Exploring Effects of Homogenization on an OpenMC Depletion Analysis of a TRISO Fueled, Helium Cooled Microreactor

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Outline

1. Virtual Test Bed Gas-Cooled Microreactor
2. OpenMC Model
3. Results and Discussion
4. Next Steps

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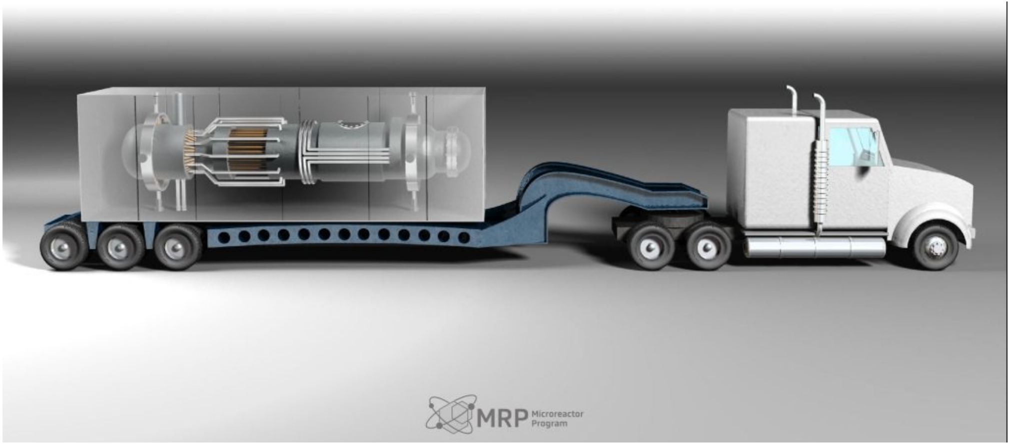
Virtual Test Bed [1]

Microreactors [2]



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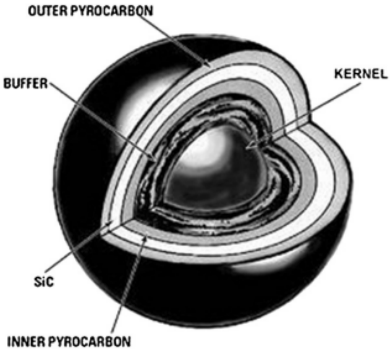

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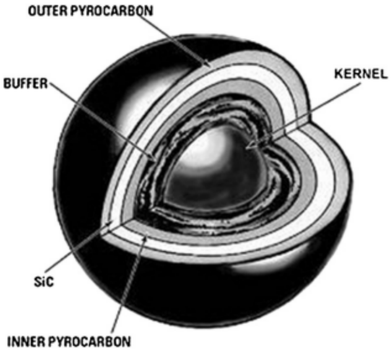

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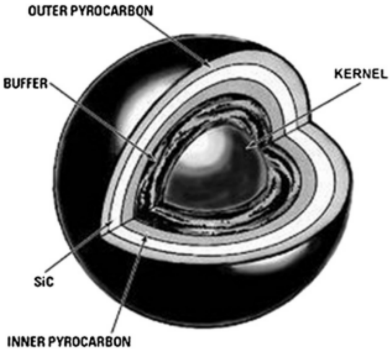

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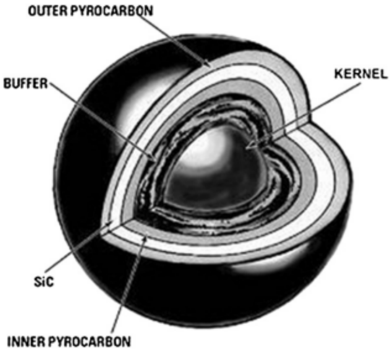

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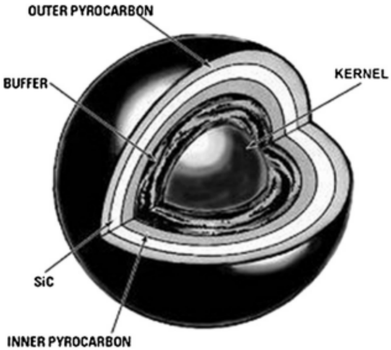

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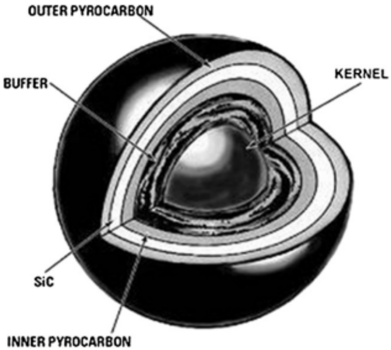

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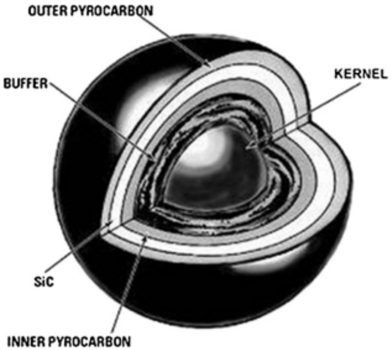

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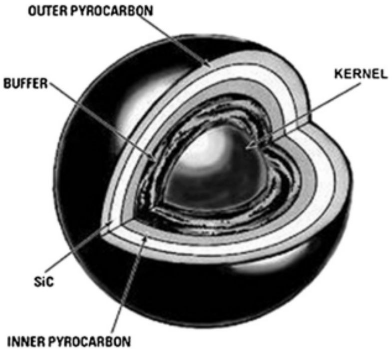

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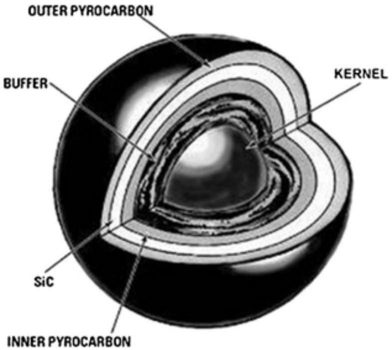

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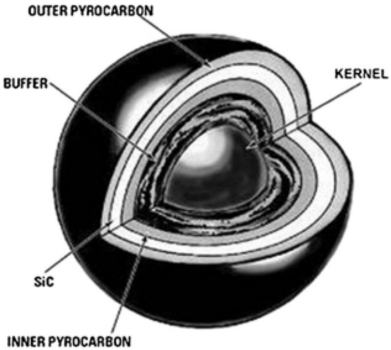

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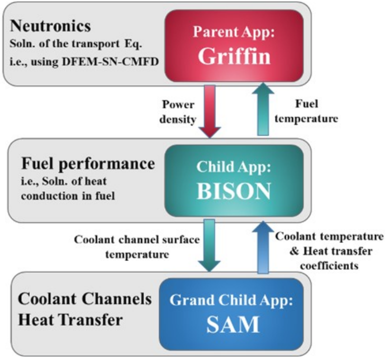

MultiApp hierarchy of preliminary GCMR models. Image from [6].

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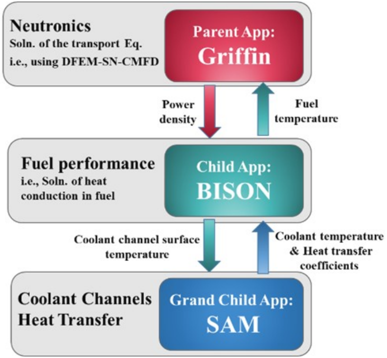

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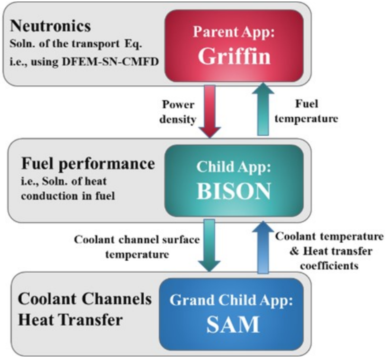

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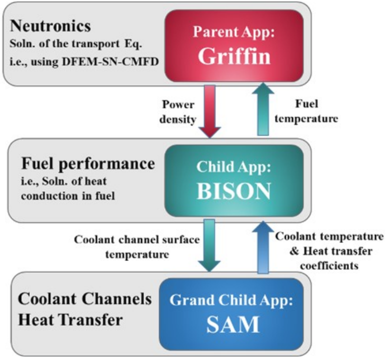

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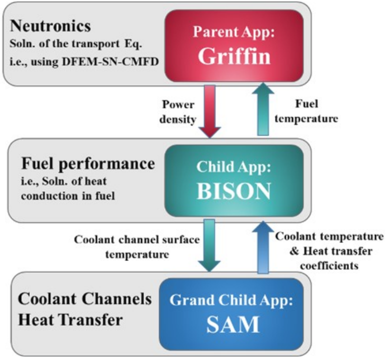

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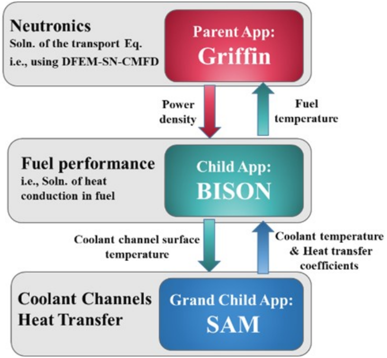
- For a full core model, it will be prohibitively expensive to model every TRISO explicitly



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- Comparing both homogenizations to the fully explicit case can be used as a basis for deciding how proceed with a full core model.

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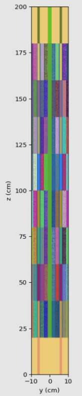
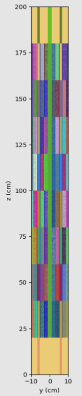


YZ slice of reactor

OpenMC Model



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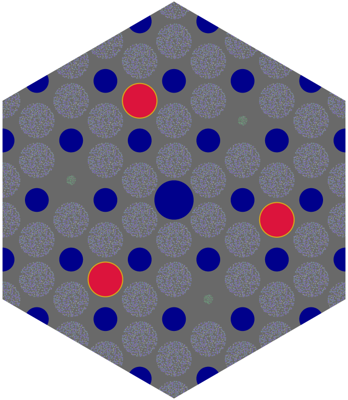

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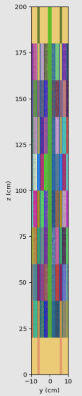

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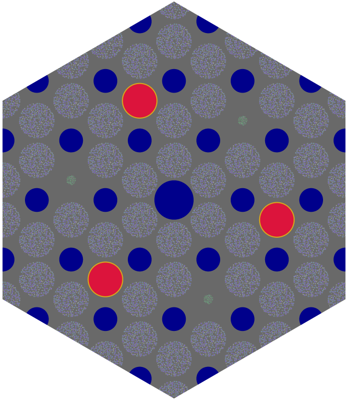

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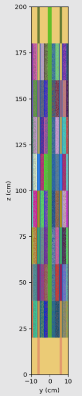

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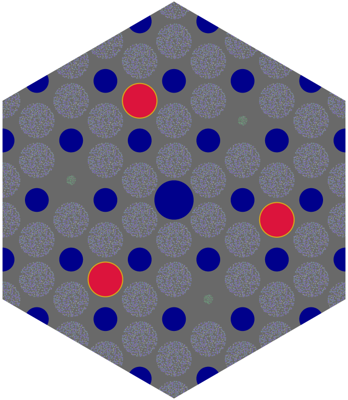

XY slice of reactor

- materials in XY slice
  - gray = graphite

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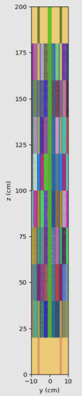

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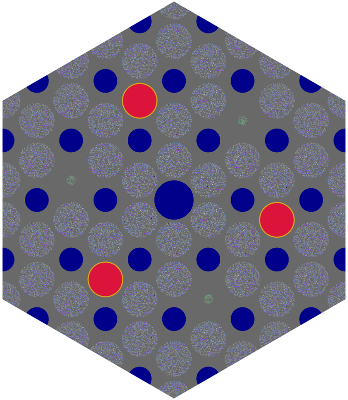

XY slice of reactor

- materials in XY slice
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  - blue = helium

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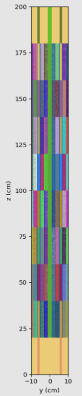

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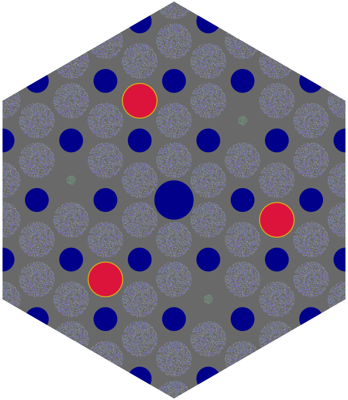

XY slice of reactor

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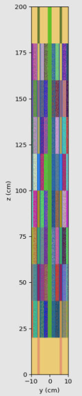

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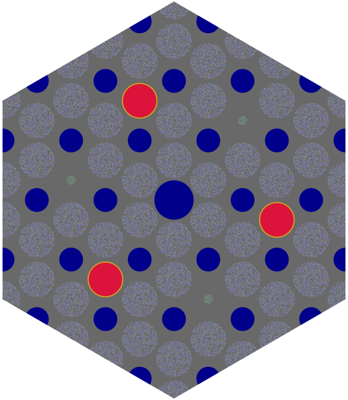

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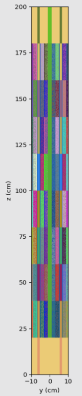

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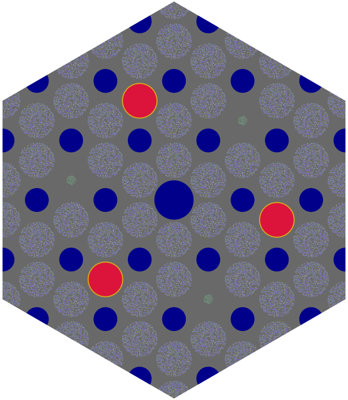

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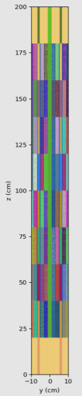

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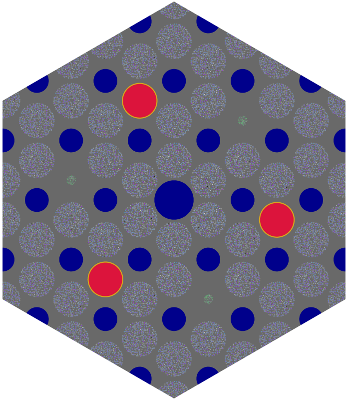

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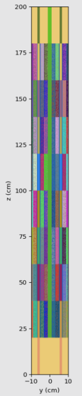

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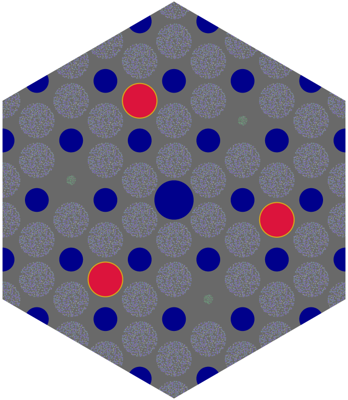

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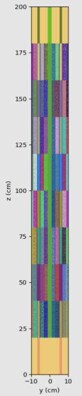

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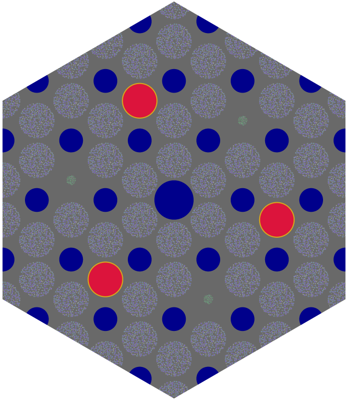

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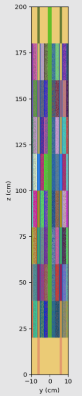

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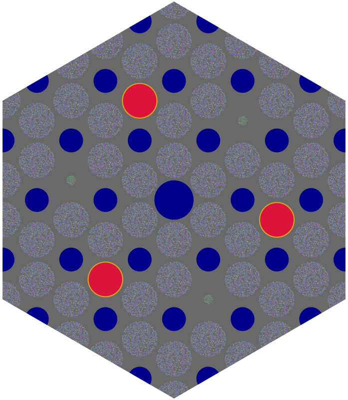

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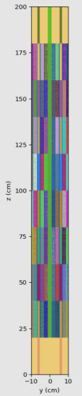

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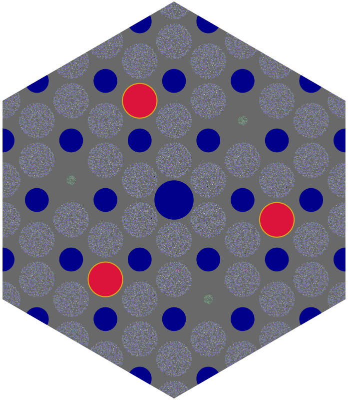

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- pin pitch = 2cm
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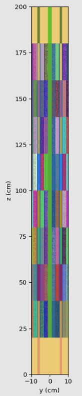
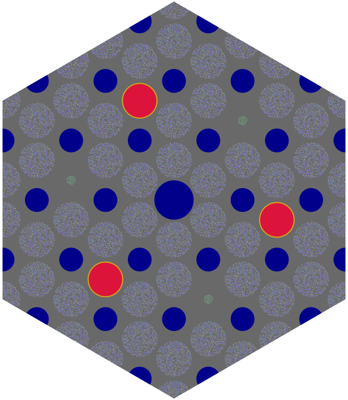
OpenMC Model



YZ slice of reactor



XY slice of reactor

- materials in XY slice
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  - blue = helium
  - red = YH2 moderator
  - gold = FeCrAL envelope
  - green = B4C poison spheres
  - purple dots = TRISO
- 8 axial layers in the core
- 2 axial layers per reflector
- pin pitch = 2cm
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- vacuum BC at z = 0, z = 200 cm

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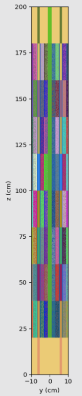

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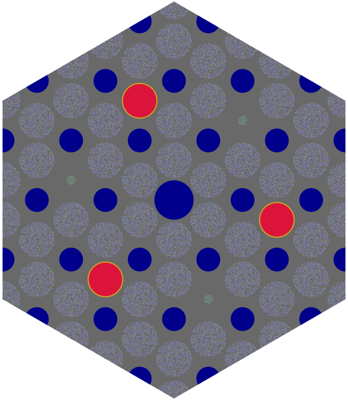

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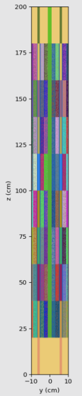

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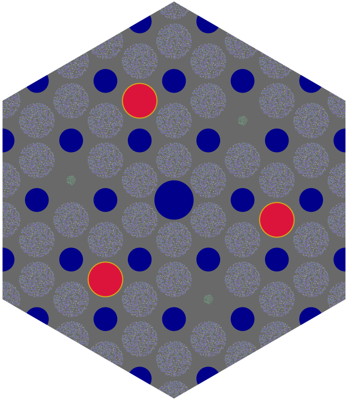

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- images via openmc-plotter

System Parameters

geometric parameters		
fuel compact radius 0.90 cm	poison compact radius 0.25 cm	moderator compact radius 0.843 cm
control compact radius 0.99 cm	coolant compact radius 0.60 cm	FeCrAl thickness 0.05 cm
Cr coating thickness	reflector heights	core height
0.007 cm	20 cm	160 cm

operation and design parameters		
fuel packing fraction	poison packing fraction	enrichment
0.4 -	0.25 -	19.95%
inlet temperature	outlet temperature	outlet pressure
873.15 K	1133.65 K	7 MPa

Depletion Theory

Depletion Theory

- Depletion simulations numerically solve the Bateman equations for the number densities $N_i(t)$:

$$\frac{dN_i}{dt} = \sum_j \left[\int_0^\infty \sigma_{j\to i}(E,t)\phi(E,t)dE + \lambda_{j\to i} \right] N_j(t) - \left[\int_0^\infty \sigma_i(E,t)\phi(E,t)dE + \sum_j \lambda_{i\to j} \right] N_i(t). \quad (1)$$

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- We can represent the system of equations in matrix form to solve for a nuclide vector $\mathbf{N}(t) \in \mathbb{R}^n$

$$\frac{d\mathbf{N}}{dt} = \mathbf{A}(\mathbf{N}, t)\mathbf{N} \qquad \text{WITH} \qquad \mathbf{N}(0) = \mathbf{N}_0, \quad (2)$$

where $\mathbf{A} \in \mathbb{R}^{n\times n}$ is commonly referred to as the burnup matrix.

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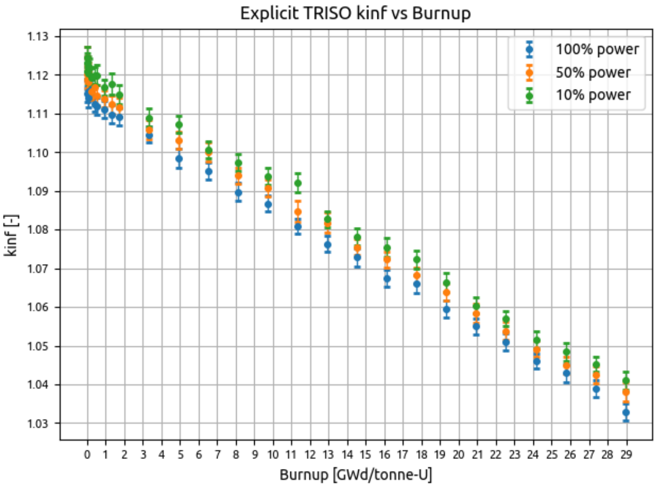
Fully-explicit k_{inf} versus burnup with 2σ error bars up to $\sim$29 GWd/tonne-U



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- Average $\Delta\rho$ compared with the explicit reference at every power with 2σ uncertainties

$\overline{\Delta\rho}$	explicit - homogenized	explicit - kernel only
100% power	1533 $\pm$ 55 pcm	-158 $\pm$ 55 pcm
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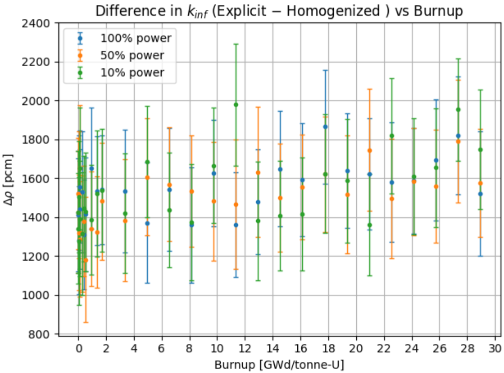
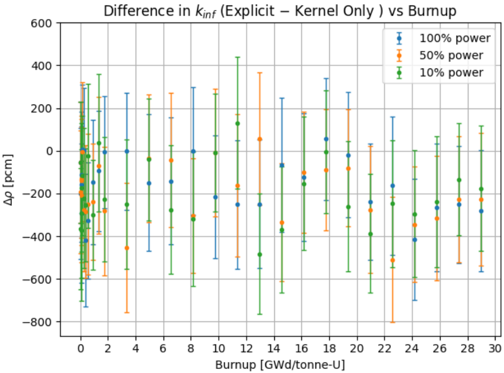
- Kernel only $\Delta\rho$ on average performs about 1 order of magnitude better than full homogenization.

$\Delta\rho$ with 2σ error as a function of burnup up to $\sim$29 GWd/tonne-U





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- A next iteration on fuel homogenization would be to leave the graphite background alone and only homogenize within a TRISO to create a **two layer** homogenization that packs TRISO fuel particles with a UCO fuel kernel at the center and all other layers homogenized together.

Acknowledgements

- The first author was supported in part by the US Nuclear Regulatory Commission's Graduate Fellowship Program administered by the University of Wisconsin-Madison.
- The OpenMC team!
- The Center for High Throughput Computing at the University of Wisconsin - Madison
- Co-authors: Patrick Shriwise, Benjamin Lindley, and Paul P.H. Wilson.

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Open Source Projects

- OpenMC website: https://openmc.org/
- OpenMC repository: https://github.com/openmc-dev/openmc
- VTB: https://mooseframework.inl.gov/virtual_test_bed/
- VTB repository: https://github.com/idaholab/virtual_test_bed
- Add me on LinkedIn (lewisgross1296) and GitHub (lewisgross1296)!

Equilibrium Xenon-135 Number Densities

Table: All units are atom per cubic centimeter. Since the first five time steps are used to converge xenon, the numbers below are the average of the fifth to the last value for xenon number density.

representation	explicit	kernel only	homogenized
100% power	2.43127×10^{16}	2.41845×10^{16}	1.19125×10^{15}
50% power	1.31047×10^{16}	1.30864×10^{16}	6.45668×10^{14}
10% power	2.82398×10^{15}	2.81919×10^{15}	1.38810×10^{14}

- These equilibrium values explain the observed trend at fresh fuel – and for much of the simulation – that lower power with the same total burnup has more excess Reactivity.
- The higher the power, the more Xenon-135 is produced during the initial jump to steady state, contributing to a larger negative reactivity insertion.

Plutonium 241 at Each Power for the Fully Explicit Case