



ADVANCED REACTOR SAFEGUARDS & SECURITY

Enhanced Pebble Bed Burnup Data for Predictive Modeling

BNL-5925299

PRESENTED BY

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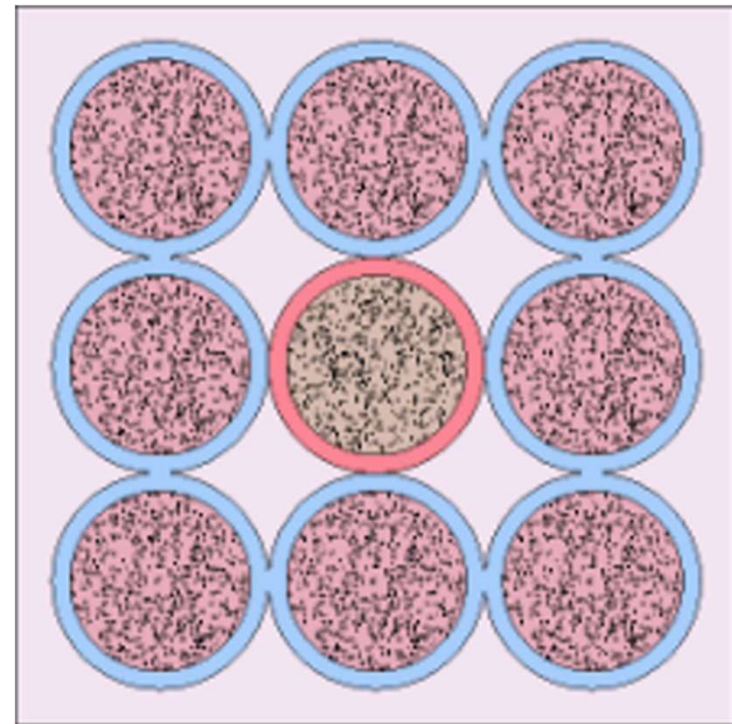
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Introduction



- In a previous approach we developed a very simple lattice burnup model.
- Keeping the model as simple as possible would also help alleviate the computational demand.
- At each burn step we sampled new powers and used the restart feature to maintain the burnup chain.



Initial Approach



- Performing dynamic burnup simulation of a reactor core has two parts.
- A tool to perform burnup, decay cooling and radiation transport.
- Another tool to update the pebble locations as pebbles traverse the core to the exit.
- OpenMC is a Monte Carlo code for simulating neutron and gamma transport in matter.
- LIGGGHTS is a software for simulating particle and granular material behavior using Discrete Element Method (DEM).



Motivation



- Pebble bed reactors (PBRs) operate with fuel spheres which circulate the core.
- Gen IV advanced reactor types also include PBRs.
- Some advanced reactor designs are being proposed based on the pebble bed technology such as X-Energy Xe-100.
- Estimating burnup and transmutation for a specific pebble requires the consideration of local flux/power.
- Also, gamma source terms from used or recirculated pebbles need to account for decay cooling and material attenuation.



Motivation

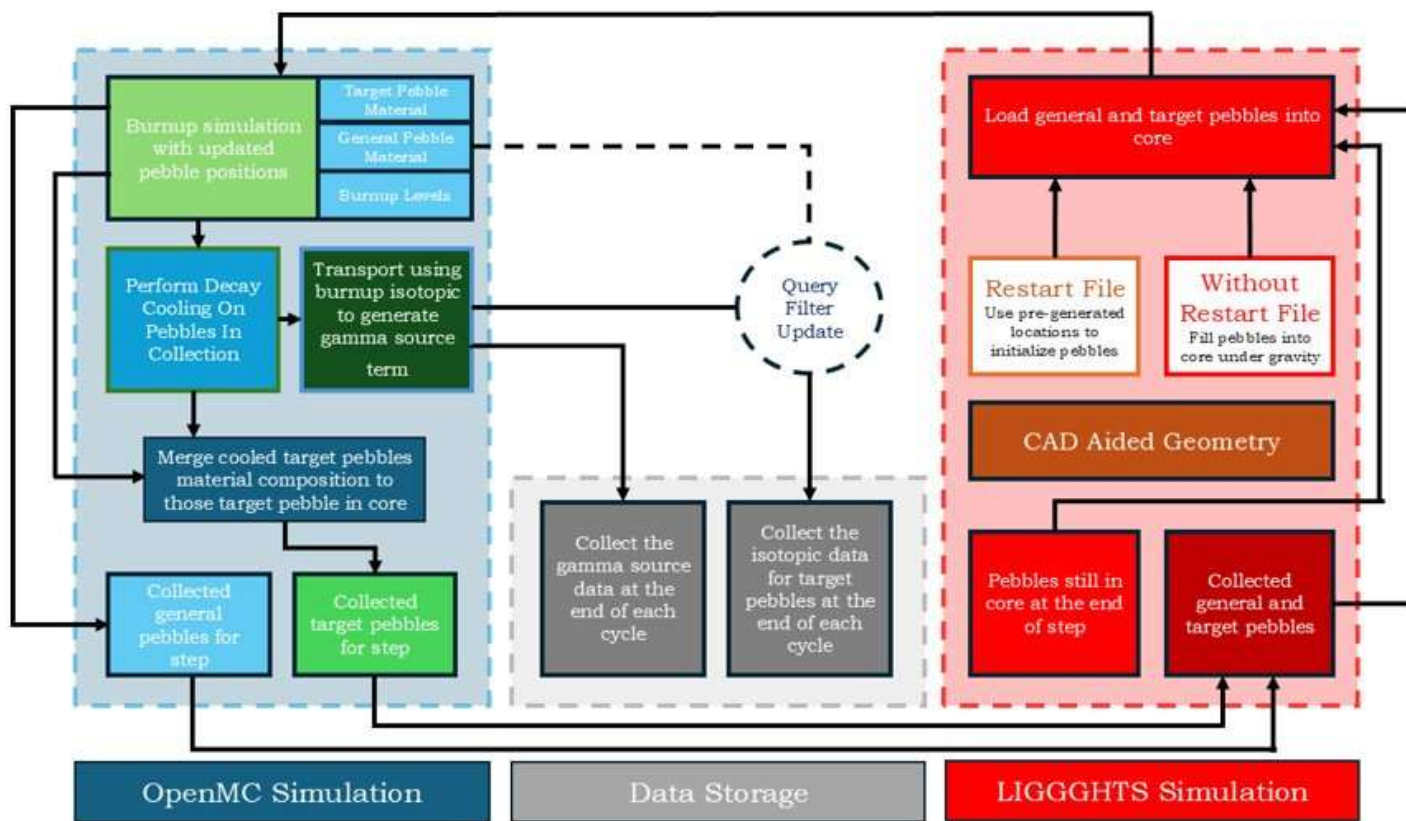


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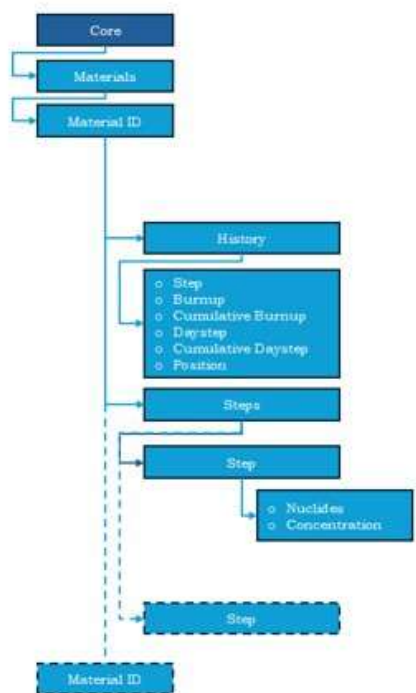




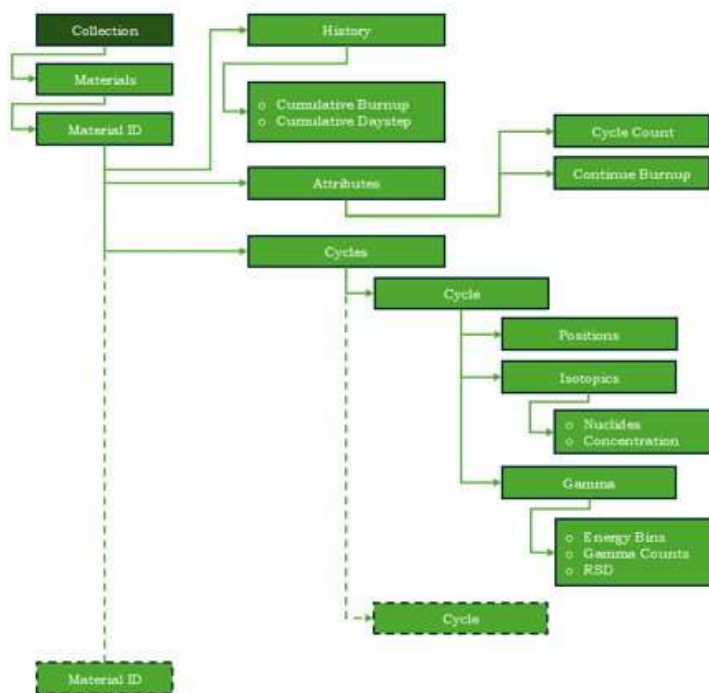
General System Flowchart



Data Management



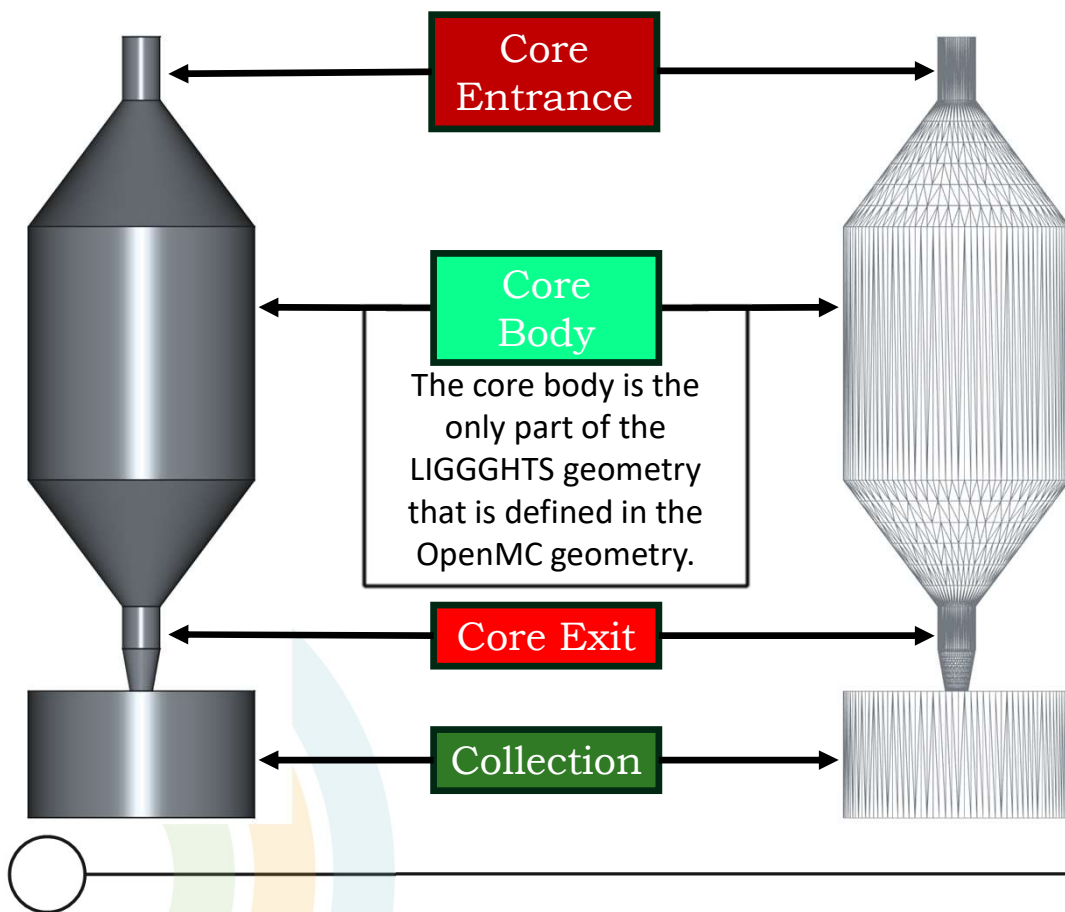
Core.h5



Collection.h5



Generic Reactor Model



Parameters	Specifications
Thermal Power (MW_{th})	40.0
Power Density (MW/m^3)	2.0
Volume (m^3)	~20.0
Target/General pebbles	50/54,950
Inner/Outer pebble radius (cm)	2.5/4.0
Core diameter and height (cm)	300/300
Control rods (B,C)	10
Number of TRISOs	20,000
Coolant/Moderator	Helium/Graphite
Core Temperature ($^{\circ}K$)	600
Fuel Composition	UCO (15.0% ^{235}U)
Fuel Density (g/cm^3)	10.5

Simulation Parameters



LIGGGHTS Parameters

Parameters	Pebble to Pebble	Pebble to Wall
Young's modulus (Pa)	1.0E+07	1.0E+07
Poisson ratio	3.0E-01	3.0E-01
Coefficient of friction	2.5E-01	2.5E-01
Coefficient of restitution	5.0E-01	5.0E-01
Coefficient of rolling friction	1.0E-02	1.0E-02

OpenMC Parameters

Parameter	Reactor Burnup	Decay Cooling	Gamma Transport
Batches	100	100	100
Particles	250,000	1,000,000	1,000,000
Time step (days)	5 increments	2	-
Core power (MW)	40	0	-

Process Visualization



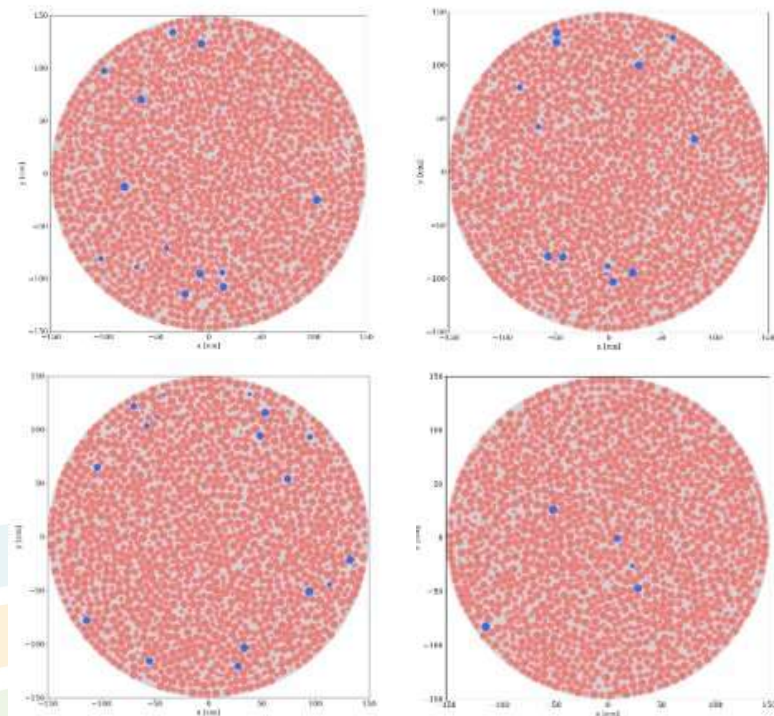
- ParaView was used to recreate the simulation and render a video of the core loading, extraction and reinsertion of pebbles.
- An Effective Full Power Day (EFPD) of operation is estimated to result in about **100 – 150 pebbles** collected.



Core

Collection

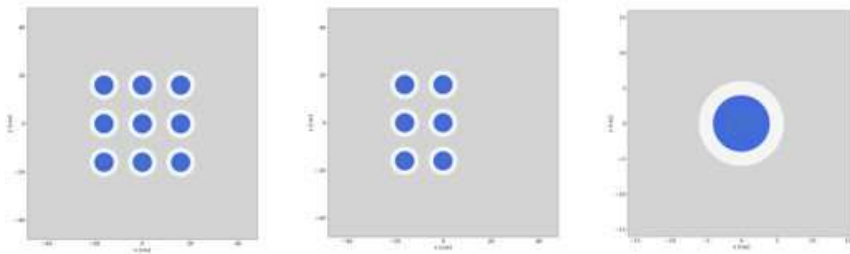
Burnup Geometry



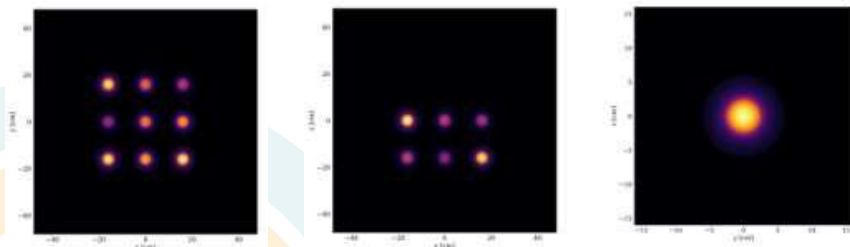
Slice Revealing Target and General Pebbles

- The images shown here focuses on the pebbles in the core.
-
- There are also 10 control rods embedded in the reflector around the core which is not displayed here.
-
- The figure displays the state of the core when the pebble cross a reference location.

Decay Cooling Geometry



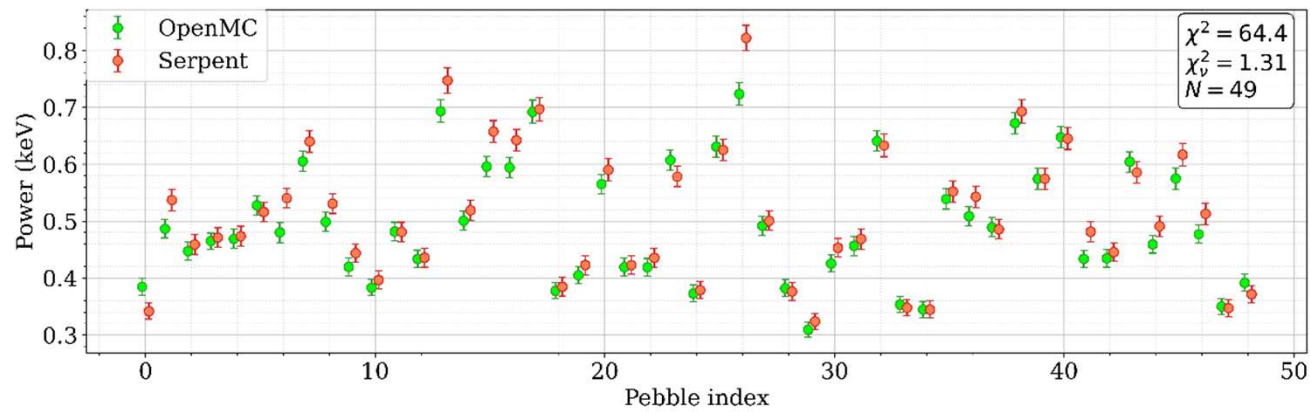
Decay cooling geometry



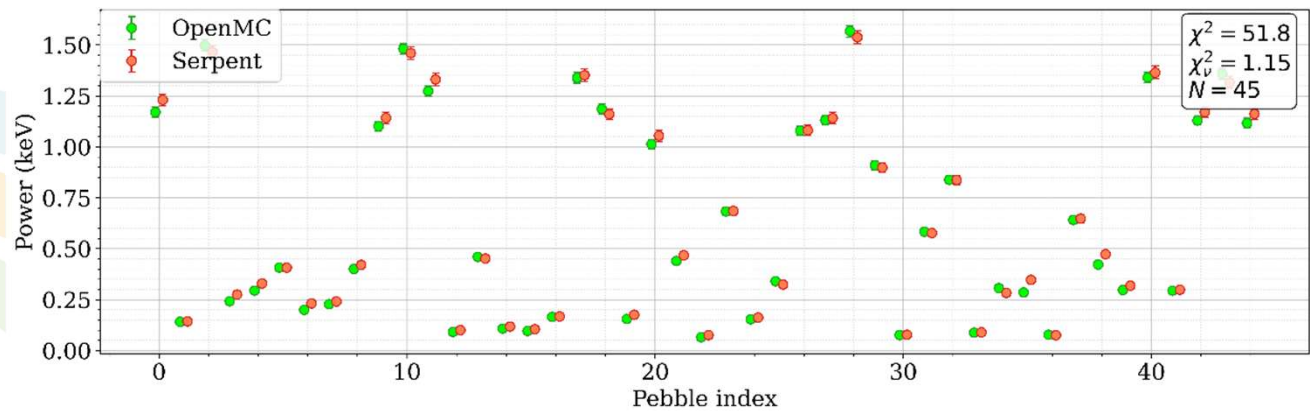
Gamma Intensity of Pebbles

- All collected target pebbles for a given cycle are cooling in a grid like geometry.
- The decay cooling and gamma source stages retain the same geometry, since all decayed pebbles undergo gamma transport to account for the material attenuation.
- Intensities or flux varies for each pebble as each pebble has different activities.

Validation



Target pebbles power distribution after 20 days



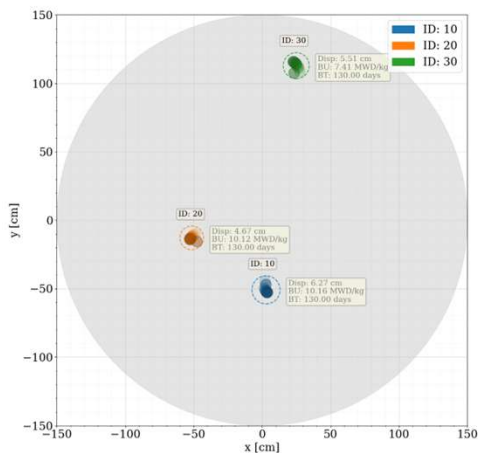
Target pebbles power distribution after 200 days

Result and Discussions

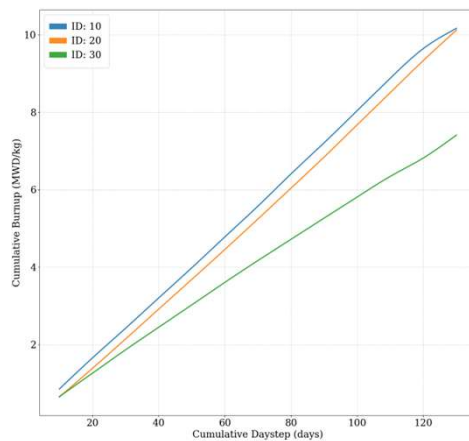


- The results presented here are a subset of the outcome of this work.
- Results for three representative target pebbles are presented for cycles 1 and 6.
- A total of 4 studies were analyzed to provide some perspective of the pebble physics and behavior.
- **Pebble path analysis** to observe behavior of random pebble motion.
- **Pebble burnup and isotopic analysis** to study the burnup curves and selected isotopic production and transmutation.
- **Gamma source analysis**
- **Computational performance.**

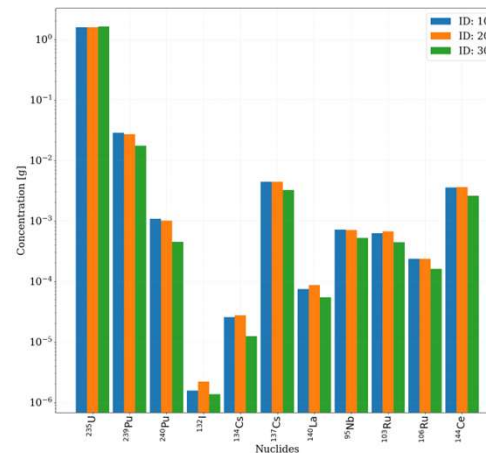
Results [Cycle – 1]



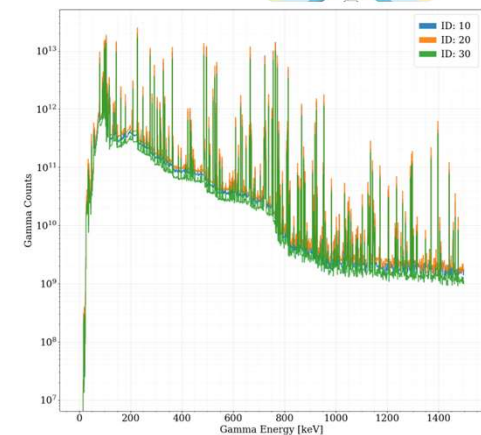
Pebble Path



Burnup Curve



Isotope Concentrations

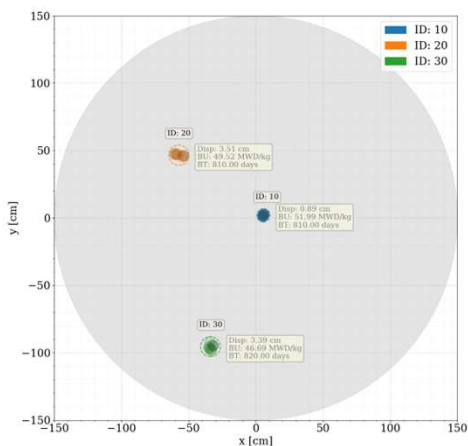


Gamma Source

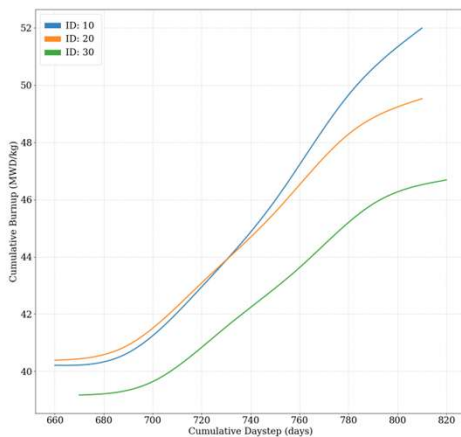
- Pebbles closer to the peripheries of the core have a gentle burnup curve compared to pebbles going through the center.
- For the pebbles in the center of the core there is an overall larger net count of gammas compared to those at the edges.



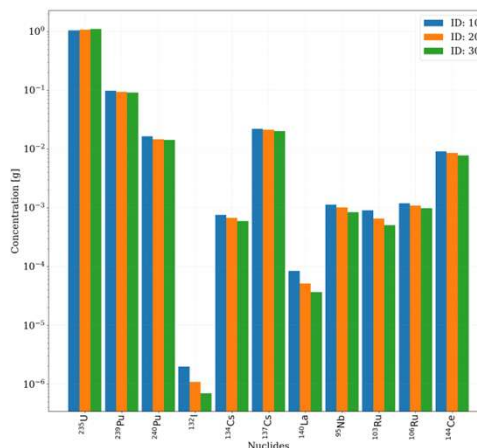
Results [Cycle – 6]



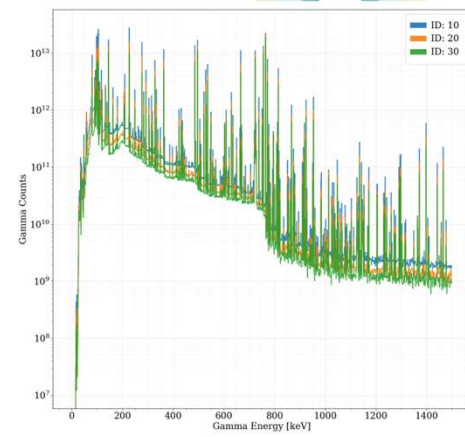
Pebble Path



Burnup Curve



Isotope Concentrations



Gamma Source

- For cycles order than the 1st one, the burnup curve typically s-curve shape.
- The lower and upper portions of the curve have gentle slope since the power at the top and bottom tend to be lower than the middle.





Results [Path Analysis]

- Pebbles don't deviate much from their initial.
- This agrees with the motivation to use radial approximation.
- These approximations radially divide the core into **4 – 8** parts which in our generic model amounts to thicknesses of about **18.75 cm - 37.5 cm**.

Cycle	Number of Pebbles	Mean (cm)	Std. Dev. (cm)	RSD (%)
1	50	6.86	3.45	50.26
2	49	7.65	3.98	51.97
3	48	7.19	4.29	59.70
4	44	6.27	3.22	51.32
5	41	5.51	2.99	54.29
6	40	5.91	3.73	63.09



Results [Computational Performance]

- Simulation such as this are computation intensive.
- Due to the repeated burnup simulations as well as the DEM pebble location updates.
- On the average with the setup we have, tracking pebbles for 6 – 8 cycles could take **4 – 6 days** to complete.
- We are limited on memory to track more than **100 pebbles**.

Simulation Stage	Simulation time per step (mins)	
	4 Nodes	6 Nodes
Burnup	22.0	15.0
Decay Cooling	5.0	5.0
Radiation Decay	27.0	20.0
DEM	25.0 – 120.0	15.0 – 100.0
Total Runtime per step	79.0 – 174.0	55.0 – 140.0

Trial	Histories (10 ⁷)	Nodes (112 cores)	Total Steps	Total Simulation Time (hrs.)
1	2.5	4	46	72
2	2.5	6	57	72
3	10.0	6	66	117

Conclusions



- Integrating LIGGGHTS with OpenMC provides a platform to produce more realistic PBR data for predictive modeling.
- To replicate the NDA approaches proposed for online burnup estimation using some of suggested isotopes, uncertainty needs to be considered.
- Burnup curve shows that pebbles at the peripheries and at the center show unique attributes.
- The gamma source produced for pebbles exhibit attribute patterns that show expected behavior with the trajectory of pebbles in the core and cycle-to-cycle consistency.



Future Work



- Produce a limited set of gamma spectra based on the simulation platform to train and test ML algorithm for predictive performance.
- Investigate approaches adopting large number of target burnable pebbles and control rod adjustment for reactivity drop compensation.



Acknowledgement



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