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BY

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THESIS

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Abstract

Acknowledgments

Acks.

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Chapter 1

Introduction

outline:

- Motivation

    - climate change

    - gen IV > gen III

    - microreactors alleviate many of the construction/installation issues associated with larger reactors

    - pebbles using TRISO particles are an ideal fuel form, if there are no plans to reprocess (the US currently does not)

- Objectives

    - establish a basic model for a HTGR pebble-bed microreactor

    - characterize the effects of random pebble placement on the results

    - describe a scale-down from a basic 200 MWth design to a 20 MWth microreactor

1.1 Motivation

The effects of global warming are becoming increasingly severe. (***include NASA facts?***). In the interest of reducing the global carbon footprint, a desire for carbon-free, sustainable energy is growing. With this interest comes a bevy of new research in the next generation of nuclear reactors.

One such class of reactors are the high temperature gas-cooled reactor, or HTGR. While HTGRs can have a variety of fuel forms, of particular interest are pebble bed reactors. A pebble-type fuel generally consists of a sphere of graphite, approximately the size of a billiard ball, embedded with TRISO particles. The fuel kernels in these TRISO particles are surrounded in multiple layers of carbon and silicon carbide, and, along with the graphite that creates the sphere proper, form a durable, compact fuel form. In addition, the pebbles are able to be refueled online, reducing the need for planned shutdowns.

The next generation of nuclear reactors also include designs significantly smaller than the conventional Light Water Reactor(LWR) seen in the USA today. So-called Small Modular Reactors, or SMRs, these reactors are small enough to be shipped, reactor pressure vessel and all, in a standard shipping truck or train. The pressure vessels can also be produced in a factory of standard size (**** I dislike this wording. but can't think of another way to put it****). SMRs can be deployed in a variety of new settings, such as isolated towns or work sites, or many can be stationed together in one plant to fill the role of a single larger reactor.

This work used a pebble-bed HTG-SMR as a starting point, and modeled a fairly generic 200MWth reactor based on existing designs - named Sangamon200. Then it scaled down to a target size - a 20MWth pebble bed HTGR. "Microreactors" such as these are generally 70 MWth or less, and can be deployed in areas where only a small amount of power is needed, used for research and testing, or be used to supply heat for other industrial processes, such as producing hydrogen.

The 20MWth model, which will hereafter be referred to as Sangamon20, is of a highly simplified design, which can be used in future testing and analysis.

*******why modular: reutler and lohnert*********

1.2   Objectives

Chapter 2

Literature Review

***(General notes/questions

- I wasn't sure how much to include about the Cisneros thesis and BEAU. It's true that it informed how I handled the pebbles - knowing they move in slug flow, for example - but I didn't use any of the lattice models that thesis did, and while I would like to explore the fuel burnup a bit more in depth next, I'm not sure that fits this thesis right now

- I think we talked about the fact that i can afford to go into more detail on PBMR because of the long time spent on it, but I'll wait for the first review to add anything

- I was going to include a brief section on some micro reactor designs from recent years, but I don't really have a set method for selecting which designs and articles I should mention, and I don't want it to seem random or hodge-podge. (if I do make a few paragraphs about this, would it be appropriate to reference Roberto's thesis? technically I think it definitely fits, I mean more in the context of being polite/proper)

)***

2.1   Computational Model

2.1.1   Serpent

Serpent 2 is "a multi-purpose three-dimensional continuous-energy Monte Carlo particle transport code" [1] from the VTT Technical Research Center of Finland. The first iteration, Serpent 1, began development in 2004. The development of Serpent 2 is presently ongoing. Serpent 2 has three main applications: traditional reactor physics, coupled multi-physics, and neutron and photon transport. In order to create and model complex geometries, Serpent uses constructive solid geometry (CSG), which defines homogeneous material cells using user-defined universes, cells, lattices, and specially-defined nested objects to define particle and pebble geometries.

Using these special objects and the particle dispersal routine in Serpent, TRISO particles and pebble bed reactors can be modeled. The particle dispersal routine works by first establishing a user defined container for the particles,

such as a cylinder. The user then defines the size of the particles - all of which are assumed to be perfect spheres - and either the number of particles, or the packing fraction of particles in the container. Serpent then randomly generates coordinates for the center of the dispersed particles. For each location, Serpent checks that the entire particle is inside the container, and that it does not overlap with any other particles. It then prints a text file with the coordinates of each particle center, along with the radii and the universe they're located in. Serpent has been tested with up to 60 million individual particles.

Physics are based on a combination of classical kinematics, ENDF reaction laws, and random sampling. For particle transport, Serpent uses surface tracking and Woodcock-delta tracking. For material data, Serpent uses ACE format libraries for microscopic cross sections, and pre-generates macroscopic cross sections before beginning transport. To further speed-up calculations, Serpent uses a unionized energy grid.

Serpent has been validated against MCNP, and validation is ongoing for radiation shielding and criticality safety analysis. While the differences between Serpent and other Monte Carlo codes are generally small, Serpent experiences the same issues validating its results as other Monte Carlo programs, related to small differences in data libraries.

2.1.2   Experience from BEAU

BEAU, or Burnup Equilibrium Analysis Utility, was developed by Dr.Cisneros to model depletion and multiple burnup states for a continuously refueled molten-salt PBMR. While a full examination of all possible pebble burnups and compositions is not the target of this work, the experience in modeling a pebble bed reactor was invaluable. In particular, the development of the Mark 1 PB-FHR (pebble-bed fluoride salt cooled high temperature reactor), the methods to model pebbles, and the flow of pebbles through the core, informed the Sangamon20 design.

2.2   The High Temperature Gas Cooled Reactor: Beginnings and Concepts

High temperature gas cooled reactors, or HTGRs, are one of the more commonly seen Generation IV reactor designs. It most often uses helium as a coolant, and graphite as a moderator in thermal designs. Fuel is in the form of tristructural-isotropic, or TRISO particles. TRISO particles use a small kernel of fuel, less than half a millimeter across, surrounded by layers of carbon and silicon carbide to protect the fuel kernel and prevent the leakage of radioisotopes ***(would it also be accurate to say the layers provide moderating material? I know that graphite is a great moderator, but I would think the main purpose is safety and to prevent leaching, and moderation is really in the graphite the particles are embedded in)***. These TRISO particles are then embedded in graphite to form a usable fuel element. In prismatic HTGRs, the graphite is in the shape of hexagonal columns. In pebble-bed reactors,

the graphite is in the shape of spheres, around the size of a billiard ball. Many of these pebbles are loaded into the core, and slowly move through the bottom in a manner not dissimilar to grain in silos.

HTGRs, however, are not a new concept. Preliminary concepts for a gas-cooled reactor were created as early as 1942. Farrington Daniels - more commonly known for work in chemistry and solar power technology - is attributed with establishing the first theoretical designs. A professor from the University of Wisconsin, Professor Daniel's work with Oak Ridge National Laboratory (ORNL) nailed-down the most basic characteristics of the HTGR. The choice of helium for coolant, graphite for moderator, the direct gas turbine cycle, and the use of uranium or thorium carbides for fuel all came from his work [2].

Professor Daniels recognized early on the importance of a small power-producing unit with low initial costs and ease of transport in developing nations - a sentiment that has resurfaced in recent years in the designs for small modular reactors. Daniels' first design was for a simple high-temperature pebble pile. A little over a decade later, improvements to turbine technology prompted him to propose a direct-cycle helium cooled reactor. However, before any construction could start, the Atomic Energy Commission opted to support Light Water Reactor (LWR) technology instead [2].
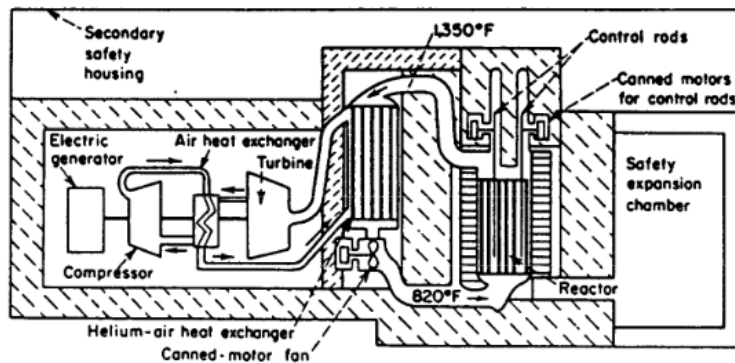

Figure 2.1: Side-View of the 1955 Daniels' Concept, [2]

Figures 2.1 and 2.2 show the design of the 1955 design proposed by Professor Daniels. Like many modern modular reactor plant designs, Professor Daniels suggested that the reactor be mostly underground. A key difference between the Farrington Daniels designs and modern HTGRs is the fuel form. While modern designs use TRISO particles embedded in graphite, the Daniels' design uses solid graphite blocks, with channels for both coolant and fuel. Within the fuel channels, fuel was loaded in either a pellet or cartridge form, both a mixture of 10% uranium dicarbide and graphite powder. In addition to these fuel channels, the design included an outer ring of graphite reflector in which thorium was used to breed U-233. Control rods were made of boron-containing molybdenum. Additional safety rods made of the same were held above the core by steel wires that would melt in the case of an accident, dropping the safety rods into the core [2].
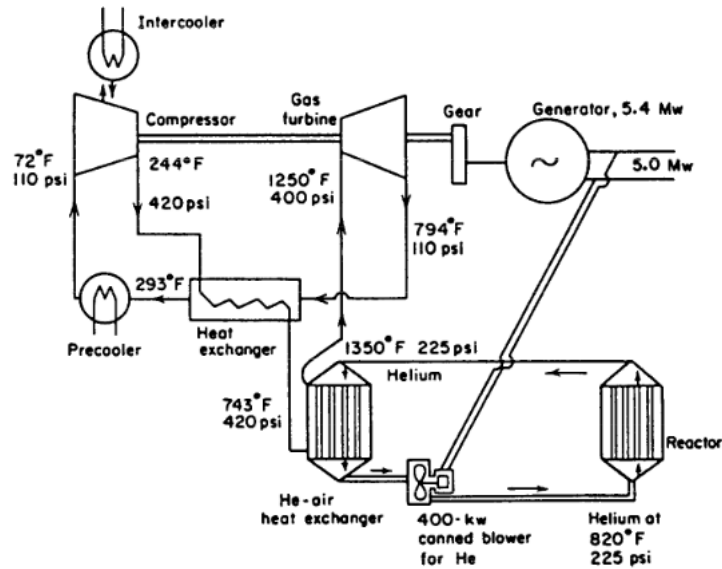
5

Figure 2.2: Diagram of Coolant Flow in the 1955 Daniel's Concept, [2]

2.3 Earliest Operational HTGRs

The earliest operational HTGRs were first started in the 1960s. The AVR, from Germany, Dragon, operating in the UK, and Peach Bottom 1, which operated in the US [3].

2.3.1 Dragon

The Dragon prismatic HTGR was a test reactor operated in Winfrith, UK, from 1964 to 1975, making it the oldest of the reactors discussed in this chapter. It operated at inlet and outlet temperatures of 350°C and 750°C and a power of 20MWt [3]. Dragon's main purpose was to test reactor materials, with an emphasis on fuels. It originally used uranium and thorium as fuel, but switched to a purely uranium-based fuel with a lower enrichment later in life. The fuel elements themselves were similar in shape to the Daniels' design - hexagonal prisms with fuel rod channels.

Contrary to the fuel philosophy seen today, Dragon originally allowed fission products to be released from fuel elements into the circulating helium coolant. The fission products would then be purged from the helium. However, Dragon later switched to a coated-particle fuel when it became clear that having such large fission product releases would be difficult to manage [2].

2.3.2 Peach Bottom 1

Peach Bottom 1 operated from 1966 to 1974, by the Philadelphia Electric Company. It was the first operational HTGR in the US, and the first to produce electric power. It was slightly larger than Dragon, at a nameplate capacity

of 115 MWt/40MWe and a slightly lower operating temperature range at 327°C to 700°C inlet to outlet [3]. Like Dragon, Peach Bottom 1 was a prismatic reactor, however, Peach Bottom used coated uranium and thorium carbide particles from the beginning. The original fuel used a single coating of pyrolytic carbon. However, after multiple fuel failures, Peach Bottom upgraded to bistructural isotropic, or BISO, fuels by adding an additional layer. Peach Bottom would later upgrade the fuel once again by adding a silicon carbide layer, forming TRISO particles [3]. One operational benefit of upgrading to TRISO particles from BISO particles was that the superior fission product retention meant that Peach Bottom 1 could remove the helium purging systems. In addition to the inner fuel region, Peach Bottom, like the Daniels' design, bred U-233 in an outer region using thorium.

Beyond changing the number and materials for fuel coatings, the experiences in Peach Bottom 1 helped to develop HTGR fuel elements. Operators saw that by using the graphite moderating material to dilute the fuel, the fuel could be diluted further compared to other diluents. This of course has the advantage of saving fuel material, but also improved heat transfer and reduced radiation damage. Additionally, operational experience showed that, in order to prevent the creation and buildup of U-236 and Np-237, which are poisons, the U-235 and U-233 should be kept separate [2].

In the end, Peach Bottom 1 closed when it was determined to be uneconomical.

2.3.3 AVR

The Arbeitsgemeinschaft Versuchsreaktor (AVR) was an experimental pebble-bed reactor operated in the Jülich Research Center from 1967 to 1988. It had a capacity of 46 MWt/15MWe, with inlet and outlet temperatures of 275°C and 950°C [3]. In fact, the AVR reached the highest operating temperatures of any commercial nuclear plant. Like the others in this early time period. the AVR used a combination of uranium and thorium fuels, though the AVR began with BISO particles. The core held around 100,000 graphite pebbles, almost a third of which had fuel in them.

Despite not being built for experimental purposes, the AVR still housed many experiments that improved our body of knowledge in HTGR technology. During the first few years of its life, the goal of the AVR was to demonstrate that it was a reliable technology. After this inital period, the AVR could shift to allowing various experiments.

A step was to show that the reactor could operate safely, could control the core power and temperatures and safely shut down and remain sub-critical for long periods of time. This proved to be quite the undertaking, as the AVR shifted from highly enriched to low enriched fuel over time, which caused a large variety in fuel pebble compositions, on top of the range of compositions inherent to a multi-pass pebble cycle.

The AVR also provided data to validate models of pebble-bed reactors, and conducted an experiment to better characterize the radial distribution of temperatures in the core. A number of marked pebbles were loaded into the core, each housing a series of wires that would melt at a certain temperature, the lowest being 655°C, the highest

1280°C. The pebble positions were tracked based on pebble flow data, and when the spheres were ejected, the were examined to determine what temperatures the pebbles had experienced. Despite the outlet temperature being determined to be 950°C, multiple pebbles experienced a temperature greater than or equal to the 1280°C maximum temperature in the melt wires. It was noted that these pebbles went through a zone with a spike in local power density [4].

The AVR also demonstrated the inherent safety of HTGR reactors in accident scenarios by purposefully causing failure of active cooling system "accidents". In the first, the the coolant blowers were shutoff, and no shutdown rods were inserted while operating at full power. The operators additionally shut the main circuit valves to prevent natural circulation to regions outside the active core. Overall, the changes to core temperatures were unremarkable. The hottest regions cooled, while the coldest regions warmed up. Additionally, due to negative temperature feedback coefficients, the reactor power immediately declined in response to the "accident". The temperature slowly rose to 2 MW again over 24 hours, only to level out around 300 kW. A further test provided data on loss of coolant and depressurization accidents. As before, the core temperature changes were not particularly drastic. The upper core region was seen cooling, while the lower, originally cooler core region slowly rose in temperature. This experiment's data was used to validate HTGR computer models, which allowed the results to be aid in the analysis of other HTGRs [4].

Beyond accident safety, the AVR allowed for testing and demonstration of the safety qualities of TRISO and BISO fuel elements, especially relating to high temperature tolerance and fission product retention. Inital tests were conducted with BISO based pebbles, then later transitioned to TRISO, then low-enriched TRISO pebbles. The TRISO-LEU pebbles were shown to have good fission product retention compared to their BISO-based predecessors, based on the results of sampling the activity of the circulating helium to to the presence of released fission products. Beyond radioisotopes being directly released into the coolant gas, the AVR also showed that in order to accurately characterize the source term of am HTGR pebble bed reactor, one must take the dust from the pebbles into account. Dust from the pebbles bumping and scraping against each other was found deposited on reactor surfaces in the primary loop. It was found that 60 kg of dust had accumulated by the end of the reactor's life, which averages to 3 kg of dust each year. Measurements of specific activity in the dust showed that the activities of Cs-137, Cs-134, I-131, Sr-90, and Co-60 were on the order of $10^6 \frac{Bq}{g}$. Even though there is relatively little dust, the activity of this dust is fairly high, especially compared to the activity of the coolant gas [4].

(I'm going to include here the two tables comparing the activities of the coolant gas and dust activities. However, the one for gas is (reasonably) by volume, while the dust is by mass. Should I use the density of helium at operating temperature to convert the gas activity to be in Bq/g, and make a new table (citing my source), or leave as-is?)

Table 2
Specific activities of the primary coolant gas [Bq/m^3 (ISA)]

ΣFission noble gas	4.6×10^8
Tritium	3.7×10^7
C 14	1.9×10^7
Cs-137	3.0×10^2
I-131	5.2×10^2
Ag-110m	4.9×10^1
Sr-90	2.0×10^2
Co-60	1.0×10^1

Figure 2.3: Helium Coolant Specific Activities [4]

Table 3
Specific activities on dust [10^6 Bq/g]. The variation range results from measurements at different sampling locations and different times

Cs-137	2 – 96
Cs-134	0.7 – 27
I-131	0 – 3
Ag-110m	0.1 – 43
Sr-89	0.6 – 42
Sr-90	19 – 363
Co-60	0.2 – 8

Figure 2.4: Pebble Dust Specific Activities [4]

2.4 Modern HTGRs

2.4.1 PBMR

The PBMR is a South African pebble bed HTGR design. While it did not ultimately make it to construction, its design has offered invaluable insight to later HTGR pebble bed designs. The PBMR is largely based on the German High Temperature Reactor (HTR) designs, and has a nameplate thermal power of 400 MW, with inlet-outlet temperatures of 500 °C to 900 °C. It is a modular design, with each unit containing a graphite moderated, helium-cooled core housed in a steel pressure vessel. In accident scenarios, the PBMR would rely on passive safety features using conduction and convection to provide cooling.
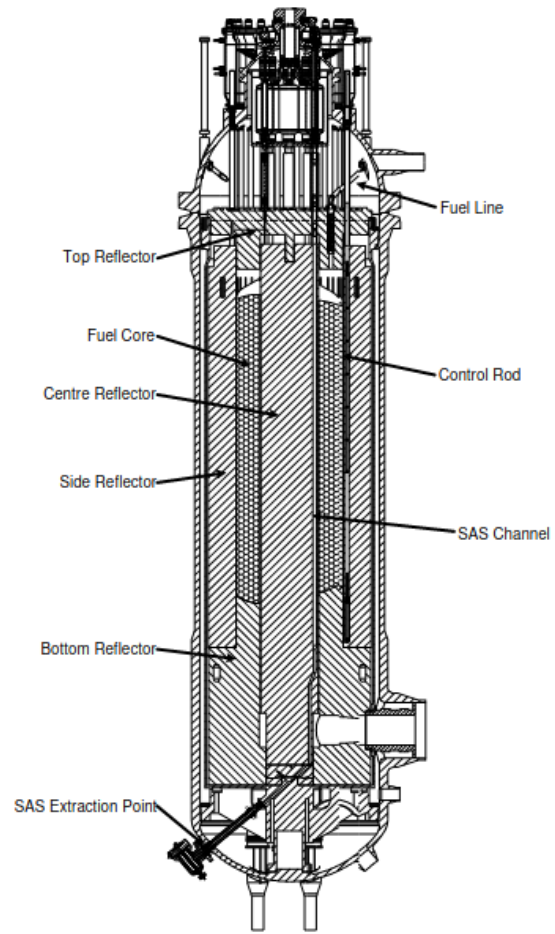
Figure 2.5: PBMR Schematic: Vertical Cross-section [5]

Each core unit would hold around half a million pebbles, which used LEU based TRISO particles as the fuel form. These TRISO particles are pressed into a 2.5cm radius graphite sphere, which then has an additional 0.5 cm thick layer of graphite pressed around it, to form a 3.0 cm radius pebble - around the size of a billiard ball. The pebbles would undergo a six-pass multi-pass cycle to reach a target end burnup of 92,000 $\frac{MWd}{tU}$ [5].

2.4.2   Next Generation Nuclear Plant (NGNP

Like the PBMR, the NGNP did not make it to construction. However, the work in analyzing reactor designs and materials is still applicable to other work. The NGNP project downselected its design choices to two models - a prismatic HTGR and a pebble-bed HTGR. While the NGNP project eventually opted for the Areva prismatic HTGR design [6] due to reasons related to pebble costs, it was noted that, technologically speaking, there was no inherent advantage or disadvantage bewteen the two technologies [7].

Even though the reactor didn't make it to construction or operation, the NGNP project, and the resulting white papers, have provided an invaluable licensing example for generation IV reactors with the NRC. As much of the current NRC guidelines are based upon LWR technology, work towards validating HTGR materials still has to be developed [8].

2.4.3   X-energy

Based on experience working on the PBMR project, the X-energy Xe-100 is a 200 MWt HTGR pebble-bed SMR. It is similar in design to all of its predecessors, featuring LEU TRISO particle fuel in 3.0 cm radius pebbles. While the Xe-100, or similar demonstration plant, has not been built as of this publication, the project ***(company? work? design?)*** is still ongoing. It is this reactor, and by extension, the PBMR, that the micro-reactor described in this thesis is most heavily influenced by.

The Xe-100 uses approximately 220,000 pebbles in a six-pass cycle, and fuel pebbles identical to the ones intended for the PBMR [9]. However, while the number of passes is the same, the target end burnup for the pebbles is higher, at 160,000 $\frac{MWd}{tU}$ [10]. Another key difference from the PBMR beyond size is the lack of central reflector.

While the Xe-100 has not been built, there have been studies conducted by ORNL providing data on the production and material properties of the PBMR-type fuel pebble.

Chapter 3

Methodology

Parameter	Sangamon200	Sangamon20
Thermal Power [MW]	200	20
Average Core Temperature [K]	800K	800K
Enrichment	15.5%	19.75%
Average Core Pressure [MPa]	5.9	5.9
Core Diameter [cm]	248	180
Core Height [cm]	1150	180
Reflector Thickness [cm]	90	75
Number of Pebbles	220,000	23,000

Table 3.1: Reactor Parameters: Sangamon200 and Sangamon20

All neutronics simulations are performed using Serpent2.0 [11] . Pebbles are individually modeled, with locations generated using Serpent2.0's particle dispersal routine (***should I go into more detail on the dispersal routine?***). Each pebble in the full-core model has the TRISO-filled "fueled-core" homogenized by volume.
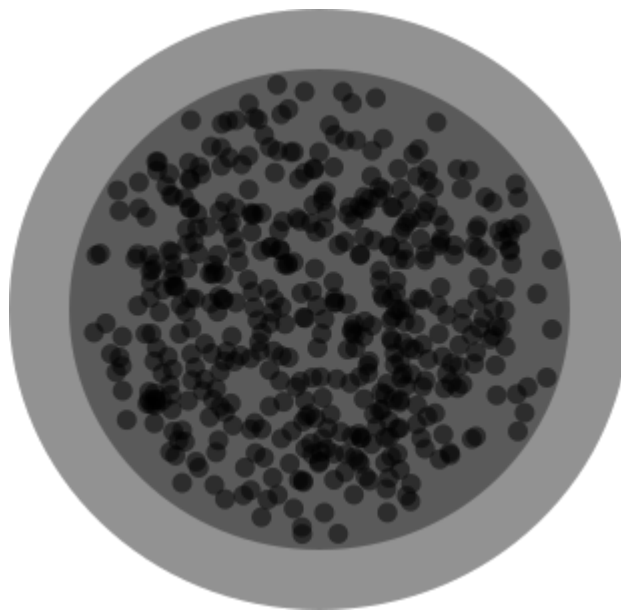
Figure 3.1: Pebble Zones
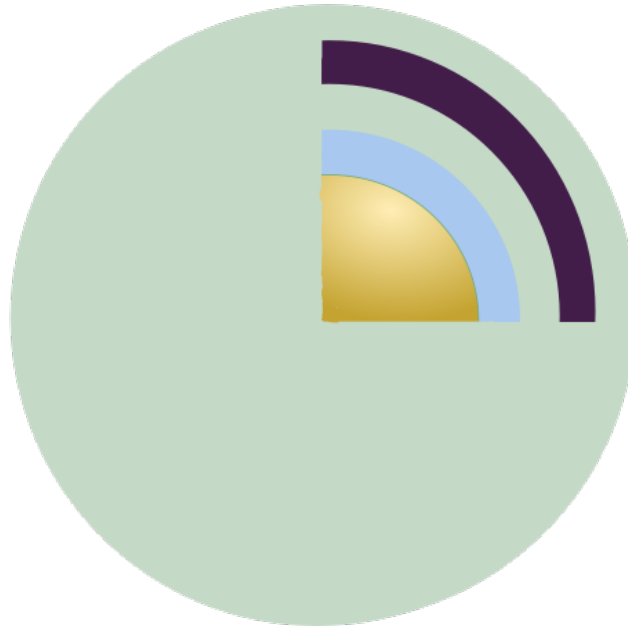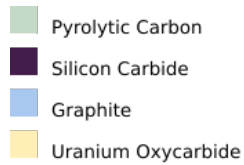
Figure 3.2: TRISO Particle Layers (not to scale)

Parameter	Value
Fueled-Center Radius [cm]	2.5
Graphite Outer Shell Thickness [cm]	0.5cm
Total Radius [cm]	3.0
TRISO Particles per Pebble	18,000

Table 3.2: Pebble Parameters

Parameter	Value
Uranium Oxycarbide Kernel Radius [cm]	0.02125
Graphite Layer Thickness [cm]	0.03075
Inner Pyrolytic Carbon Layer Thickness [cm]	0.03475
Silicon Carbide Layer Thickness [cm]	0.03825
Outer Pyrolytic Carbon Layer Thickness [cm]	0.04225

Table 3.3: Particle Parameters

Fuel isotopic composition aside, the pebbles are identical in both reactor designs. Both reactors feature a 6-month multi-pass cycle, with each pass through the core taking 6 months. That is to say, a pebble will go through six 6-month passes before leaving the core.

3.1 Sangamon200

Sangamon200 is a 200 MWth helium cooled reactor. It is an Xe-100 inspired design, and further informed by previous work on reactors such as the PBMR. Parameters are generally pulled from literature, or made by averaging given values in literature. For unspecified reactor dimensions, a rough estimate is approximated by assuming provided figures of a design are to scale, and converting measurements in pixels to cm.

Sangamon200 is still, however, a simplification of previously established designs. The "cone" formed at the top and bottom of the reactor core is averaged to a flat surface, to create a cylindrical core shape. The graphite reflector surrounds it, with no barriers between the reflector and helium/pebble-filled active core region. In effect, the reflector is the container for the pebbles. These are the only simulated parts of the reactor. It is assumed no control rods are being used. In addition, the graphite reflector is defined as a solid cylindrical shell.

While Sangamon200 is not the focus of this assessment, some neutronics features were determined to aid in Sangamon20's design. A surface current detector was placed in the reflector, just inside the outer bound of the reflector, as shown in 3.3.

$h_{reactor} = h_{inner} + 2(t_{reflector})$

r_{inner}

h_{inner}

$t_{reflector}$

$r_{det} = r_{reactor} - 1 \; [cm]$

$r_{reactor} = r_{inner} + t_{reflector}$

•(0.0,0.0,0.0)

$t_{reflector}$

$h_{det} = h_{reactor} - 2 [cm]$
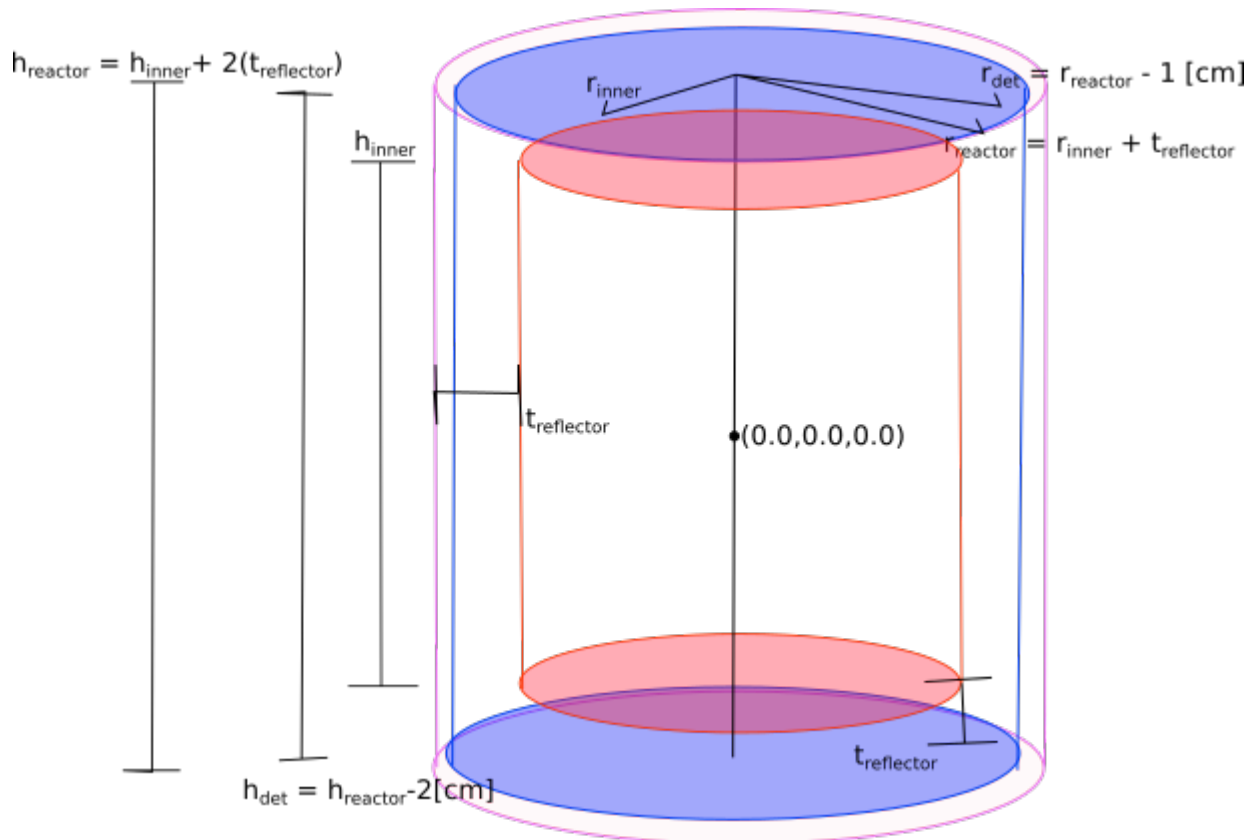
Figure 3.3: Detector Placement Inside Reflector

This detector measures the outward neutron current (*** serpent outputs units of [number/s], is current still the

best word? ***) in $[\frac{\#}{s}]$. To arrive at the unit of $[\frac{\#}{cm^2 s}]$ most are familiar with, the reported outward current is divided by the detector's surface area thus:

$$J^+[\frac{\#}{cm^2 s}] = \frac{J^+[\frac{\#}{s}]}{S_{det}[cm^2]} \tag{3.1}$$

After accounting for the surface area, the outward current at the detector is 7.351e+11.

3.2 Sangamon20

Sangamon20 is a 20 MWth helium-cooled pebble bed reactor, fueled with 19.75% enriched uranium oxycarbide. While the capacity of Sangamon20 is 10% that of Sangamon200, it isn't accurate to simply scale Sangamon200's dimensions down to 10% of their original values.

3.2.1 Inner Core Volume Determination

The first assumption made in the scale-down is that Sangamon200 and Sangamon20 have the same power density, or $\frac{kW}{g\,fuel}$ (*** I called this "power density" as that is how serpent refers to this value. But, given that it is per unit mass, is "specific power" a better term?***).

It is simple enough to calculate the mass of fuel in Sangamon200:

$$M_{f,200} = \frac{4}{3}\pi r_u^3 \rho_u n_T n_{p,200} \tag{3.2}$$

where

$$
\begin{aligned}
M_{f,200} &= \text{ mass of fuel in Sangamon200[g]}\\
r_u &= \text{ the radius of the UCO kernel inside a TRISO particle[cm]}\\
\rho_u &= \text{ the density of UCO in } [\tfrac{g}{cc}]\\
n_T &= \text{ number of TRISO particles in one pebble}\\
n_p &= \text{ number of pebbles in Sangamon200} \tag{3.3}
\end{aligned}
$$

Using the parameters in 3.1, the power density of Sangamon200 and Sangamon20 is 0.11 $[\frac{kW}{g}]$. With a power

capacity of 20 MWth, one can calculate the total mass of UCO in Sangamon20 as

$$M_{f,20} = \frac{20 * 10^3 [kW]}{0.11 [\frac{kW}{g}]} = 181818.18 [g] \tag{3.4}$$

The mass of fuel in a single pebble can be found using the density of UCO and the total volume of UCO kernels in a single pebble, as above. The number of pebbles in the entire reactor, then, is found by dividing the total mass of fuel by the mass of fuel in one pebble, as follows:

$$n_{p,20} = \frac{M_{f,20}}{\frac{4}{3} r_u^3 n_T \rho_u} \tag{3.5}$$

Rounding up - there can only be complete pebbles - we arrive at the number of pebbles in 3.1.

Knowing the number of pebbles is insufficient - the exact dimensions of the active core region are still undefined. To determine the volume of this space, the concept of the packing fraction - the ratio of the volume of objects (the pebbles) to the total volume of their container (the active core) - can be used. The packing of even uniform objects in a 3-dimensional space is a complicated problem, often analyzed in the context of material studies or grain silos [12]. For this reactor, it is assumed the pebble behavior can be described as random loose packing [12] - the pebbles have unsystematically fallen into the core and the core is not shaken. Such packing generally has a packing fraction in the range of 0.56 to 0.60 [12]. Using the definition of the packing fraction, and previously defined terms, the active core volume is

$$V_{c,20} = \frac{n_{p,20} \frac{4}{3} \pi r_p^3}{\phi} \tag{3.6}$$

Using the formula for the volume of a cylinder, one can plot possible sets of $r_{c,20}$ and $h_{c,20}$ that satisfy the volume requirement.

The most critical configurations for a cylinder are either a *square* shape, in which the height is equal to the diameter, or a *flat* shape in which diameter is significantly greater than height. As a flat shape is disadvantageous for a reactor, the former is chosen. The point indicated in 3.4 shows the radius and height selected for Sangamon20 - a radius of 90 cm, and a height of 180 cm.

3.2.2 Graphite Reflector Thickness Determination

The reflector must be sufficiently thick to keep the reactor critical, and protect the pressure vessel. To ensure this, the outward current must be less than or equal to the outward current in Sangamon200 at the outer reflector boundary. The detector layout in Sangamon20 is identical to 3.3.
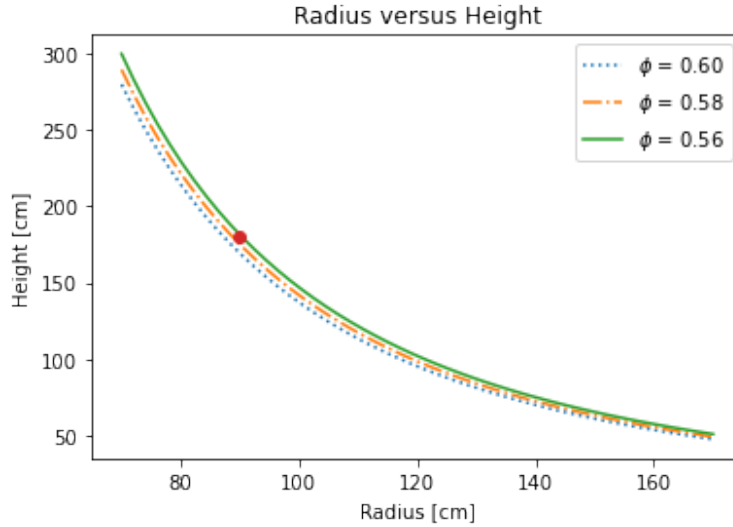
Figure 3.4: Curve of Possible Height and Radii by Packing Fraction

3.3 Fuel Composition

The number of passes the pebble has theoretically experienced determines its isotopic composition. Seven possible pebble compositions exist, one for each of the six 6-month passes, plus an additional composition for fresh pebbles. The seven pebble compositions are represented equally in number in the core, and they are randomly distributed throughout the core.

The exact isotopic composition is approximated by running a burnup calculation using Serpent2 for a single pebble in a cube. It uses a reflective boundary condition to simulate the presence of other pebbles or the reflector. The void in the square is filled with helium. While the full-core models homogenize the pebbles, the single-pebble burnup model individually models each TRISO particle. Just as with the location of the pebbles in the full core, the Serpent2 particle dispersal routine generated the TRISO particle locations.

Once the isotopic compositions are determined, the pebbles are homogenized by volume, to improve performance. The volume of a TRISO particle, and more specifically, a UCO kernel, is assumed constant.

3.4 Reactor Sensitivity to Pebble Locations and Symmetry

As the pebble locations and compositions are determined randomly, it is entirely possible to have bands in the reactor where multiple pebbles of same (or similar) burnup form lines or pockets. In the interest of better characterizing the neutronics of the reactor, a sensitivity analysis tested various pebble composition locations. The *shuffling* test maintained the pebble locations, but changed what composition the individual pebbles were. A second test completely changed the location of the pebbles in the core by randomly dispersing them again. The
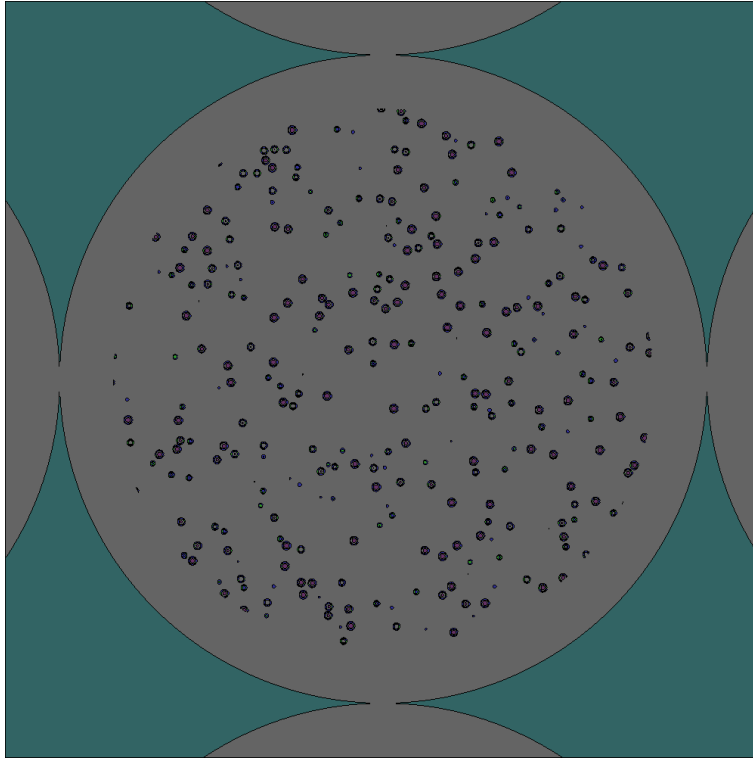
Figure 3.5: Geometry of the Single-Pebble Burnup Calculation: Sangamon20

third analyzed the effects of utilizing a symmetry simplification, in order to improve computational speed. The core was approximated using a $\frac{1}{6}$ slice. The slice used to simplify changed in each test, shown in 3.6. In each test, all other parameters remain the same.
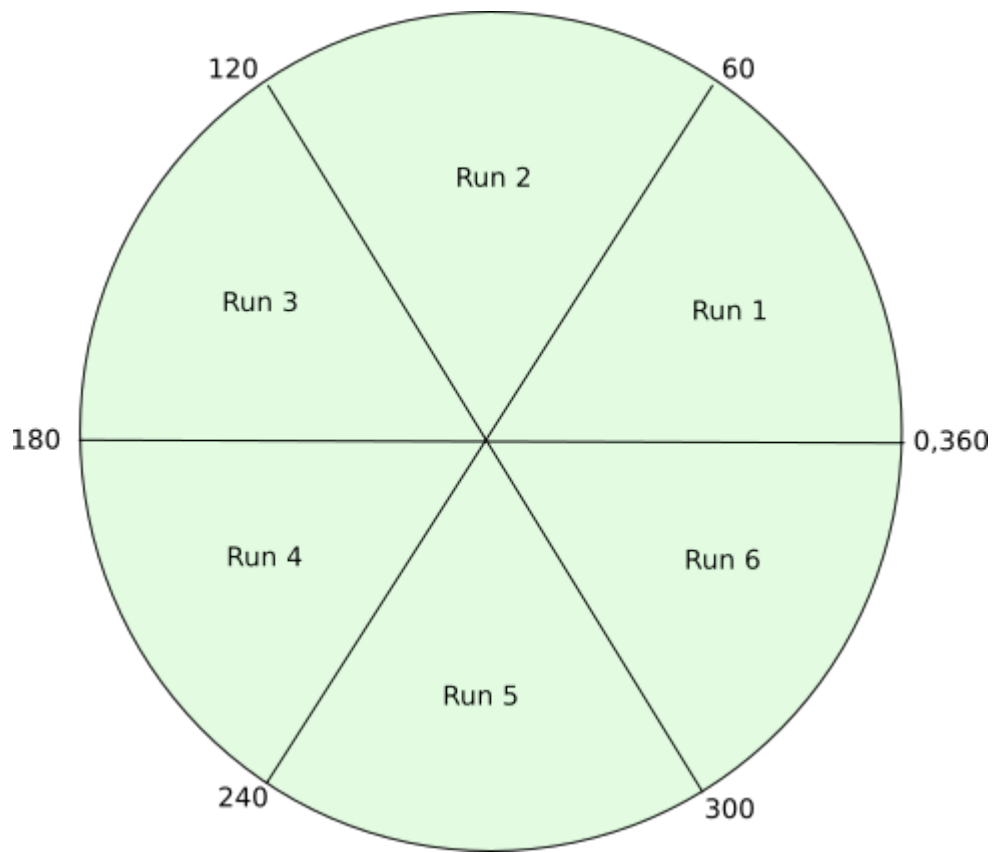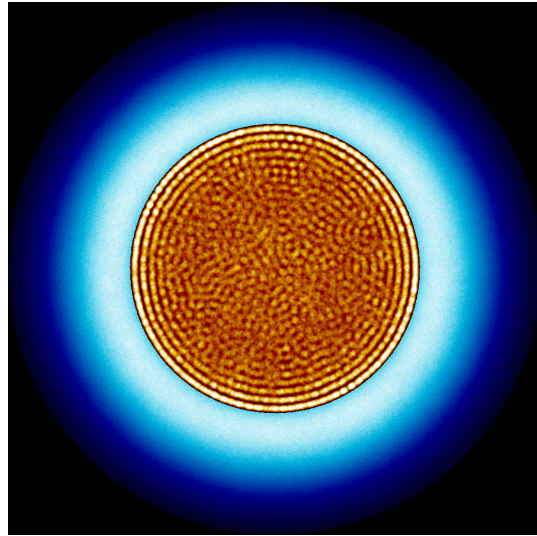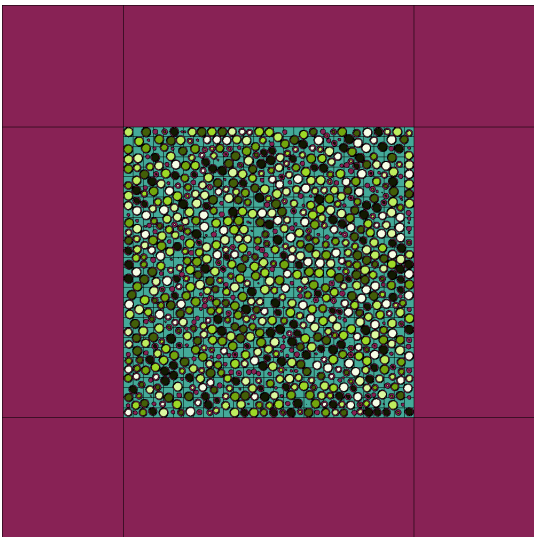
Figure 3.6: Symmetry Test Run Layouts

Chapter 4

Results

results

(a) Fresh

(b) One Pass

(c) Two Passes

(d) Three Passes

(e) Four Passes

(f) Five Passes

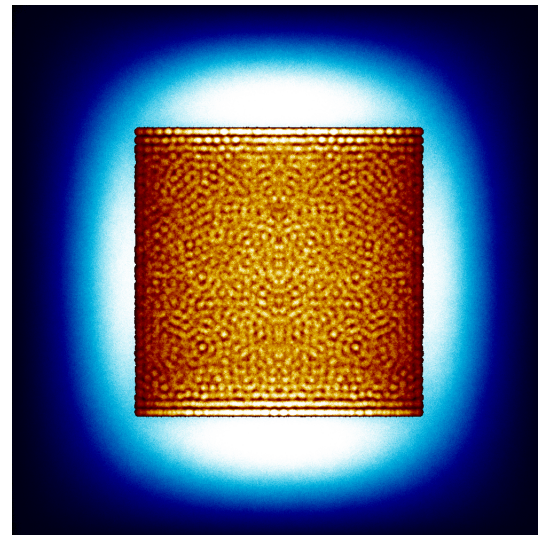(g) Six Passes
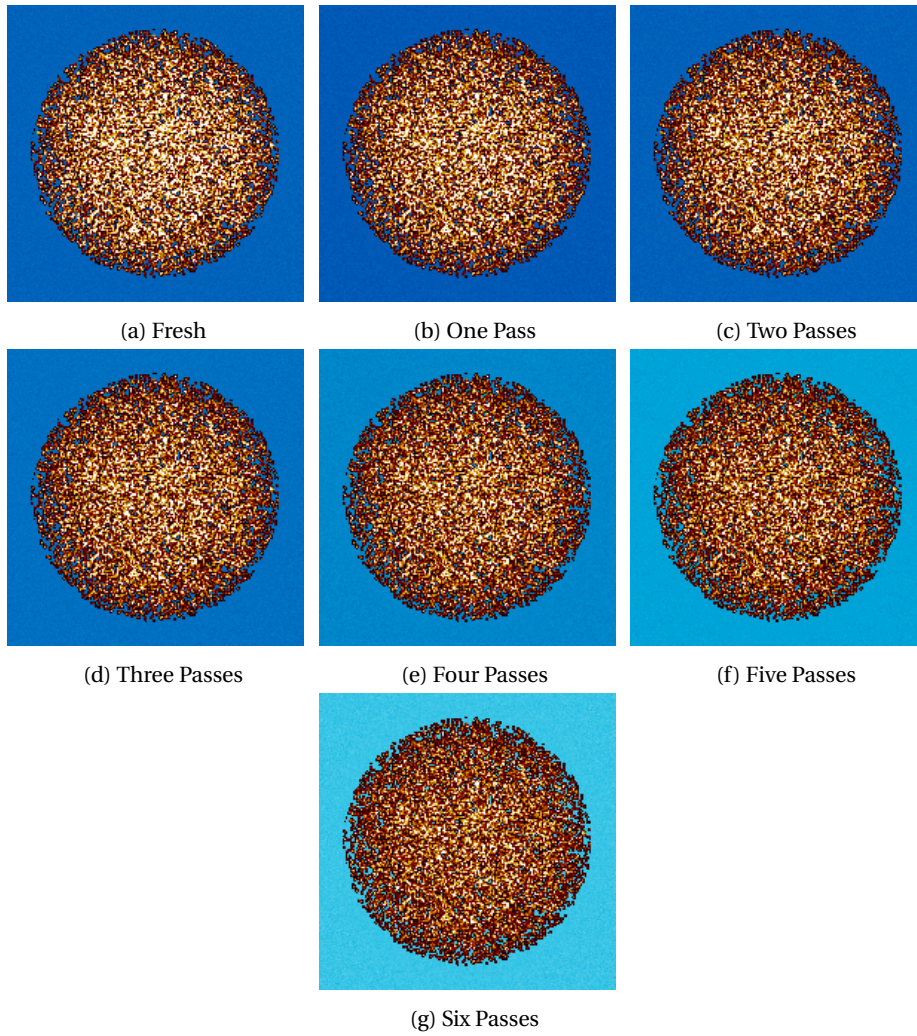
Figure 4.1: Mesh Figures For Single Pebble Burnup
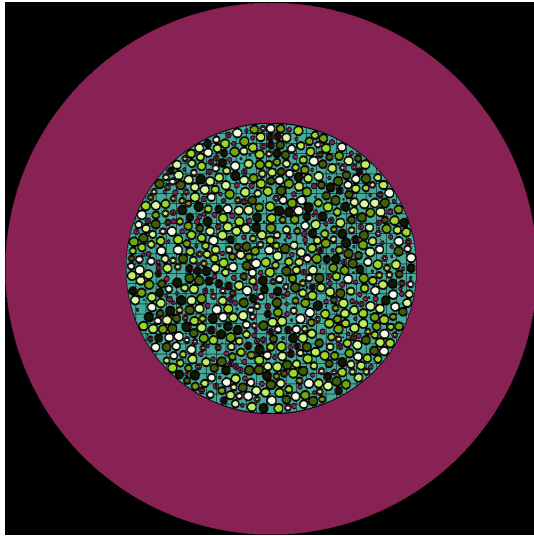
(a) Radial Cross Section at y=0

(b) Radial Mesh

(c) Axial Cross Section at z=0
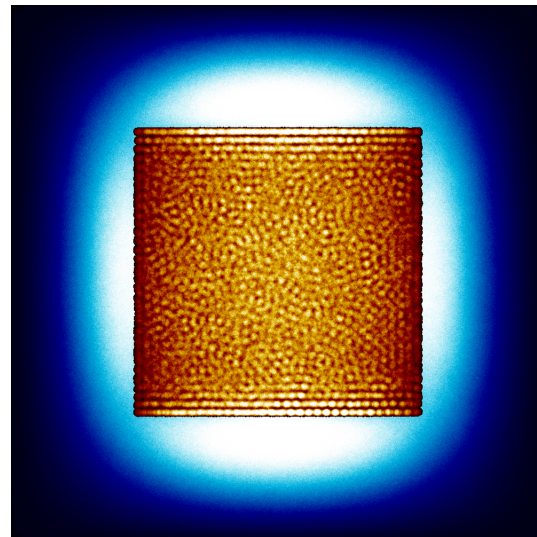
(d) Axial Mesh

Figure 4.2: Full Core
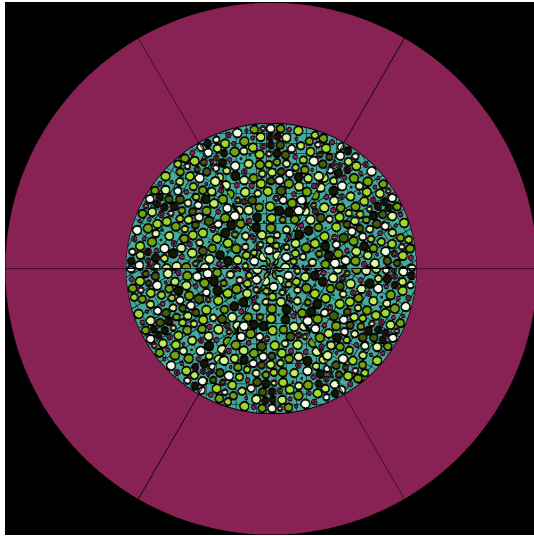
(a) Radial Cross Section at y=0
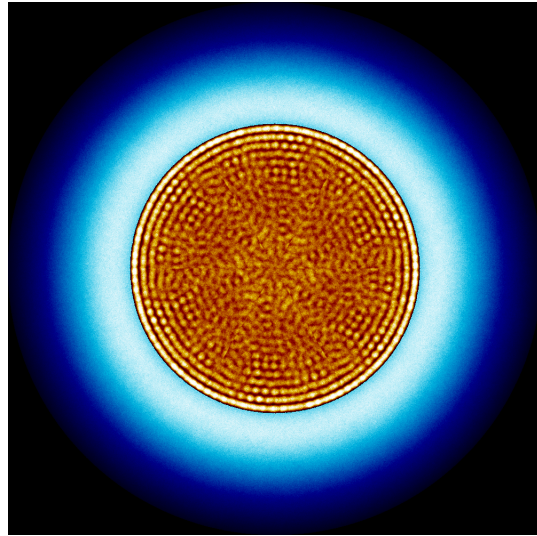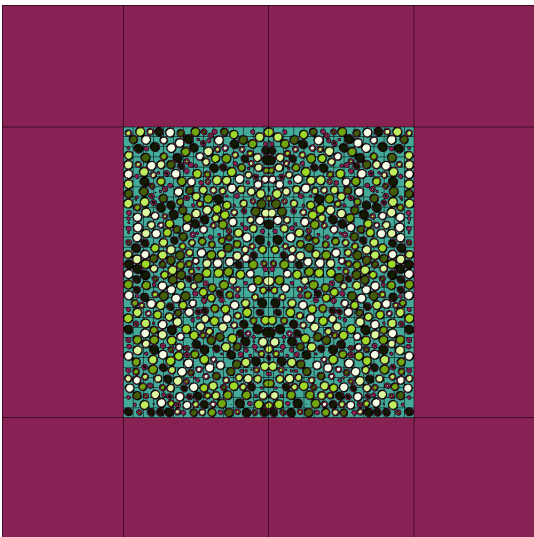
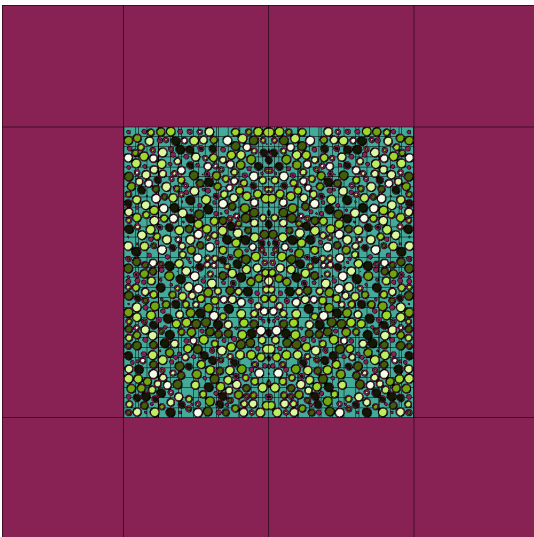(b) Radial Mesh

(c) Axial Cross Section at z=0
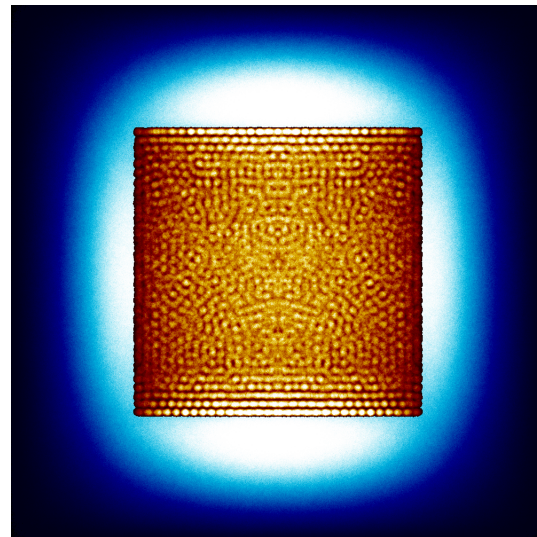
(d) Axial Mesh
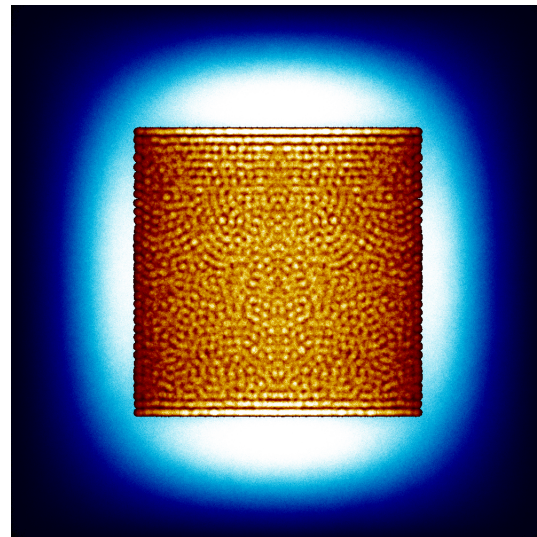
Figure 4.3: Sensitivity Analysis: 60° - 120°
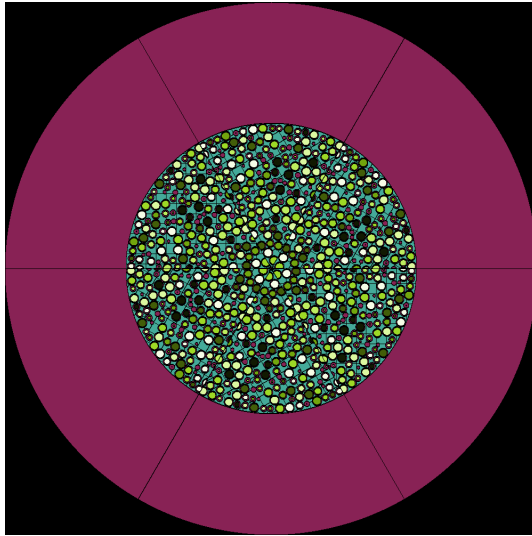
(a) Radial Cross Section at y=0
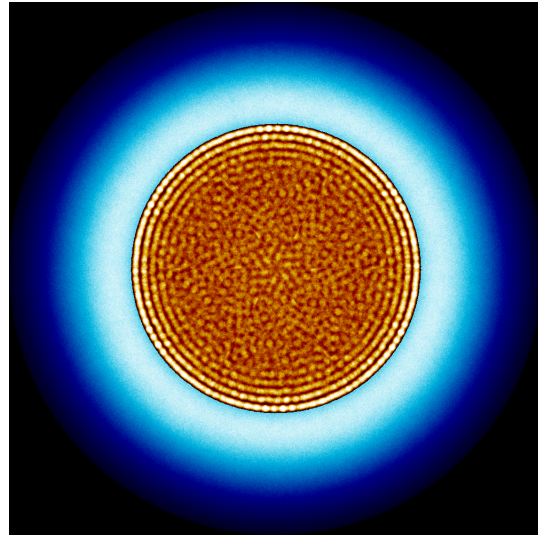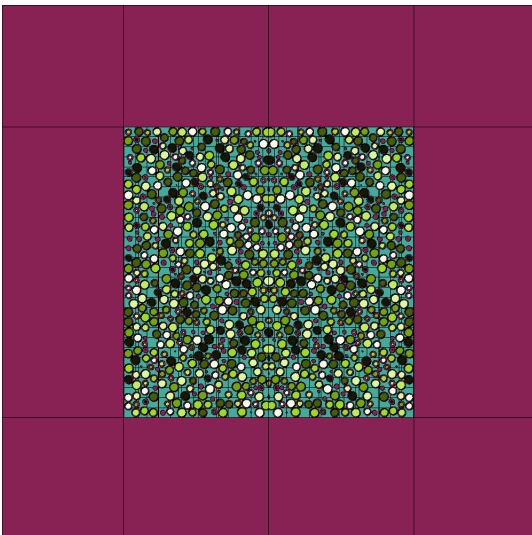
(b) Radial Mesh

(c) Axial Cross Section at z=0

(d) Axial Mesh

Figure 4.4: Sensitivity Analysis: 120° - 180°
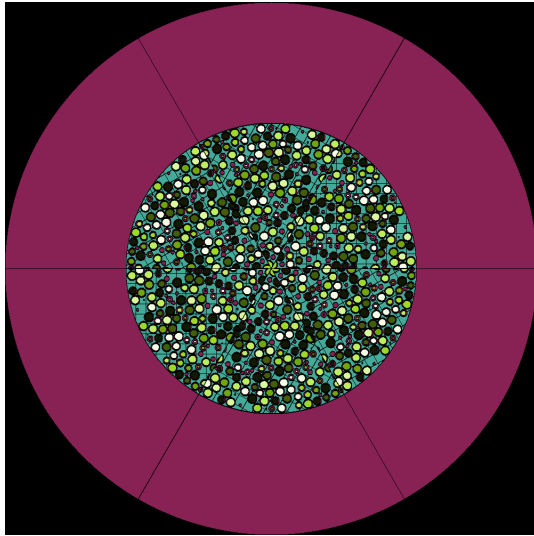
(a) Radial Cross Section at y=0
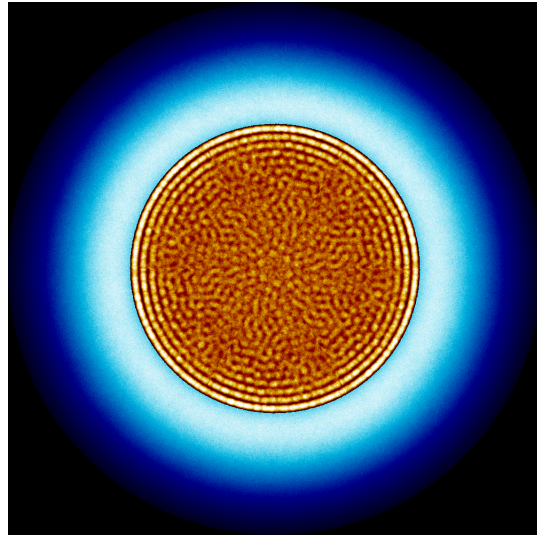
(b) Radial Mesh
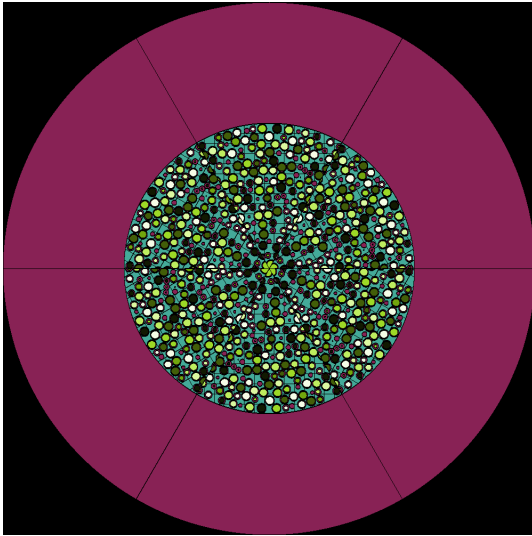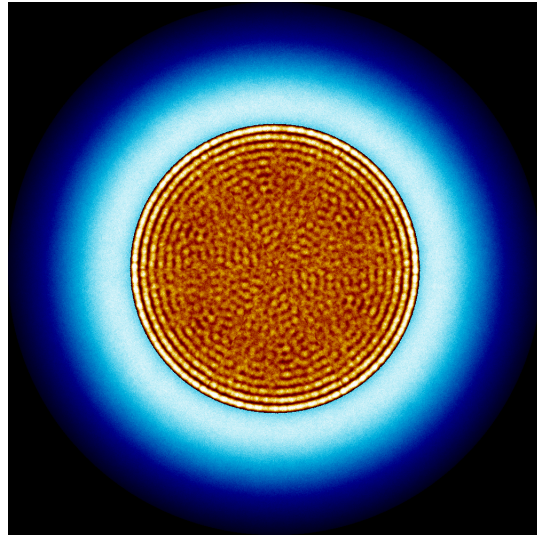

(c) Axial Cross Section at z=0

(d) Axial Mesh
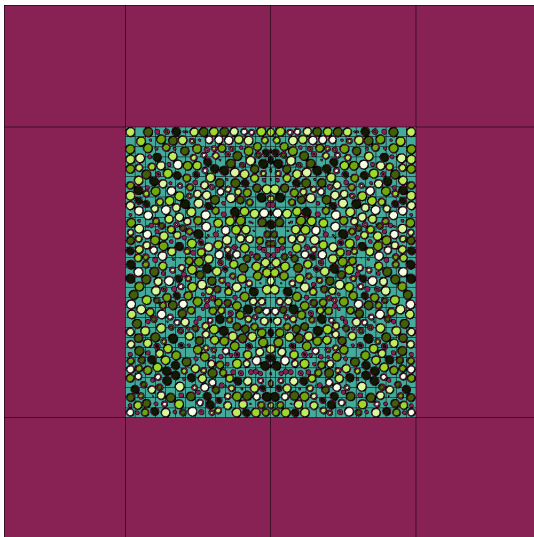
Figure 4.5: Sensitivity Analysis: 180° - 240°

(a) Radial Cross Section at y=0

(b) Radial Mesh

(c) Axial Cross Section at z=0

(d) Axial Mesh

Figure 4.6: Sensitivity Analysis: 240° - 300°
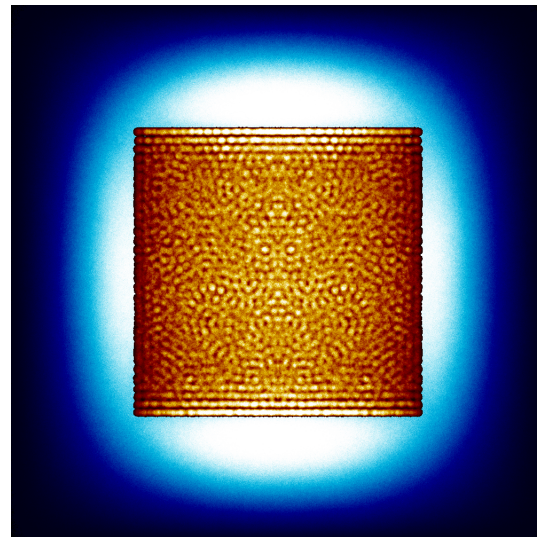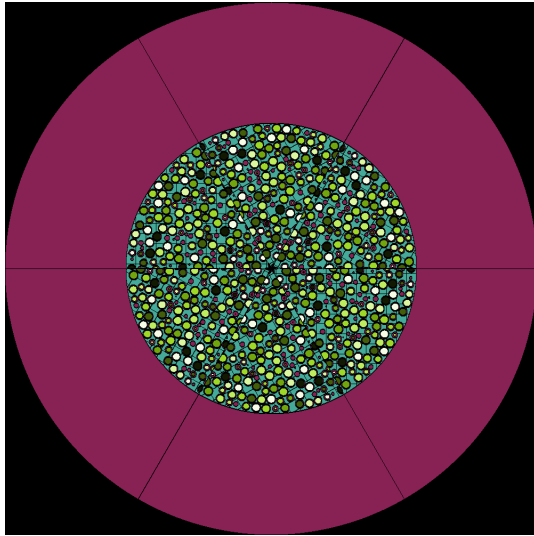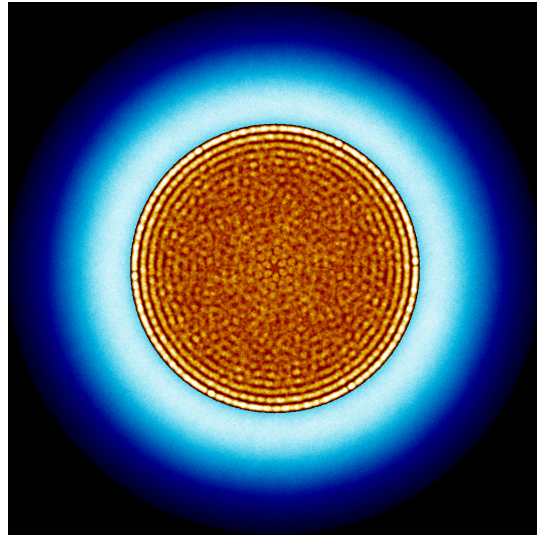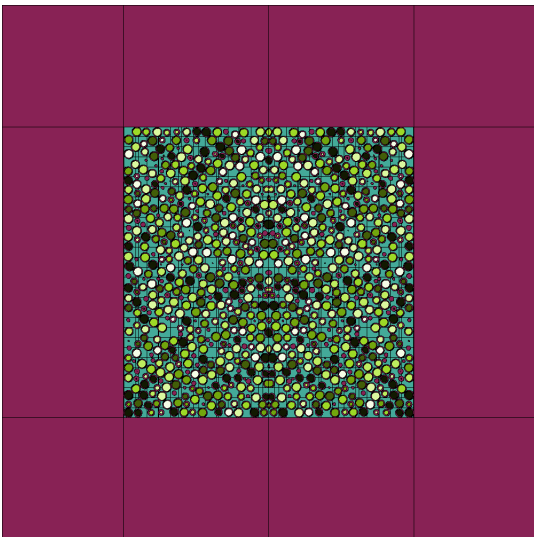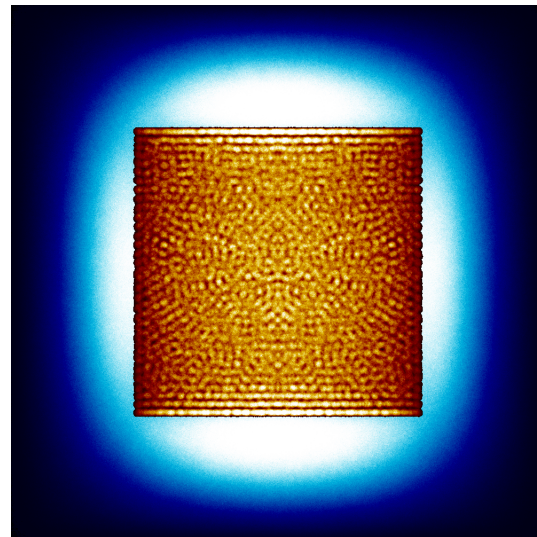
(a) Radial Cross Section at y=0

(b) Radial Mesh

(c) Axial Cross Section at z=0

(d) Axial Mesh

Figure 4.7: Sensitivity Analysis: 300° - 360°

Chapter 5

Conclusion

conclusion

Appendix

Appendix.

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