Pebble Database for PBR MC&A – NEUP

Advanced Reactor Safeguards Spring Working Group Meeting, October 31 – November 2, 2023

Braden Goddard

VCU College of Engineering
Mechanical and Nuclear Engineering

Project Team

Core VCU team

- Braden Goddard (PI)
- Zeyun Wu (co-PI)
- Zachary Crouch (Ph.D. student)
- Kashminder Mehta (Ph.D. student)
- Ben Impson (undergrad)

External advisory team

- Claudio Gariazzo (ANL)
- Yonggang Cui (BNL)
- Philip Gibbs (ORNL)
- Donny Hartanto (ORNL)

- Project duration: Oct. 2022 – Sept. 2024
- Funding amount: $400k

The Challenge

- Knowing the nuclear and radiological material content in used pebbles is important for:
  - Safeguards
  - Facility operations
  - Waste management
  - Etc.

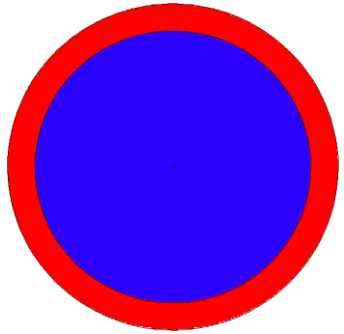
- Used pebbles are measured relatively quickly after discharge and there path through the reactor can vary between pebbles
  - Traditional LWR gamma and neutron NDA correlations may not be applicable

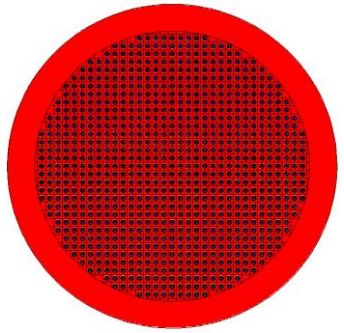
Project Goal

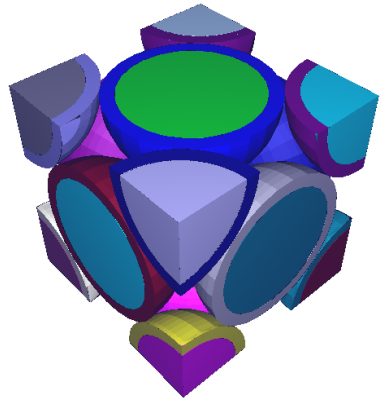
- Create a data library of used pebble NDA signatures
  - Gamma spectra (HPGe)
  - Neutron counts
- Validate data library using an independent code
  - INDEPTH (ORIGEN)
  - OpenMC
- Document methodology used to create the data library
  - Focus is Xe-100

Previous Work

- Initial work as focused on:
  - Recruiting and training students
  - Creating pebble variations to understand modeling sensitivities
    - Reflective boundary mirror vs white
    - Homogeneous vs heterogeneous
    - Simple cubic vs face centered cubic
    - Latticed TRISO particles vs semi-random
    - Effect of clipped TRISO particles
    - Reflective boundary at pebble surface vs cube with helium







Comparison of “Random” Cases

- There are different methods to simulate the randomness seen in particle distributions
- It is believed that the method employed by OpenMC most closely matches the real distribution of particles

Model	k_∞
Uniform	1.50820 ± 0.00007
URAN	1.50929 ± 0.00006
Semi-Random	1.51203 ± 0.00008
Random-OpenMC	1.51071 ± 0.00012

Conclusions from INMM 2023 Presentation

- All TRISO fuel is the same
  - Excluding enrichment
- Fuel is manufactured as specified in the nuclear industry
- 1% perturbations will have an ~300 pcm or less change in fresh fuel
- Changes that effect moderation appear to have large impacts on nuclear material content in spent fuel
  - More analyses is needed
- TRISO particle distribution is difficult to model perfectly

B. Goddard, Z. Crouch, Z. Wu, and B. Impson, "PBR Pebble Sensitivity Analyses for Material Accountancy Purposes," Proc. INMM and ESARDA Joint Meeting, Vienna, Austria, May 22 – May 26, 2023

Code Validation MCNP-OpenMC

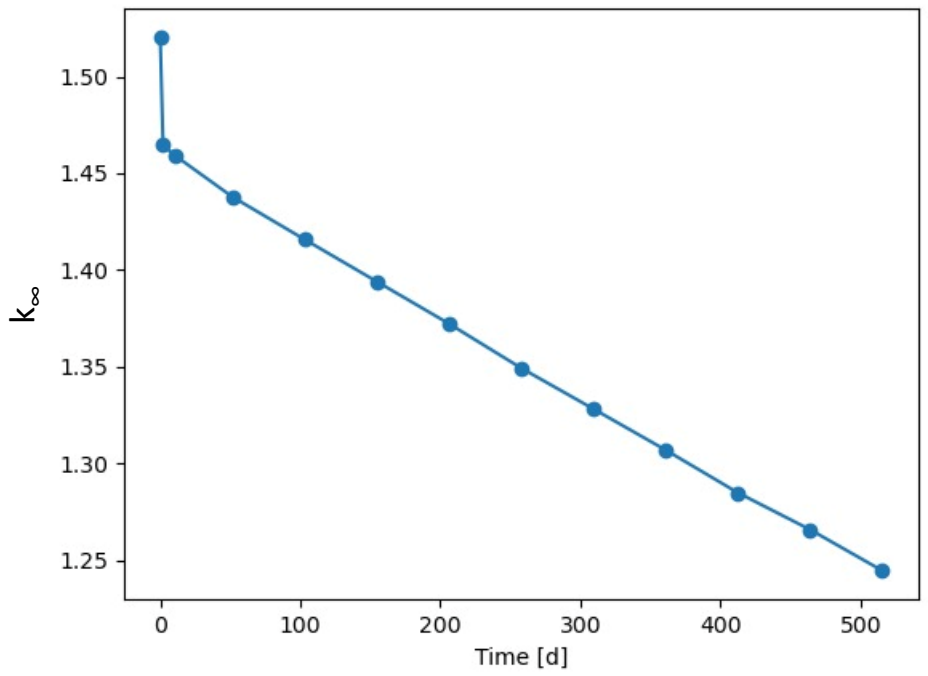
Single fresh pebble at room temperature (293.62 K)

Pebble Model		k_∞ (White B.C.)	k_∞ (Mirror B.C.)	Diff. in k_∞
Uniform	MCNP	1.60743 ± 0.00008	1.61471 ± 0.00004	-0.00728
	OpenMC	1.60818 ± 0.00011	1.61560 ± 0.00012	-0.00742
	dev. in k_∞	-67×10^{-5}	-89×10^{-5}	
URAN	MCNP	1.60830 ± 0.00005	1.61563 ± 0.00006	-0.00733
Semi-Random		1.61017 ± 0.00007	1.61723 ± 0.00006	-0.00706
Random-OpenMC	OpenMC	1.61025 ± 0.00011	1.61739 ± 0.00012	-0.00714
Compare to URAN	dev. in k_∞	187×10^{-5}	176×10^{-5}	
Compare to Semi-Random	dev. in k_∞	8×10^{-5}	16×10^{-5}	

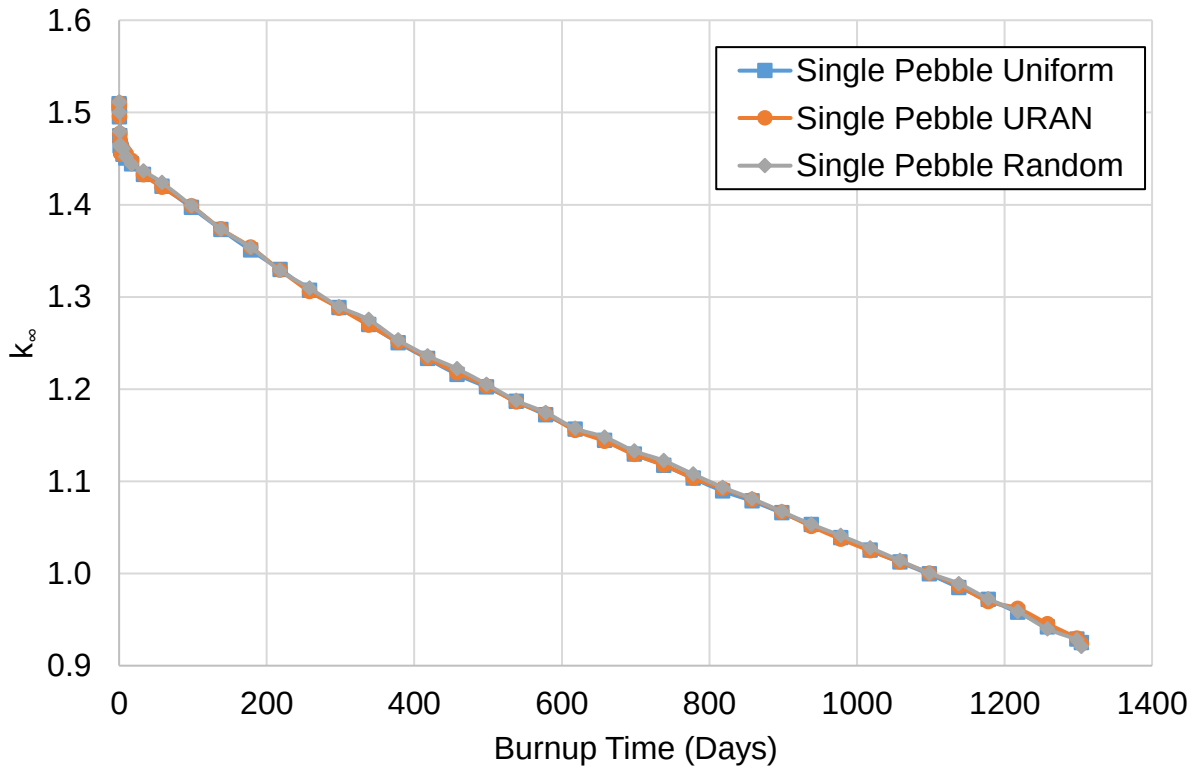
Single fresh pebble at hot temperature (1200 K)

Pebble Model		k_∞ (White B.C.)	k_∞ (Mirror B.C.)	Diff. in k_∞
Uniform	MCNP	1.50820 ± 0.00007	1.51774 ± 0.00007	-0.00954
	OpenMC	1.50789 ± 0.00012	1.51757 ± 0.00012	-0.00968
	dev. in k_∞	31×10^{-5}	17×10^{-5}	
URAN	MCNP	1.50929 ± 0.00006	1.51866 ± 0.00004	-0.00937
Semi-Random		1.51203 ± 0.00008	1.52111 ± 0.00006	-0.00908
Random-OpenMC	OpenMC	1.51071 ± 0.00012	1.51980 ± 0.00012	-0.00909
Compare to URAN	dev. in k_∞	142×10^{-5}	114×10^{-5}	
Compare to Semi-Random	dev. in k_∞	-132×10^{-5}	-131×10^{-5}	

Burnup: k_∞

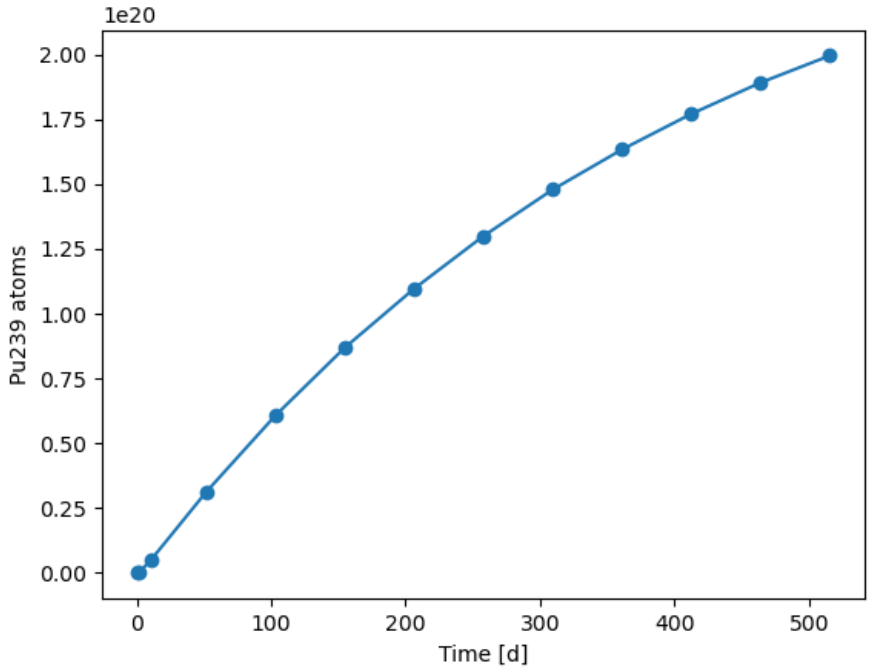


Burnup: OpenMC k_∞ mirror B.C. model

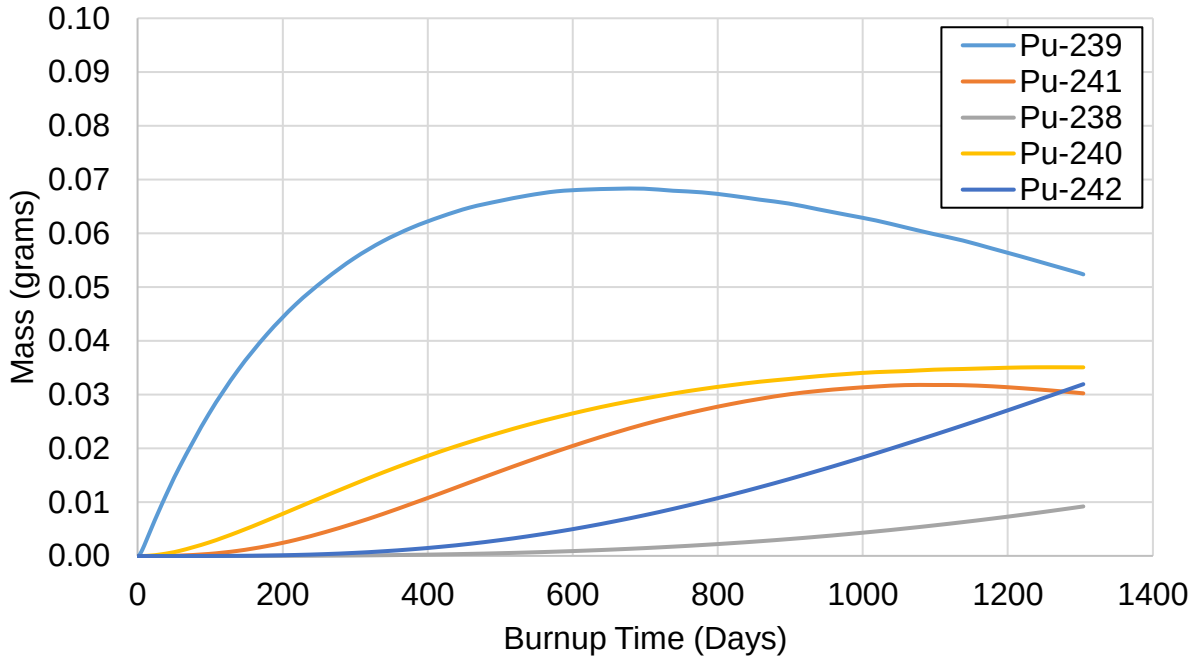


Burnup: MCNP k_∞ white B.C. model

Burnup: Plutonium Isotopic Content



Burnup: OpenMC Pu content mirror B.C. model



Burnup: MCNP Pu content white B.C. URAN model

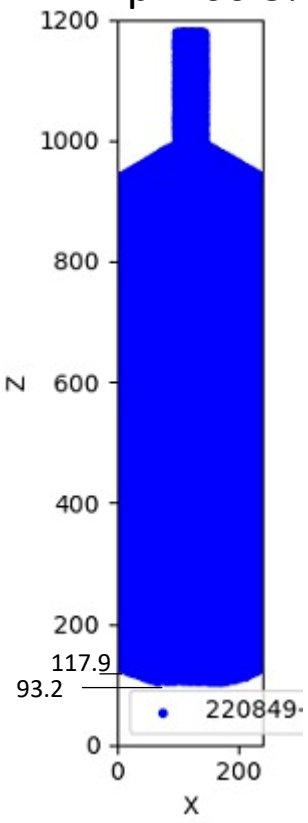
INDEPTH Validation

- Feed MCNP nuclide data into INDEPTH
  - INDEPTH library needed slight modification
    - Thanks Brandon Grogan for help
- Xe-100 reactor ORIGEN model is needed
  - Thanks Jonathan Wing for sharing your model!
- Will compare to AGR, MAGNOX, and PWR fuel models
  - INDEPTH results should not match for these models

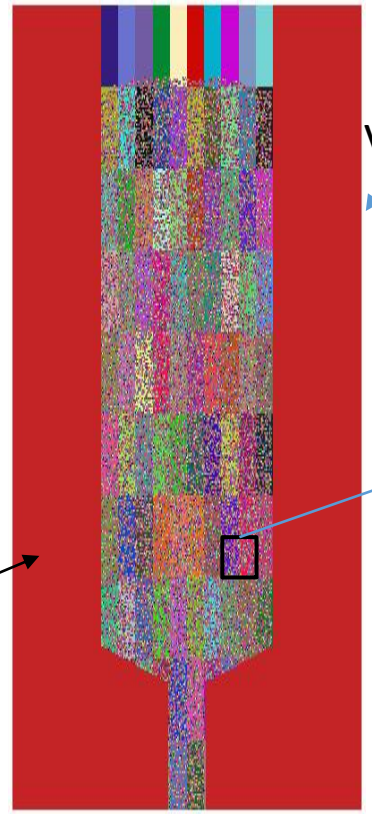
OpenMC Preliminary Full Reactor Model

Read Pebbles position from .vtk in OpenMC

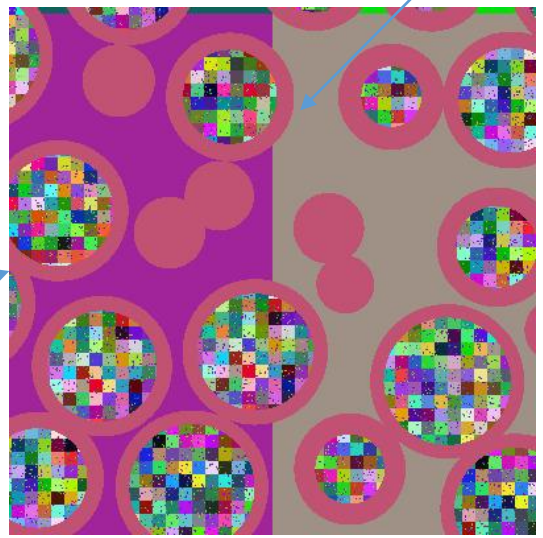
pf ~60.5%



Modelling of reactor Core and RPV in OpenMC



Helium gas
0.00286 g/cm^3



k_{eff}	Leakage fraction
1.39160 ± 0.00021	0.04780 ± 0.00005

Acknowledgements

- Savannah Fitzwater and Ben Cipiti
  - Program managers
- Claudio Gariazzo, Yonggang Cui, Philip Gibbs, Donny Hartanto
  - External advisors
- Brandon Grogan, Jonathan Wing
  - INDEPTH and SCALE assistance
- Everyone in this “room” for the constructive feedback on this work
- 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

Pebble Database for PBR MC&A – NEUP

Advanced Reactor Safeguards Spring Working Group Meeting, October 31 – November 2, 2023

Braden Goddard

VCU College of Engineering
Mechanical and Nuclear Engineering