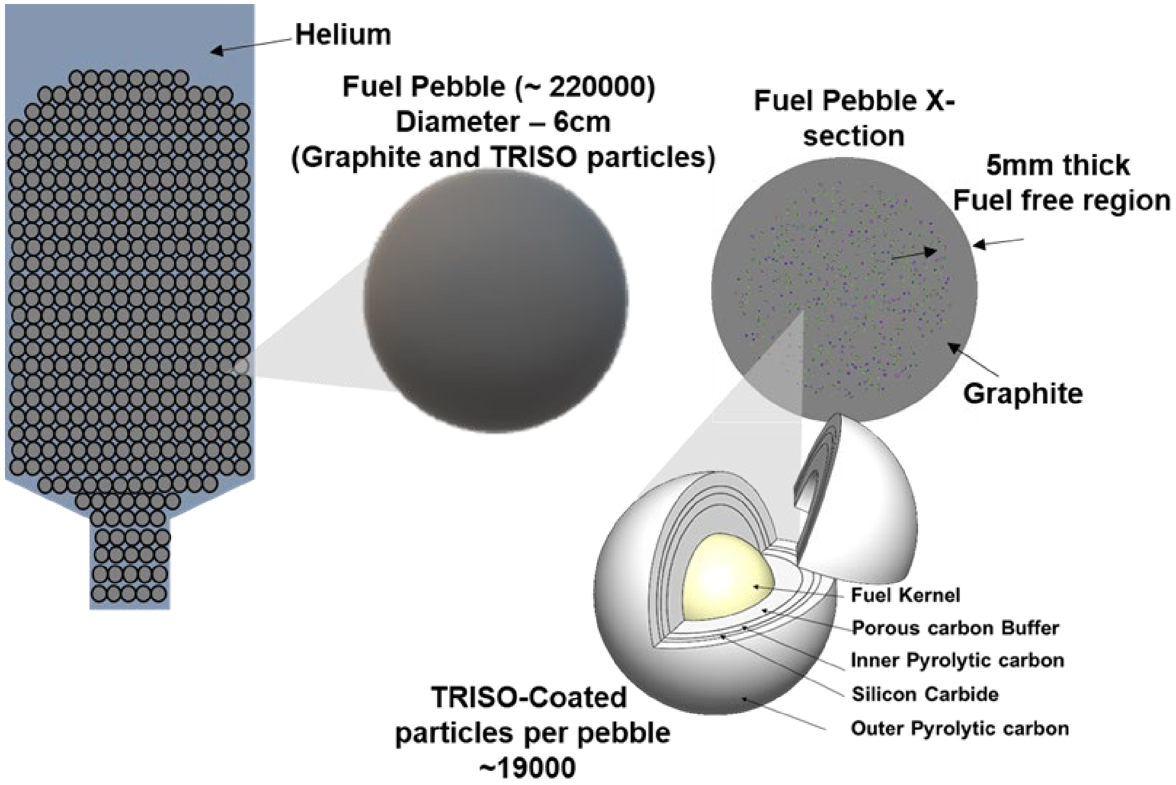
- **Currently Operating** –HTR-10 prototype at Shidaowan site, China
- **Electricity**– 210MWe

- Xe-100 reactor awarded ARDP in 2020
- World's first commercial scale advanced nuclear reactor in Washington state, U.S.
- Capacity: 200 MWt (82.5MWe)
- Scheduled delivery by 2027

Introduction of HTG-PBR

High temperature gas-cooled pebble bed reactor (HTG-PBR)

- HTG-PBR is an emerging as a next generation (Gen-IV) reactor
- Thousands of pebbles used as fuel in HT-PBR
- Each pebble is like a spherical ball filled with thousands of TRISO particles
- Helium gas transfers heat energy by flowing through pebbles structure pores
- Pebbles circulates continuously through the reactor core throughout operational lifespan



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Challenges

- Computational modeling of HTG-PBR involves addressing multiple physics aspects, including nuclear reactions, energy interaction between gas and pebbles, gas flow within the pebble bed, and continuous pebble recirculation.
- The reactor models contain complex structures, incorporating the reactor shell, moderator, and control rods, among other components.
- Ensuring accurate modeling of pebble depletion rates is essential for effective reactor performance assessment.

Objectives

- To create a comprehensive model for a full-scale High-Temperature Gas-cooled Pebble Bed Reactor (HTG-PBR) by integrating the open-source CFDEM and OpenMC codes.
- To analyze the neutronic behavior, including spatial and temporal pebble depletion, as well as conduct thermal and fluid flow analysis within the reactor core.

Computational Models (CFD-DEM)

cfdemSolverPiso

LIGGGHTS → DEM

$$m_i \frac{d\mathbf{U}_i}{dt} = \sum_{j=1}^{n_j^c} \boldsymbol{F}_{i,j}^c + \boldsymbol{F}_i^g + \left(\boldsymbol{F}_i^b + \boldsymbol{F}_i^d\right)^f + \boldsymbol{F}_{\mathbf{i,b}}$$

$$I_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum_{j=1}^{n_j^c} \boldsymbol{M}_{i,j}^c$$

OpenFOAM 5.0 → CFD

$$\frac{\partial \varepsilon\rho_f}{\partial t} + \nabla\cdot\left(\varepsilon\rho_f \boldsymbol{u}\right) = 0,$$

$$\frac{\partial \varepsilon\rho_f \boldsymbol{u}}{\partial t} + \nabla\cdot\left(\varepsilon\rho_f\boldsymbol{uu}\right) - \varepsilon\nabla\cdot\left(\mu\nabla\boldsymbol{u}\right) = -\nabla p - \boldsymbol{F}^{pf} + \varepsilon\rho_f\boldsymbol{g},$$

$$\varepsilon\rho_f C_{p,f}\frac{\partial T_f}{\partial t} + \varepsilon\rho_f C_{p,f}\nabla\bullet\mathbf{u}(\mathrm{T}_f) - \nabla\cdot(\varepsilon k_f'\nabla \mathrm{T}_f) + \alpha\left(T_f - T_s\right) = \dot{q}_f''',$$

$$\left(1-\varepsilon\right)\rho_s C_{p,s}\frac{\partial T_s}{\partial t} - \nabla\cdot(\varepsilon k_s'\nabla\mathrm{T}_s) + \alpha\left(T_s - T_f\right) = \dot{q}_s'''$$

DEM: discrete element method
CFD: computational fluid dynamics

Computational Models (OpenMC)

- OpenMC – Monte Carlo based 3D neutron transport code, analyzing neutronic behavior in reactors.

$$\Sigma_t(\vec{r},E)\psi(\vec{r},E,\vec{\Omega})+\vec{\Omega}\cdot\nabla\psi(\vec{r},E,\vec{\Omega})-\int_0^\infty dE'\int_{4\pi}d\Omega'\Sigma_s(\vec{r},E'\to E,\vec{\Omega}'\to\vec{\Omega})\psi(\vec{r},E',\vec{\Omega}')$$
$$=\frac{1}{k_{\text{eff}}}\frac{\chi(E)}{4\pi}\int_0^\infty dE'\nu(E')\Sigma_f(\vec{r},E')\phi(\vec{r},E')$$

- OpenMC utilizes the Bateman equation for pebble fuel depletion

$$\frac{dN_i(t)}{dt}=\lambda_{i-1}N_{i-1}(t)-\lambda_i N_i(t)$$

- Recently added, it offers high-performance capabilities and a user-friendly interface.

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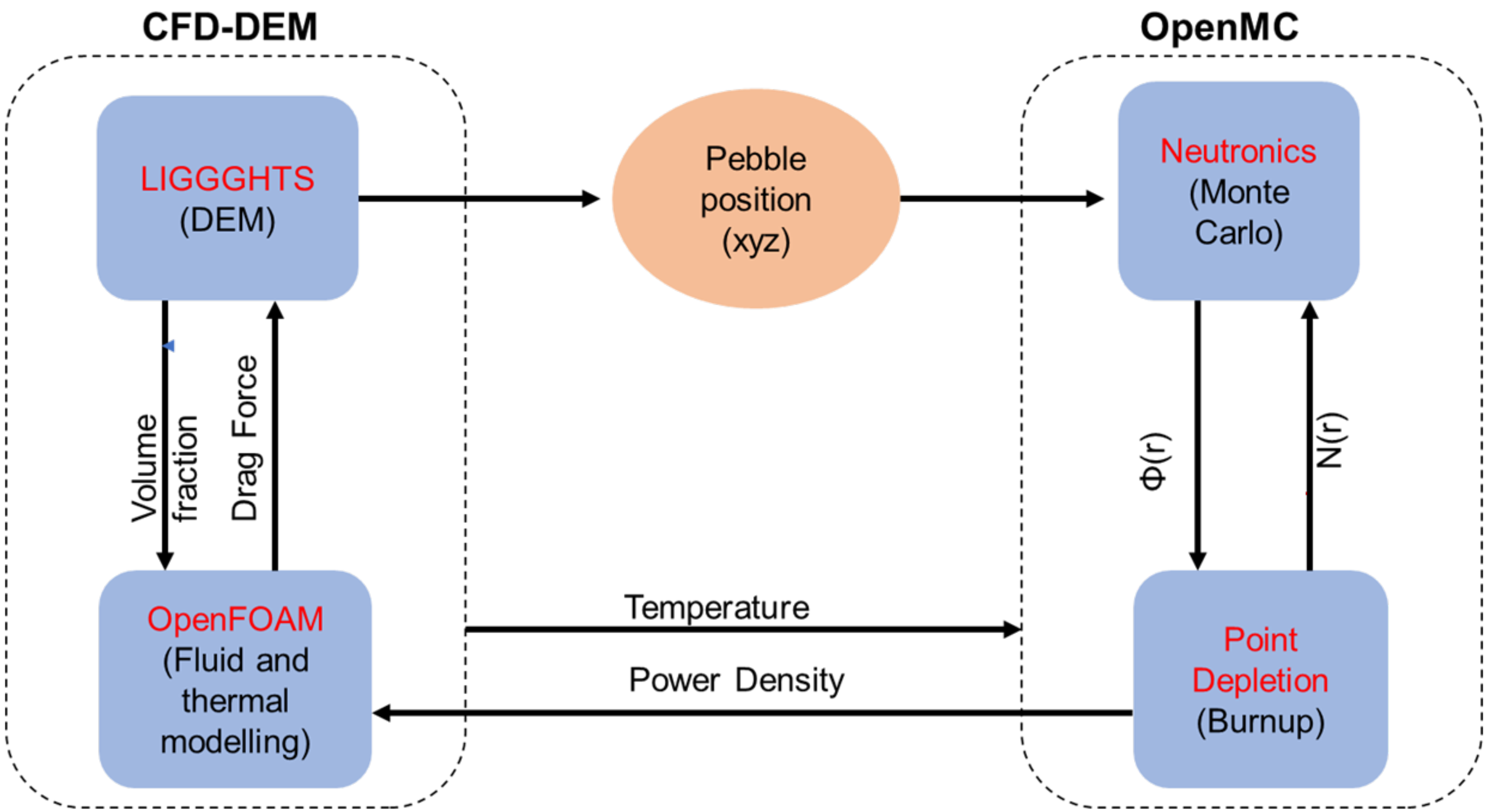
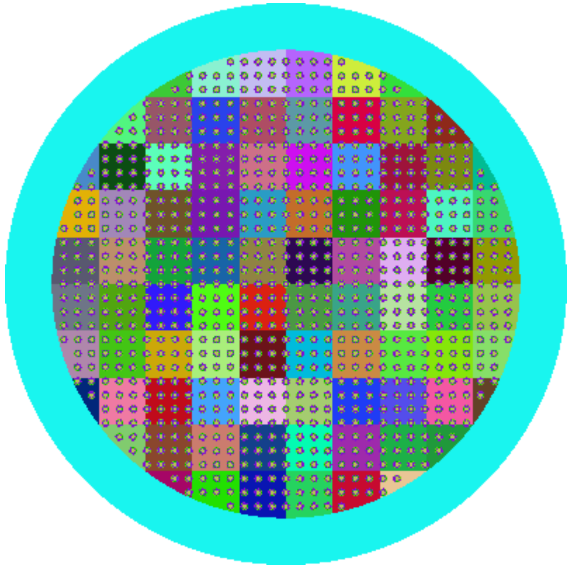
Coupling CFD-DEM and OpenMC

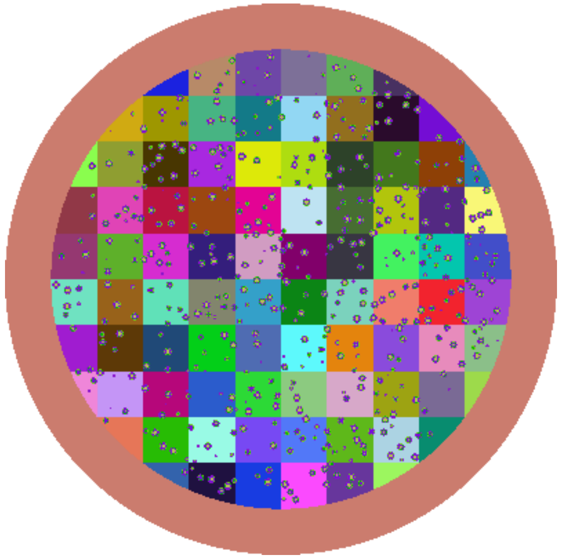


Single Pebble Model - Code Verification

- Code to Code verification of k_∞ in a single pebble with different Monte Carlo code: OpenMC and MCNP



Uniform TRISO distribution



Random TRISO distribution

Table. Pebble material composition

Material	Density (g/cm³)	Composition (atomic fraction)	Dimension (μm)
UCO Fuel	10.9	^{235}U: 0.05232 ^{238}U: 0.28101 ^{16}O: 0.49982 ^{17}O: 0.00019 C: 0.16667	425 (diameter)
Carbon Buffer	1.0	C: 1.0	100 (thickness)
PyC1	1.9	C: 1.0	40 (thickness)
PyC2	1.9	C: 1.0	40 (thickness)
SiC	3.2	C: 0.5 Si: 0.5	35 (thickness)
Graphite	1.75	C: 1.0	6 cm diameter with a 0.5 cm thickness non-fuel shell

Results at Hot Operation Condition

- k_∞ a single pebble with TRISO particles uniformly and randomly distributed at **1200 K** temperature.

Pebble Model		k_∞ (White B.C.)	k_∞ (Mirror B.C.)
Uniform	MCNP	1.50821 +/- 0.00007	1.51774 +/- 0.00007
	OpenMC	1.50789 +/- 0.00012	1.51757 +/- 0.00012
	deviation	0.00031	0.00017
Random	MCNP	1.51203+/- 0.00008	1.52111 +/- 0.00006
	OpenMC	1.51071+/- 0.00012	1.51980 +/- 0.00012
	deviation	-0.00132	0.00131

Results at Cold Operation Condition

- k_∞ of a single pebble with TRISO particles uniformly and randomly distributed at **room** temperature.

Pebble Model		k_∞ (White B.C.)	k_∞ (Mirror B.C.)
Uniform	MCNP	1.60743 +/-0.00008	1.61471+/-0.00004
	OpenMC	1.60818 +/- 0.00011	1.61560 +/- 0.00012
	deviation	-0.00067	-0.00089
Random	MCNP	1.61017 +/-0.00007	1.61723 +/-0.00006
	OpenMC	1.61025 +/-0.00011	1.61739 +/- 0.00012
	deviation	0.00008	0.00016

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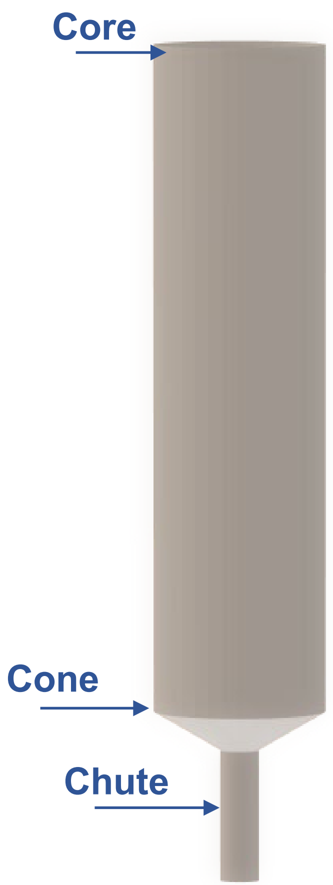
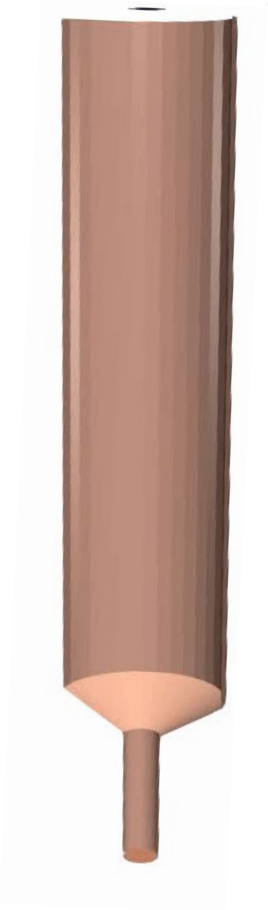
HTR-PBR Model – DEM Part



3D CAD model of HTR-PBR core

Parameter	Value
Core Radius	1.2 m
Core Height	9.4 m
Cone Height	0.554 m
Outlet Chute radius	0.26 m
Chute Height	1.85 m

Parameter	Value
Poisson's Ratio	0.12
Coefficient of Restitution	0.6
Sliding Friction Coefficient	0.3
Rolling Friction Coefficient	0.1
Number of Pebbles	220849
Pebble insertion rate	2500 per second



Video show of pebble inserting into HTR-PBR core

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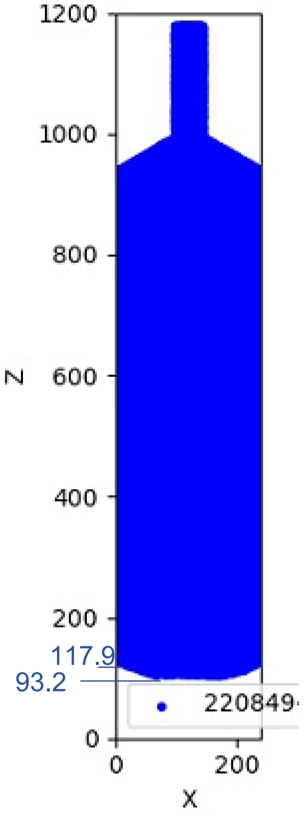
HTR-PBR Model – OpenMC Part

Pebbles positions imported from DEM to OpenMC

pf ~60.5%

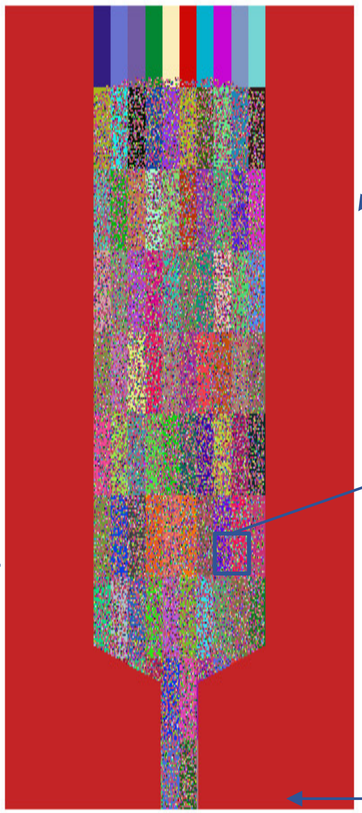


Modelling of reactor Core and RPV in OpenMC

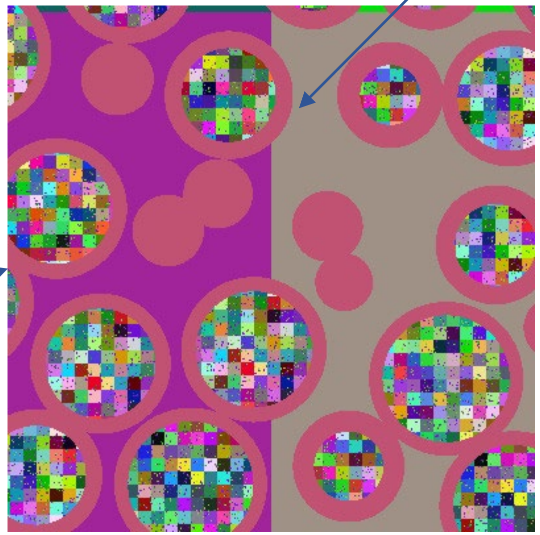
RPV – dia. 4.88 m (Graphite Material)

Reflective Top B.C.

Vacuum



Helium gas 0.00286 g/cm3



Bottom Reflector

Lattice Acceleration in reactor and pebble

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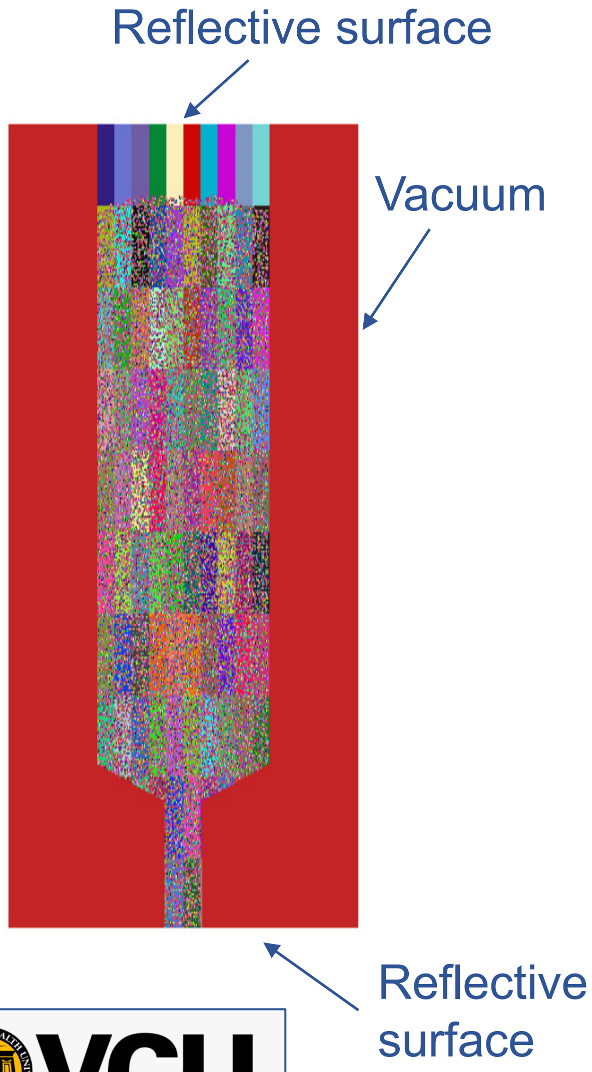
OpenMC Results (Reflective Axial B.C)



- Simulation run with initial fixed point neutron source defined in each pebble, generating 250000 neutron particles for each cycle, with a total of 100 cycles

- The workstation used for simulation as 40 cores, 1 thread per core, 2.40GHz Intel Xeon E7-8894-processors, 2880GB memory.

k_{eff}	Leakage fraction (%)	Simulation time
1.39160 +/-0.00021	4.780 +/- 0.005	3 hours

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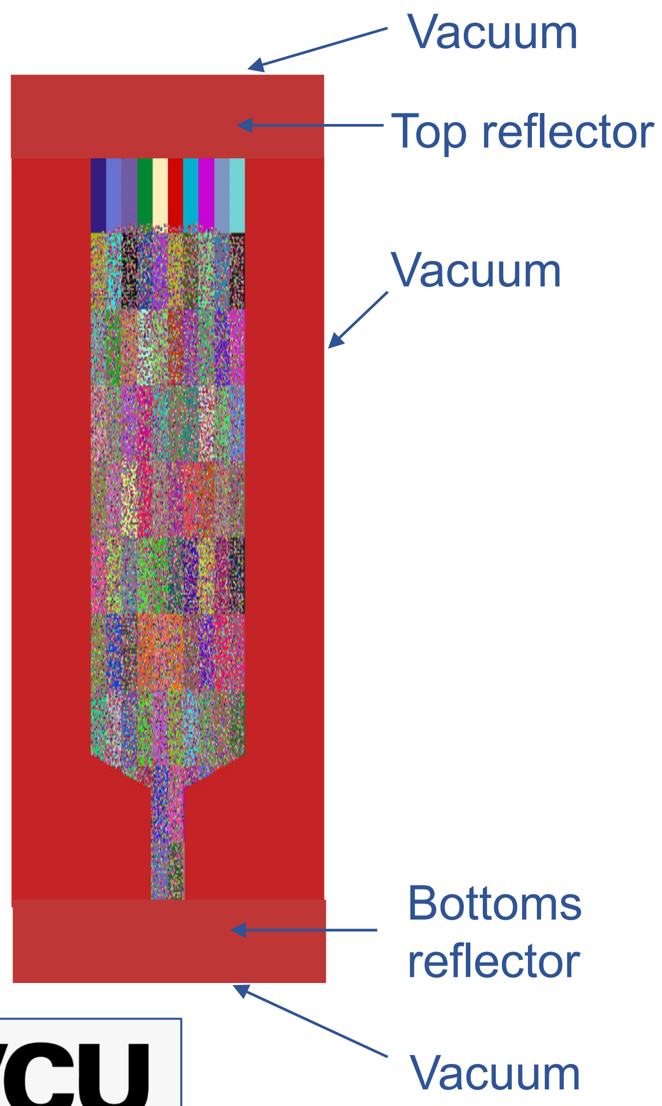
OpenMC Results (Axial Reflectors Modeled)



- Considering axial (Top and Bottom reflector) non-reflective boundary condition

k_{eff}	Leakage fraction (%)	Simulation time
1.39035+/-0.00021	4.787 +/- 0.005	3 hours

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Conclusions & Future Work

Completed work:

- Computational models of a full-scale HTG-PBR reactor
- Code verification results using a single pebble model
- Preliminary results on steady-state coupled DEM-OpenMC full core model

Ongoing and future work:

- Incorporating a more realistic reactor core design, considering pebbles movement and control rods.
- Conducting thermal and fluid analysis in packed pebble bed reactor..
- Verifying and validating the full-scale reactor against benchmark cases provided in literature and the IRPhE Handbook.

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