Engineering Expo Presentation

Multiphysics Modeling of a Pebble Bed Reactor

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Presentation Outline

1: **Background** (Slides 3-7)
- Advanced Reactors
- TRISO Fuel
- Pebble Bed Reactors

2: **Significance** (Slides 8-19)
- Homogenized Diffusion
- Pebble Tracking Transport (PTT)
- Packing Fraction

3: **Design Challenges** (Slides 20-23)
- Processing DEM Data
- Making Assumptions
- Running the Simulation

Background

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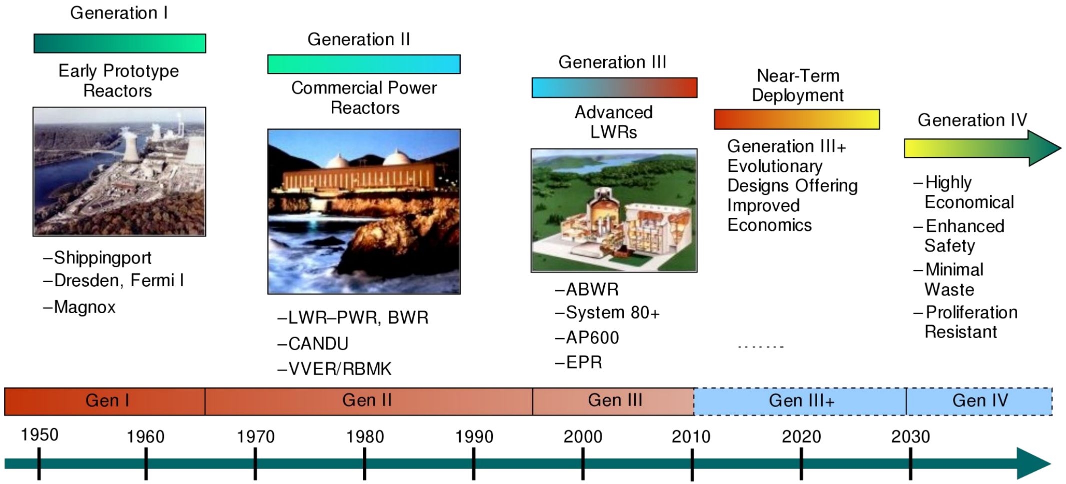
Background

Reactor Generations

- Reactor designs are split into generations
- The majority of reactors in america are generation II and III
- The industry is currently working towards Generation IV
- Gen. IV has many advantages:
  - Cost Effective
  - Inherent and Enhanced safety
  - Proliferation Resistant
- Pebble-Bed Modular Reactor (PBMR)

Generation IV: Nuclear Energy Systems Deployable no later than 2030 and offering significant advances in sustainability, safety and reliability, and economics

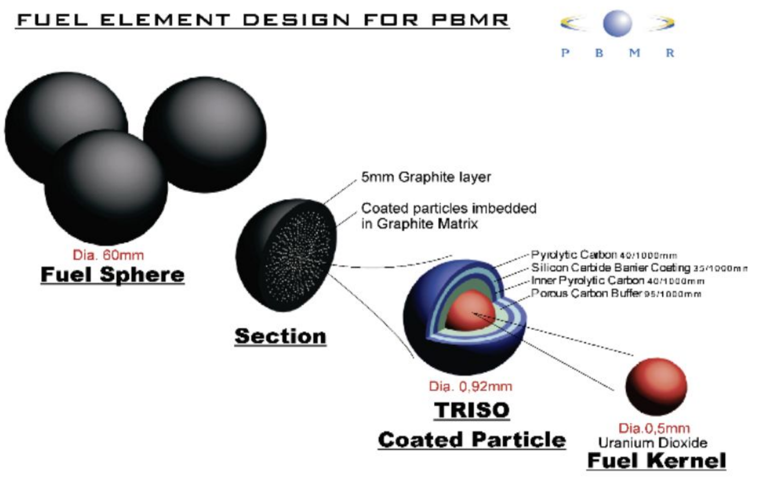


[NERAC, GIF, 2002]

Background

TRISO Fuel

- TRISO (TRI-structural ISOtropic) fuel starts with enriched uranium (UO_2) reactor fuel kernel
  - Fuel kernels are covered in multiple layers of graphite and ceramics
- The final product is a fuel sphere, these spheres have many advantages over rod forms of reactor fuel:
  - High temperature resistance, Contains the fission products, Structurally sound, and Nearly impossible to extract the uranium



[NEA, 2013]

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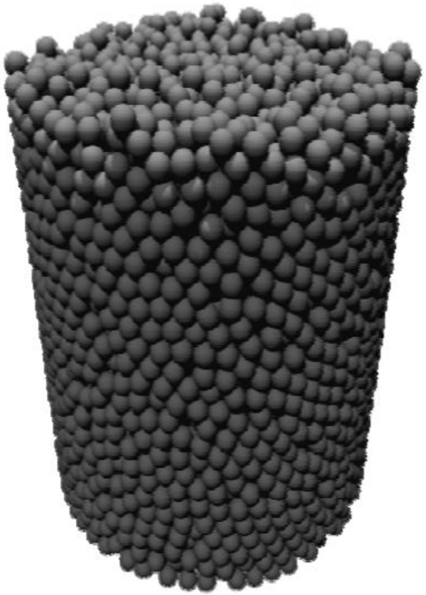
Background
Pebble Bed

- Pebble bed reactors use TRISO fuel spheres within the reactor core
- The uranium inside these fuel spheres causes a reaction which produces heat
- Helium gas is pushed through the gaps in between the pebbles to remove heat



[Cogliati, 2006]

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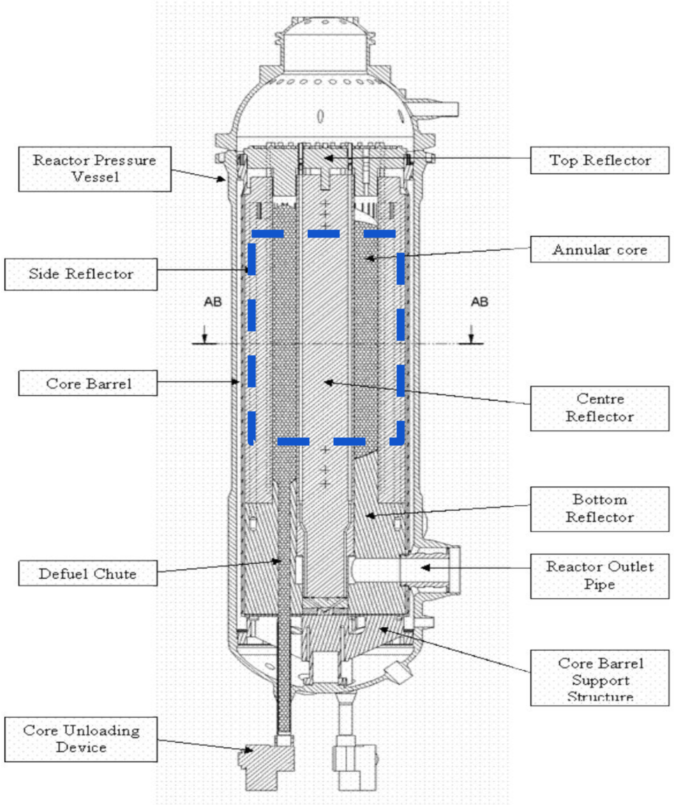
Background
Pebble Bed Reactor

- The reactor for this project is a pebble-bed reactor
- Fuel pebbles are contained within the annular region of the reactor core
- Annular means ring shaped cylinder
- We have restricted our model to just the area outlined in blue



[NEA, 2013]

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Significance

Significance

Comparison Between Two Methods

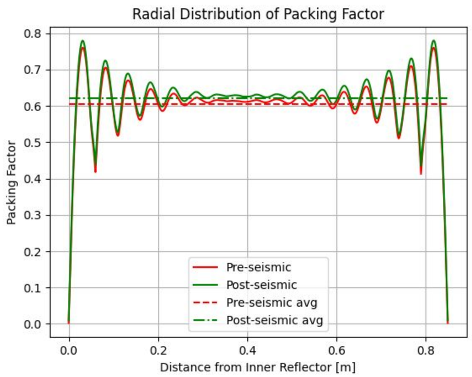
- This project compares two reactor core modeling methods
- The assumptions made in each model affect the neutron physics (neutronics)
- The first model is of a homogeneous core
  - Physically unrealistic but proven and provides acceptable results
- The second is a core using a Pebble-Tracking Transport (PTT) algorithm
  - Physically realistic but unproven and computationally expensive

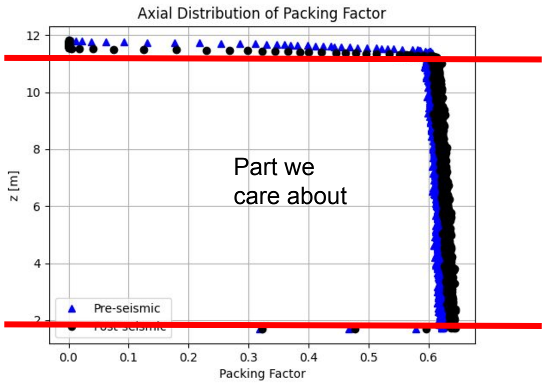
Significance

Pebble Packing Factor

- Packing fraction is the amount of space occupied by the pebbles within a certain volume.
- Important to understand fluctuations throughout the core so we can determine its impact on the reactor performance.

Packing Fraction = $\dfrac{\text{Volume of pebbles}}{\text{Volume containing pebbles}}$



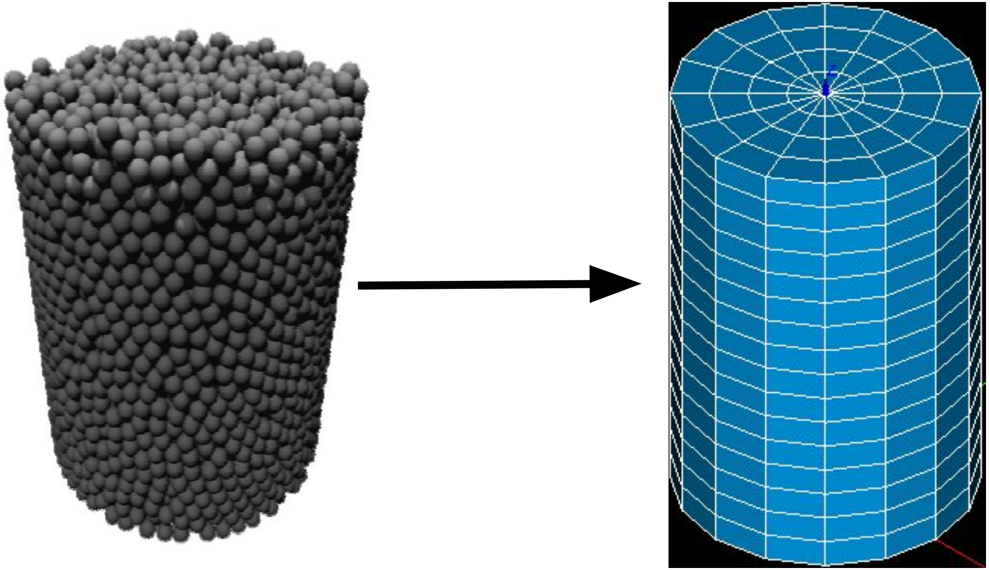


Significance

Homogeneous Model

- Assumes a single homogenized material for the core; a mixture of all the pebble materials into one "blob"

E.g.



[Cogliati, 2006]

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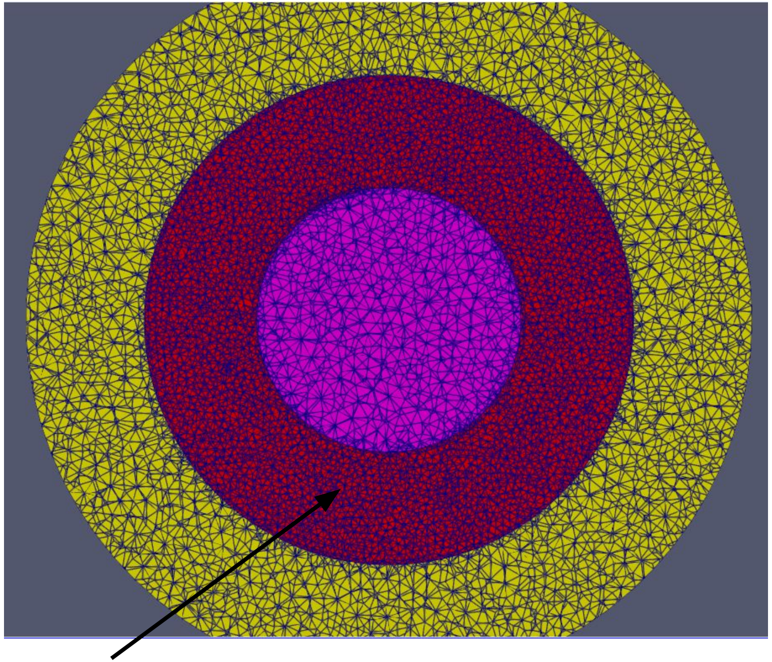
Significance

Pebble Tracking Transport Model

- Tracks each pebble individually, this is much more realistic
- More precision in neutronics modeling for the core over the homogenized method



Individual pebbles within the core region modeled as nodes

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Significance

Accident Scenarios to Compare Methods

- Two accident scenarios will be used in the comparison between modeling methods
- Accident scenarios for this project:
  - Before and after a seismic event (earthquake)
  - Depressurized Loss of Forced Coolant (DLOFC)
- These scenarios represent design-basis accidents individually and beyond design-basis accidents when coupled
  - Important for risk assessment and safety analysis for regulators like the Nuclear Regulatory Commision (NRC)

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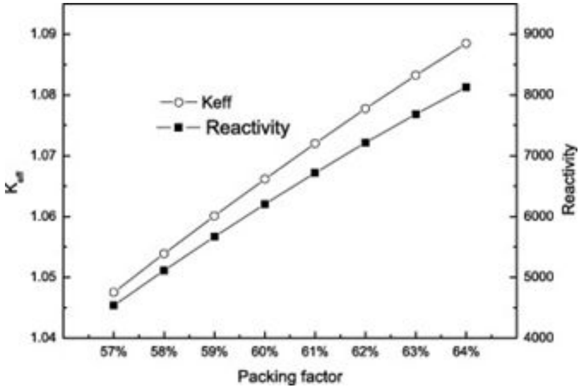
Significance

Accident Scenario: Seismic Event

- This accident scenario will simulate an earthquake
- The event will shake the core and force the pebbles to become more densely packed and therefore a higher packing fraction
- As the fuel is more densely packed, the reactivity of the core will increase which leads to increased power and temperatures

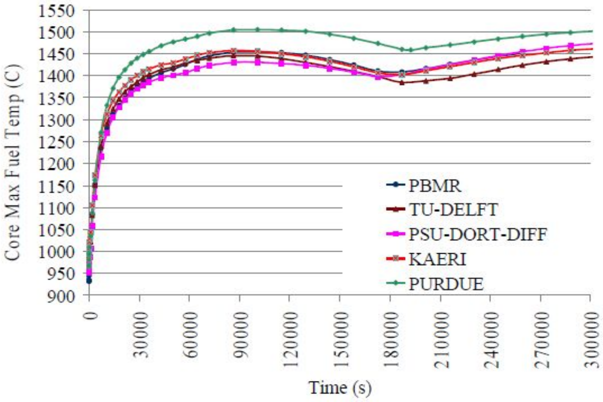


[Chen et al., 2020]

Significance

Accident Scenario: Depressurized Loss of Forced Coolant

- Depressurized Loss of Forced Coolant (DLOFC)
- In this scenario we simulate the aftermath of an accident which the reactor loses its coolant, i.e. coolant is no longer flowing through the core
- Core materials including the fuel will begin to heat up significantly
- Optimal upper limit for fuel is 1600 C



[Strydom et al., 2010]

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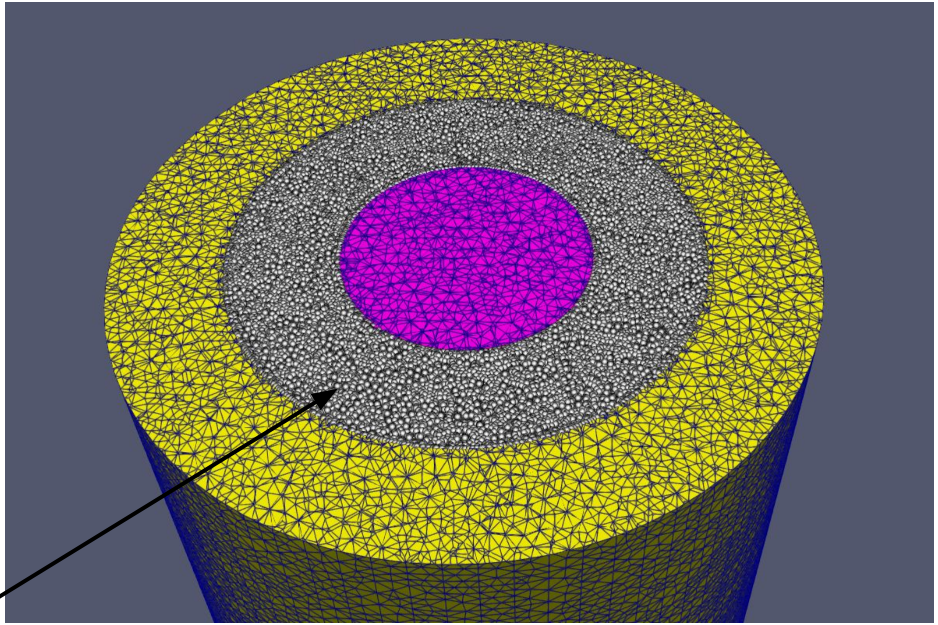
Significance
MAMMOTH

- For regulators it is important to have a comprehensive code that can represent both normal operation and an accident scenario, and MAMMOTH is promising.
- MOOSE is the INL Multi-Physics Framework that allows for the construction and solving of Partial Differential Equations (PDEs) that represent physical system behavior.
- MAMMOTH is a MOOSE Module specifically designed for simulating Reactors.
- Capable of simulating both a reactor in steady state and with transients (constant conditions vs. changing).
- A goal of this project is to evaluate the performance of MAMMOTH for PBRs.
- MAMMOTH takes an input file that includes the mesh of our core and a set of properties which we define to the core regions.

Significance

CUBIT/TETGEN

- Meshing softwares used for homogenized and the PTT base model respectively.
- CUBIT utilizes an Add-On developed by INL specifically for this style of core that optimizes the mesh for neutronics of reactors.
- TetGen is used to handle the large amount of elements for the PTT meshes, can even model individual elements.
- Both are methods that are commonly used by the industry and research professionals.



Individual pebbles within the core region

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Significance

PEBBLES

- Developed by Dr. Cogliati at INL, DEM code specifically for modeling pebble distribution.
- All fuel spheres are treated as individual elements, with their own center location and a set physical properties.
- At a starting point the real life forces acting on a pebble are converted to equations the code can interpret.
- At subsequent time steps, resultant equations from the system and collisions of elements.

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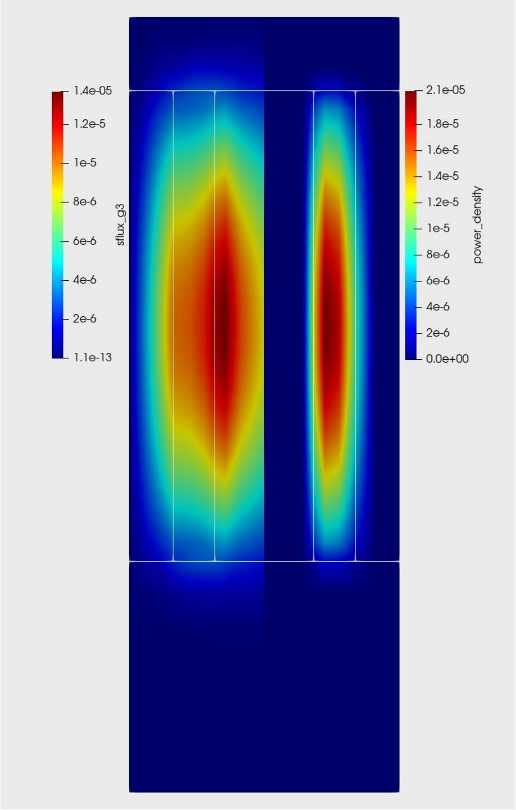
Significance

What Will These Models Show?

- Each accident scenario model will show neutronics or heat conduction results.
- On the right is a MAMMOTH output for a pre-seismic Homogenized Diffusion.
- Left part of the image represents thermal flux, right side power density.



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Design Challenges

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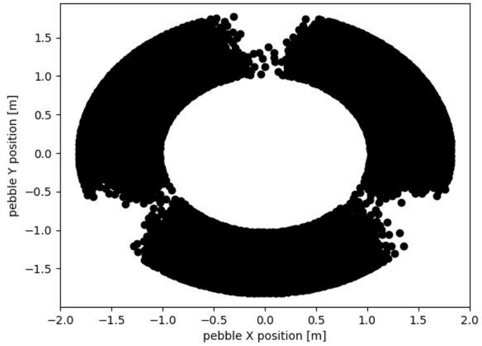
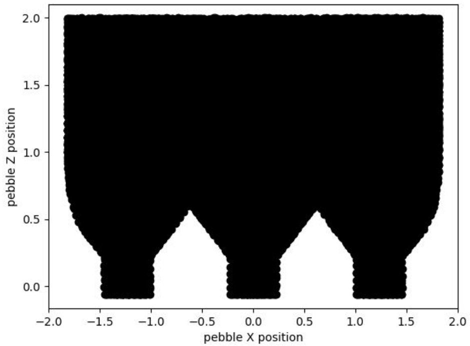
Design Challenges

Preparing Input Files

- List of 450,000 pebble center coordinates
- Need to visualize packing fraction distribution throughout the core





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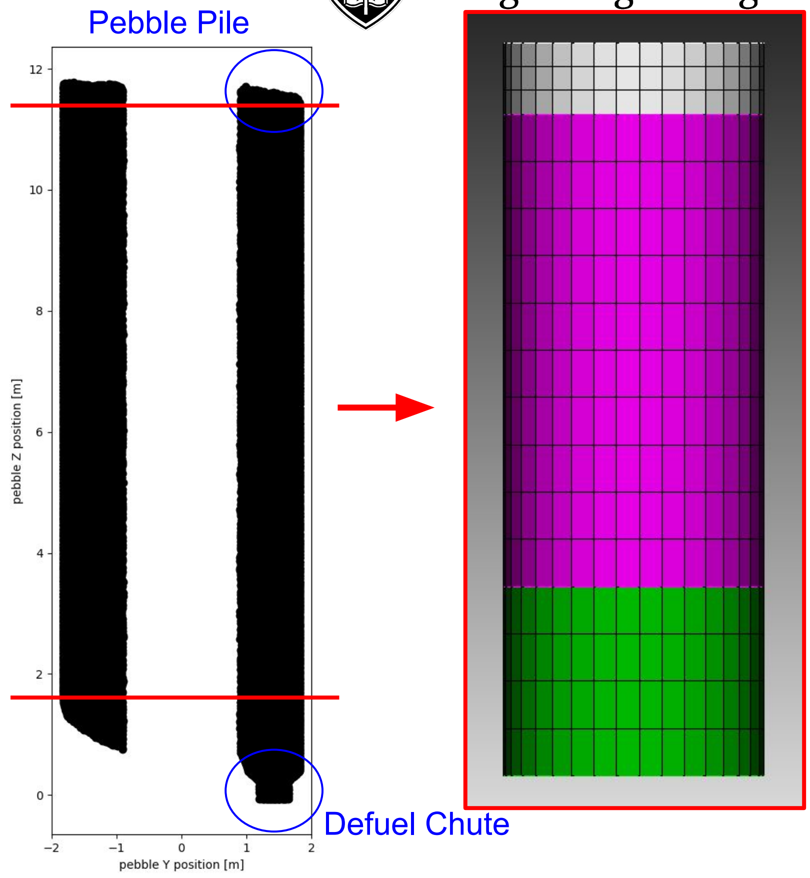
Design Challenges
Making Simplifications

- We are not going to be able to model the core perfectly.
- The key is knowing what assumptions you can reasonably make.



Design Challenges

Running the Simulation

- Important to know what your code (MAMMOTH) is actually doing
- Know what to modify between our three scenarios
- How do we implement packing factor?

Pebble-bed effective thermal conductivity:

$$(1-\epsilon)\rho_s C_{p,s}\frac{\partial T_s}{\partial t} - \nabla \cdot (\kappa_s \nabla T_s) + \alpha(T_s - T_f) + \dot{q}_s = 0$$

Porosity
(Related to packing factor)

Temperature of Solid
(What we are solving for)

Neutron Diffusion Equation:

$$\frac{1}{v}\frac{\partial \varphi}{\partial t} = s - \Sigma_a \varphi + D\nabla^2 \varphi$$

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Questions?

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