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THESIS

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Abstract

Acknowledgments

Acks.

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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

1.3 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 [1].

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 [1].

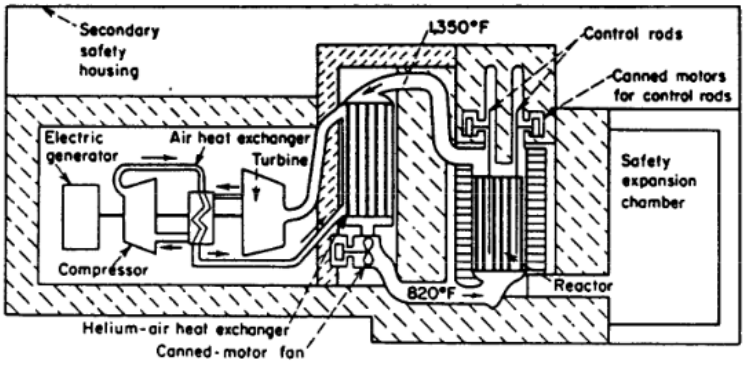


Figure 1.1: Side-View of the 1955 Daniels' Concept, [1]

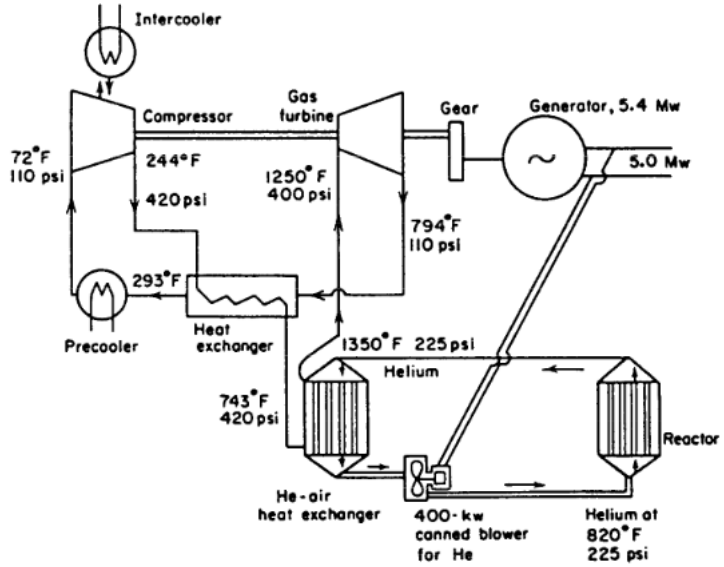


Figure 1.2: Diagram of Coolant Flow in the 1955 Daniel's Concept, [1]

Figures 1.1 and 1.2 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 [1].

1.4 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 [2].

1.4.1 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 [2]. 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 [1].

1.4.2 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 [2]. 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 [2]. 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 [1].

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

1.4.3 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 [2]. 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 [3].

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 [3].

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 [3].

(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?)

1.4.4 serpent

Serpent 2 is "a multi-purpose three-dimensional continuous-energy Monte Carlo particle transport code" [4] from the VTT Technical Research Center of Finland. The first iteration, Serpent 1, began development in 2004. The

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 1.3: Helium Coolant Specific Activities [3]

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 1.4: Pebble Dust Specific Activities [3]

development of Serpent 2 is presently ongoing. Serpent 2 has three main applications: traditional reactor physics, coupled multi-physics, and neutron and photon transport.

Chapter 2

Literature Review

2.1 Computational Models

While only Serpent 2.0 [10] is used in this thesis, work to improve HTGR modeling in one program can inform efforts in another. Therefore, modeling software beyond Serpent 2.0 is discussed in this chapter.

2.1.1 Serpent

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. Serpent has been tested with up to 60 million individual particles [4].

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 usually marginal, Serpent experiences the same issues validating its results as other Monte Carlo programs, related to small differences in data libraries [4].

2.1.2 Work in Other Software

A 1996 effort to improve MCNP developed a new sampling method for Monte Carlo. The version of MCNP that used the sampling model was dubbed MCNP-BALL. After testing by performing isotopic inventory and criticality calculations , it was seen that the MCNP-BALL code could get results accurate to 0.2%. The work developing MCNP-BALL also answered a weakness in core modeling due related to difficulties in modeling reactors with a so-called "double-heterogeneity" - having two or more types of pebble in a single reactor [43].

An additional look into MCNP HTGR simulations examined the ability to model what would normally be a stochastic geometry with uniform modeling. Specifically, TRISO particles and pebbles were placed in body centered tetragonal BCT and hexagonal close pack (HCP). In general, it was found that for very low packing fractions, such as the values seen in TRISO-in-pebble packing, the particles are generally far enough away that the differences between two crystal lattice structures are insignificant. In smaller cores with adequate reflectors, the differences between the pebble packing lattices were more significant, but manageable. However, in unreflected cores and moderators that are not graphite, this is no longer true. Additionally, the effect of completely homogenizing the coating of the TRISO particles - blending them with the graphite matrix - caused a noticeable change, specifically lowering k_{eff}. For methods using less dramatic homogenization methods, such as blending the 4 TRISO coatings into one uniform layer, an appreciable decrease in computational load was observed, and the results were marginally different from the 4-coating model [46].

BEAU, or Burnup Equilibrium Analysis Utility [12], was developed to model depletion and multiple burnup states for a continuously refueled pebble bed reactor, using the multiple burnup state method (MBSM) to do so. MBSM improves on most full-core pebble bed computational methods by modeling all burnup states for a pebble, rather than homogenizing them into a representative average pebble.

BEAU is a python-based coupling software that combines either MCNP5 or Serpent with ORIGEN2, using new interface inspired by the MOCUP code named mocup.py. Mocup.py takes the output files from an MCNP5 or Serpent simulation, and compiles the information from the simulation into an object that can be used to run depletion simulations. BEAU can be used for fuel cycle analysis and finding the maximum burnup equilibrium. It has been bench-marked against results for a pebble-bed HTGR in INL's PEBBED and VSOP [12].

2.1.3 Fuel Modeling

BEAU was used to aid in the design of a pebble bed fluoride high temperature reactor, PB-FHR, named the Mark-1 PB-FHR [12]. Much of the analysis is beyond the scope of this thesis, however, the handling of pebble locations is of interest. The Mark-1 PB-FHR handles pebble locations using a face-centered cubic (FCC) lattice in which all burnup states seen in the reactor are present. If one assumes a uniformly mixed core, the closeness of the different burnup compositions in the lattice provide a fairly good estimation.

A more general study examined the effects of pebble packing on the core neutronics in an HTGR [45]. Rather than model a full core, a unit cell was created as a reference. The study considers body centered cubic (BCC) and hexagonal close-packed (HCP). Instead of using a variety of compositions to represent an equilibrium, middle-of-life (MOL) core, an enrichment of 9.6% - lower than the standard 15% for fresh HTGR pebble-fuel - is assumed for all pebbles. For each lattice configuration, the fuel/moderator (F/M) ratio was varied, and the effects on core

neutronics and isotopic compositions examined. No significant difference between BCC and HCP cells was found. The study determined it would likely be impossible to select a truly 'optimal' energy spectrum vis-à-vis minimizing the accumulation of particularly harmful fission products. The author concluded that F/M ratios less than 1/1 favor reducing actinide inventories, while ratios greater than 1/1 can reduce the generation of fission products that would corrode the layers of the TRISO fuel.

Earlier work on HTGRs by General Atomic determined the composition of discharged thorium/uranium prismatic fuel elements. This study assumes fuel recycling to complement the breed/burn fuel cycle proposed. Additionally, the fuel cycle assumes the reactor can start with an initial feed material of 93% U-235, which is not currently feasible (at least in commercial reactors in the United States) [48].

2.2 Modern HTGRs

The following discusses more recent HTGR designs, which are the inspiration for Sangamon200 and Sangamon20.

2.2.1 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.

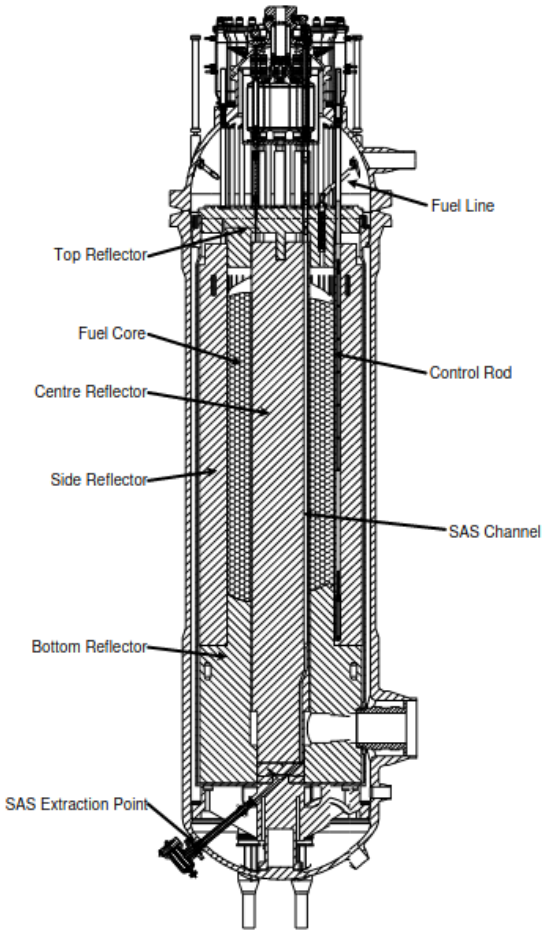


Figure 2.1: PBMR Schematic: Vertical Cross-section [5]

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].

2.2.2 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, a plethora of research conducted in support of the NGNP project is applicable to similar reactors. One such study is a whole-core depletion study of the the proposed prismatic HTGR design.

The reactor uses a once through fuel cycle, and assumed an average burnup of 100-150 $\frac{GWd}{t}$ after an 18 to 24 month stint in the core. Much of the work from this study is applicable only to prismatic designs, namely the effects of the number of batches cycling, and fuel shuffling on core neutronics [44].

2.2.3 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 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 [8]. However, while the number of passes is the same, the target end burnup for the pebbles is higher, at 160,000 $\frac{MWd}{tU}$ [9]. 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

There are two reactor models created - Sangamon200, a 200MWth design inspired by the PBMR and Xe-100. Using data from the Sangamon200 model, a scaled down reactor called the Sangamon20 was created. Both are UCO-pebble fueled, helium cooled microreactors.

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 simulations were performed using Serpent 2.0 [10]. Pebble and TRISO particle locations are both determined using the Serpent 2.0 particle dispersal routine. In Serpent 2.0, the particle dispersal algorithm first takes the number of particles, defined by the user directly, or indirectly using η_{pf}, the packing fraction, which is simply the total volume of particles in a space divided by the volume of that space. The dispersal routine also has the user define the particle radius, and the size and shape of the volume the particles are housed in. The routine first randomly determines a single point for each particle that is contained in the volume. Then, the routine uses the 'growth factor' and 'shake factor' - both described as fractions of the particle radius, and iterates. Each iteration, the size of the point's radius increases by the growth factor. Additionally, the center will move in a random direction a distance equal to the shake factor. If the particle growth would cause the particle to overlap with another particle or leave the volume, it doesn't get larger that cycle. Similarly, if the center's movement would cause overlap or leaving the containing volume, it doesn't move. The dispersal routine iterates until all particles are to their full size, contained in the volume, and do not overlap with any other particles. The routine generates an output file, where each line gives the coordinates of the particle center in x,y,z coordinates, the particle radius, and the name of the particle type, to associate it with the pbed card later.

In order to determine isotopic compositions in the pebbles, a Serpent burnup simulation of a single pebble is run in burnup steps of 180, 360, 540, 720, 900, and 1080 days - to represent 6, 6-month passes. A seventh composition is for a fresh pebble's composition. The single pebbles are the only models that utilize individually modeled TRISO particles. For the full-core models, each pebble is homogenized. Each pebble has two regions, an inner region that contains the TRISO particles embedded in graphite, and an outer region consisting only of graphite, see 3.1. Each region is homogenized by volume fraction using the mix card in Serpent.

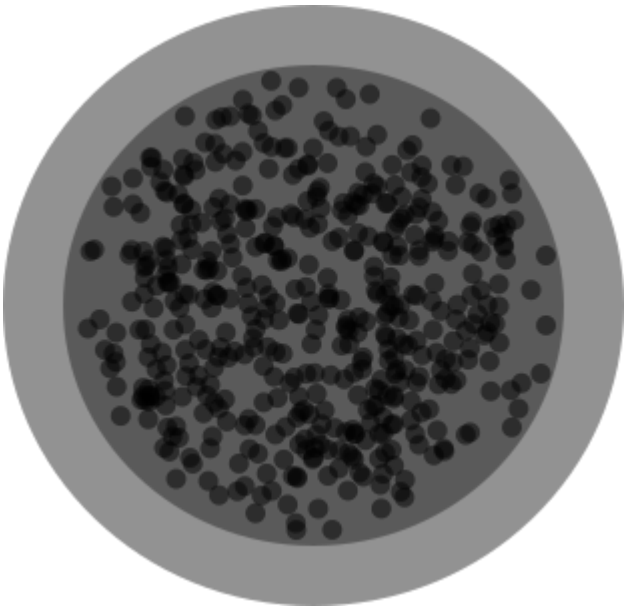


Figure 3.1: Pebble Zones

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

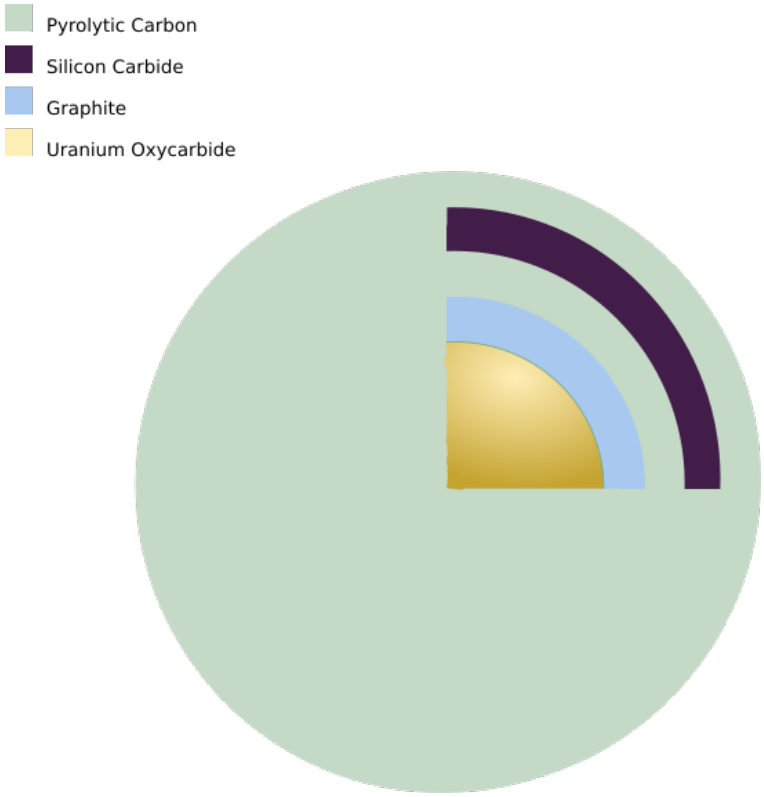


Figure 3.2: TRISO Particle Layers (not to scale)

3.1 Sangamon200

Sangamon200 is a 200 MWth helium cooled reactor, with parameters as defined in 3.1. Though the model does use some parameters from pre-established designs, it is still, a simplification. The "cone" formed at the top and bottom of the reactor core by the pebbles 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.

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:

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

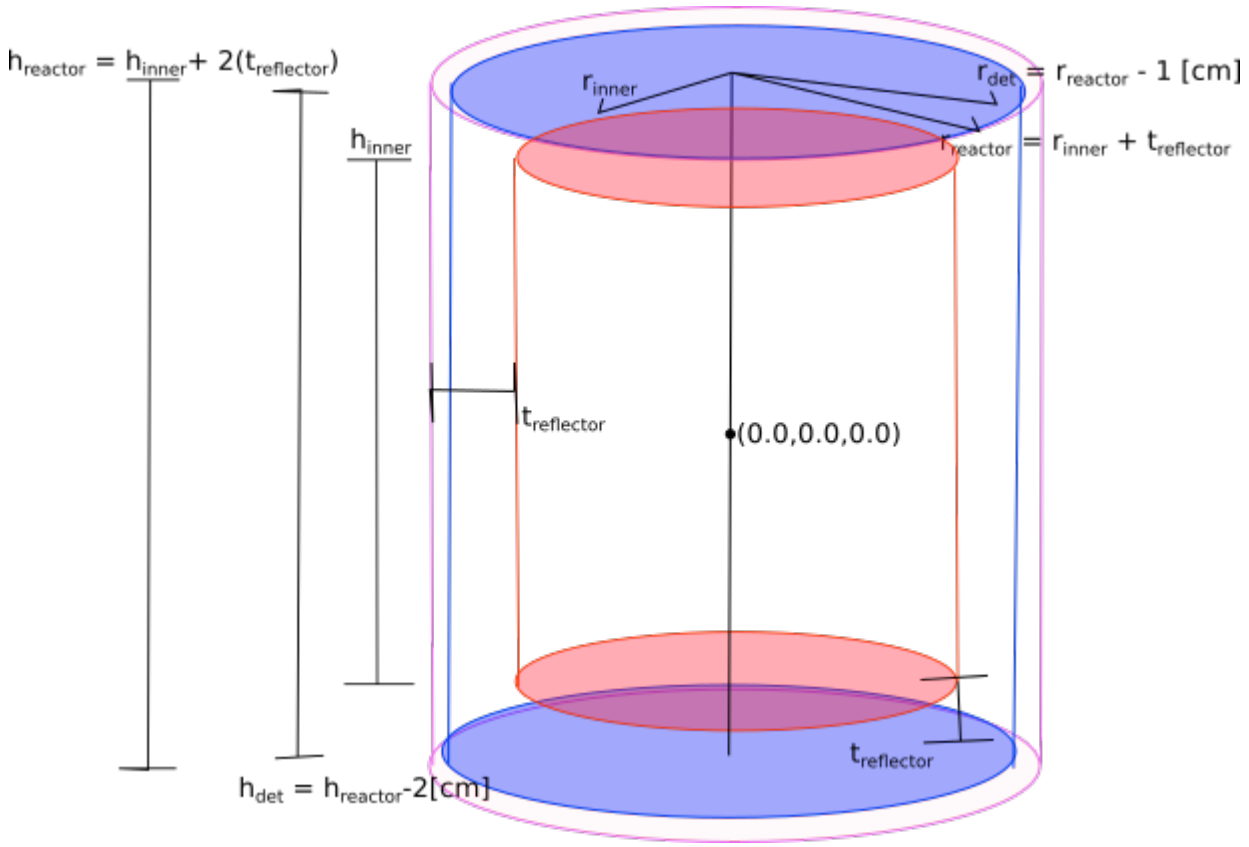


Figure 3.3: Detector Placement Inside Reflector

After accounting for the surface area, the outward current at the detector is $7.351x10^{11}$.

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 sufficient to simply scale Sangamon200's dimensions down to 10% of their original values, as that wouldn't have the correct volume for the required pebbles, and the neutronics wouldn't be preserved correctly.

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 $\frac{\text{kW}}{\text{g UCO}}$.

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

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

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

$$M_{f,20} = \frac{P[kW]}{\rho_p[\frac{kW}{g}]} = 181818.18[g] \tag{3.4}$$

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 [11]. For this reactor, it is assumed the pebble behavior can be described as random loose packing [11] - 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 [11]. 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.

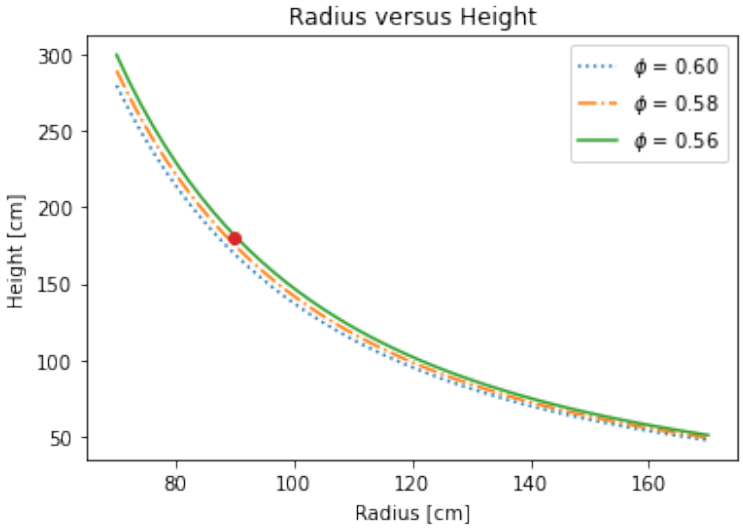


Figure 3.4: Curve of Possible Height and Radii by Packing Fraction

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 thermal 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.

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.

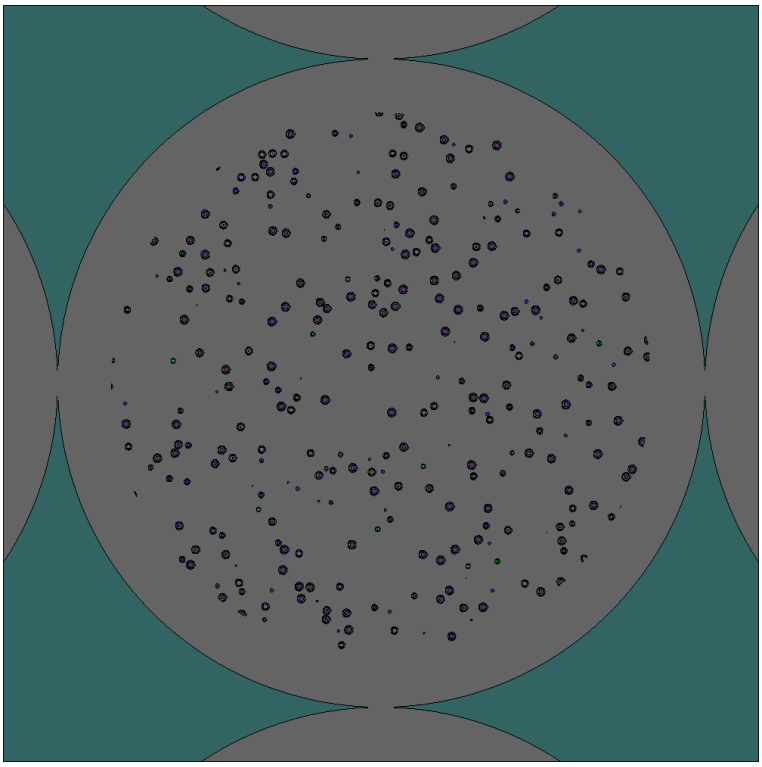


Figure 3.5: Geometry of the Single-Pebble Burnup Calculation: Sangamon20

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

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.

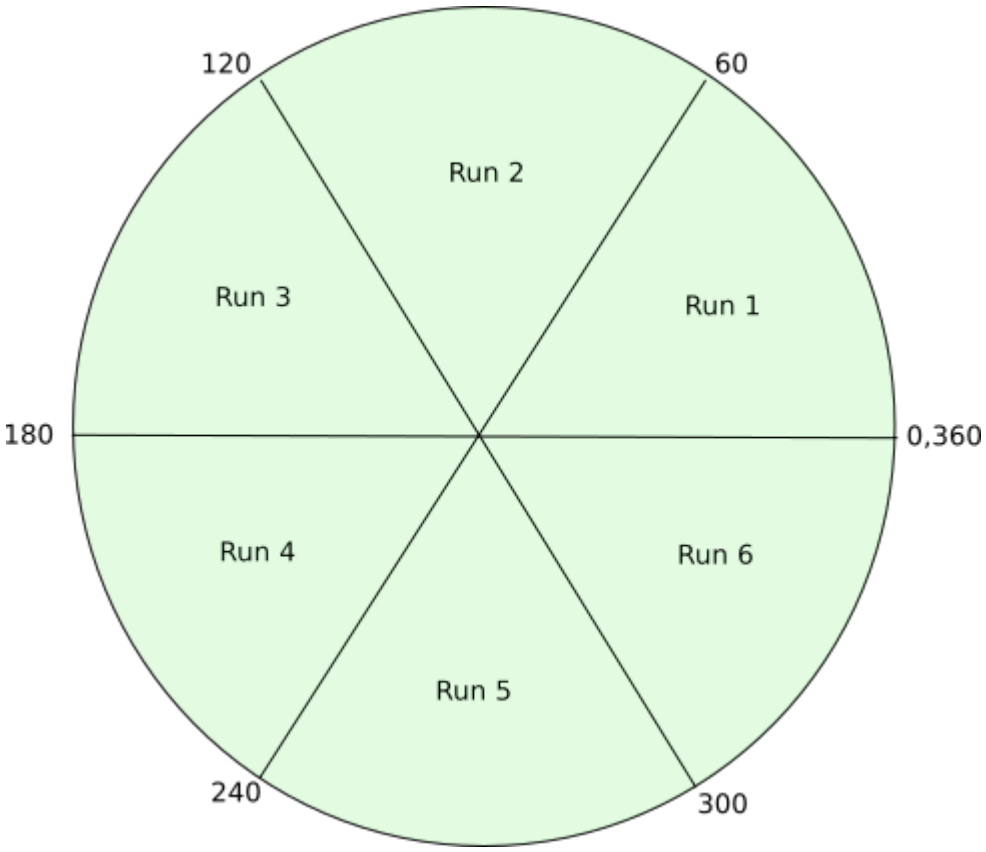


Figure 3.6: Symmetry Test Run Layouts

Chapter 4

Results

results

general outline:

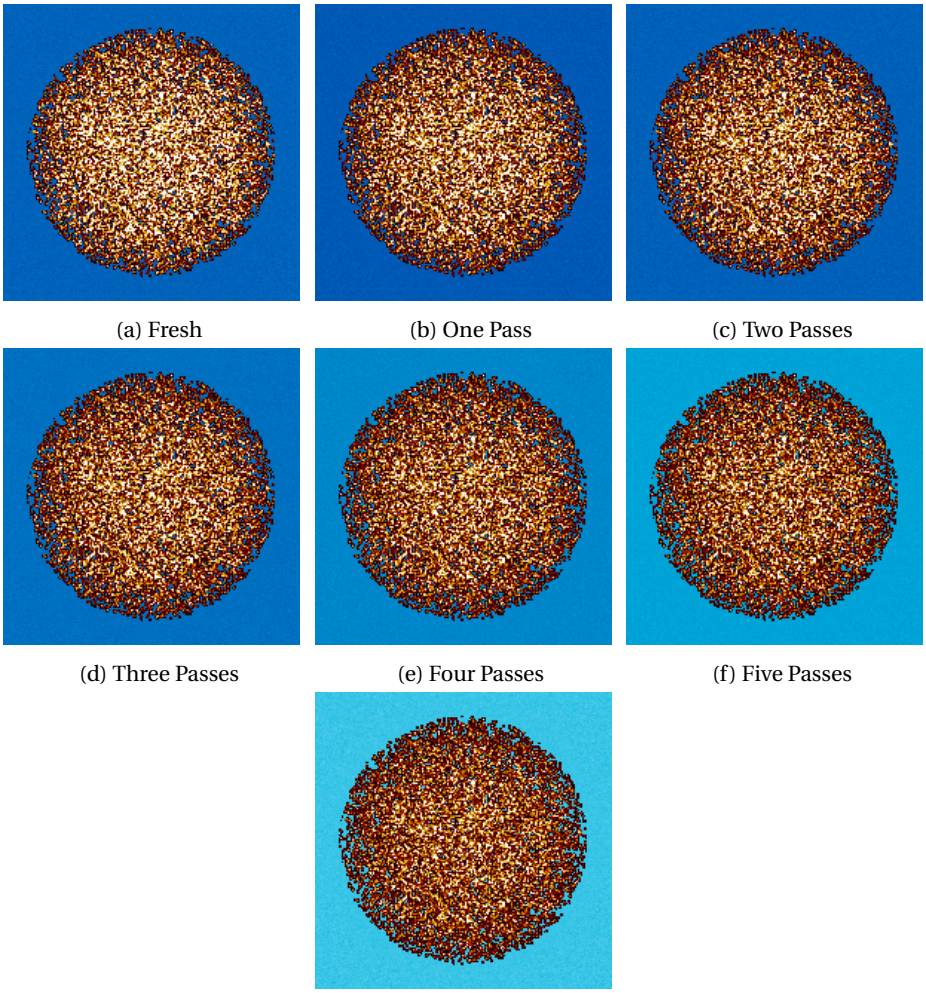
- full core model
  - radial banding on outer edge due to pebble location
  - to a lesser degree, axial banding on top/bottom
  - while not symmetrical, 'hot spots' are fairly rare, and a general gradient in the fission rate (orange) can be seen.
  - noticeable hotspots seem to be at the very top/bottom, in the middle, and at the edges in the radial image. Of course, this isn't seen in the axial mesh, because the edges of the axial mesh are only integrating over a small amount of material, while in the radial mesh, all parts integrate over the entire height of the reactor.
  - ***One point of interest (discuss in meeting?)*** is that theoretically, the centerline of the axial mesh should all be integrating over the same amount of material - a thickness corresponding to the diameter of the reactor, 165 inches, which is also the height. However, the hotspots I see at the top and bottom in the center aren't carried through the centerline. If the hotspots in the top and bottom of the axial mesh were simply because it integrated over more material, shouldn't the entire centerline be brighter?
  - I do notice a *very slight* trend to the right side of the axial mesh, at least toward the bottom
  - since the radial mesh is integrating over the same volume throughout, I expected it to show the sort of trend in fission rate I would expect from a cylindrical reactor - more intense at the center, tapering toward the edge. Certainly, the reflector (blue) is doing that with scatters. But why is the center so dark compared to the outside? is the banding that intense?
    - had a thought: the meshes integrate over space, right. It so happens that the bands here are where pebbles are perfectly lining up. What if this intensity at the edges is a misrepresentation, a limitation

of how the mesh is made? If integrating over space, and all the the space in that section are pebbles - ie, fuel, remember they are homogenized - then the effect is that the integrated space is more concentrated. As you go towards the center, and pebble location becomes random, the same 'section' integrated in isn't just fuel pebbles anymore, there could also be coolant. It's 'watering down' that section. If you look at the axial mesh, at the left and right edges you can see exactly what one pebble looks like, and it's rather dark

- sensitivity and symmetry
  - no noticeable change in the k-eff between runs, for either switching pebble comps or going to a 1/6th core
  - banding behavior highlights a potential issue in using symmetry, but for 1/6th did not significantly change the overall trends in the mesh figures
  - notably, I did compare the meshes, and for the radial symmetry at least, is is quite literally just taking the corresponding portion of the full core control and reflecting it around (i expected a little bit of a difference at least)
- flux
  - radial and axial fluxes, two group
  - 2 group flux in a fresh and 6pass pebble

4.1 Full-Core Control Model

- meshes for each burnup used in single pebble
- pebbles are not homogenized
- each pass is six months
- pebble is 3.0 cm across, with helium to fill out the cube it is inscribed in
- each corresponds to a fuel composition in the full core
- can see the outside (helium, material: blue) become paler over time (fewer scatters?)
- can see the pebble (sphere, mat: non-homogenized pebble) become darker over time (fewer fissions?)

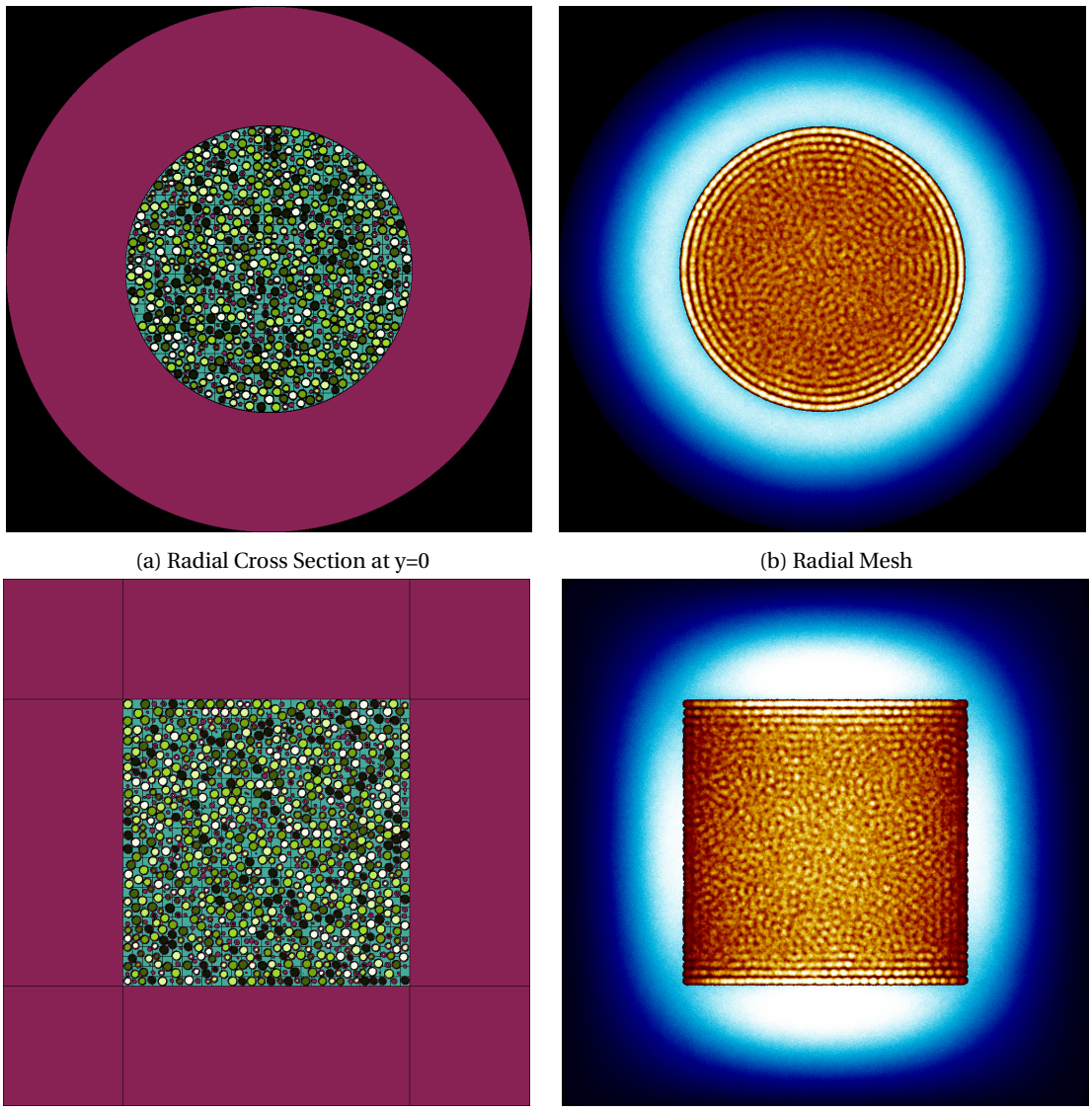


(a) Fresh (b) One Pass (c) Two Passes

(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

- full core model
- homogenized pebbles
- no symmetry setting
- rings due to pebbles naturally lining up along the outer edges due to the physical barrier of the graphite, then becoming more random towards the center
- teal is helium
- pink is graphite
- pebbles green: lighter -> darker = fresh -> burnt
- remember that the meshes are integrated to create the 2d representation, it is not the fission/scattering in that cross section alone

The burnup models of the single pebble inscribed in a cube of helium provide the middle-of-life compositions used in the Sangamon20 full-core models. The exact compositions are provided in the appendix. Overall, the behavior of the single-pebble burnup models over time are as expected. As the pebble is more burned, the fission and scattering rates decrease in the fuel pebble and surrounding helium, respectively. The presence of 'holes' in the mesh aren't unexpected - the packing fraction of TRISO particles in the pebbles is significantly lower than the packing fraction of pebbles in the reactor.

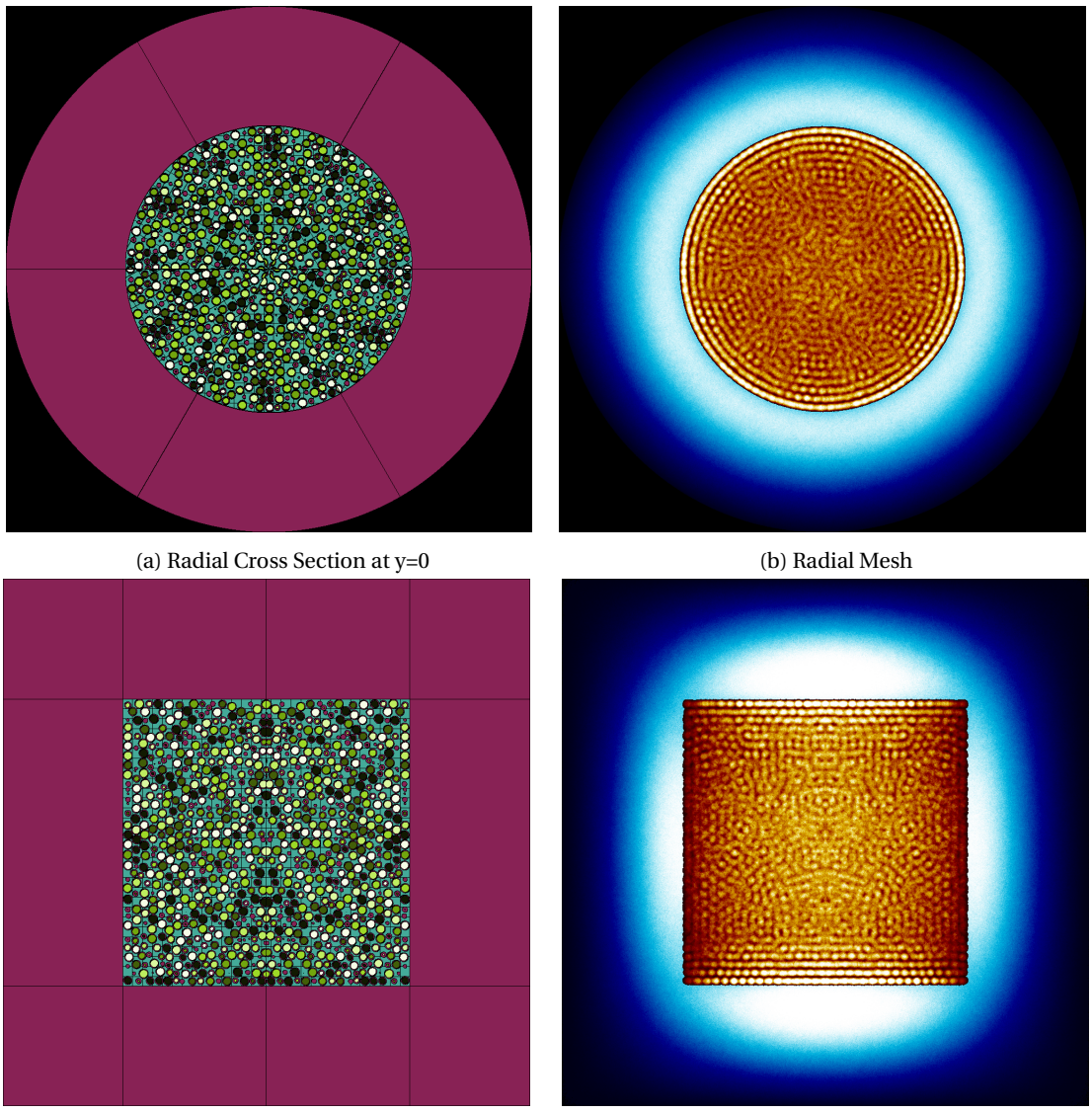
The homogenized pebbles in the full-core model are much more uniform throughout the pebble compared to the heterogeneous pebbles, as one might expect. A more interesting feature is the presence of radial rings in the outer reactor core. These rings are more clearly seen in the mesh, but as the geometry cross-section shows, this phenomenon is due to the physical layout of the pebbles. Towards the outside, the pebbles have the walls of the reactor to line up against, and so their location is uniform. As you approach the center, without a physical barrier, the pebbles are able to find more 'random' positions. This phenomenon also makes sense when one considers the mechanics of the Serpent 2.0 growth and shake algorithm. As discussed in the Methods chapter, the growth and shake factors are very small fractions of pebble radius. The dispersal routine determines pebble locations iteratively, and once the initial center point is determined, moves and grows each pebble the minimum amount required to fit the routine's three criterion: 1) the particle is at its full size, 2) the particle doesn't overlap with any other particles, and 3) the particle is fully contained in the boundaries of the container. Naturally, then, any particle spawned relatively close to the outer bound would line up with it as the algorithm 'shakes' the particles.

4.2 Sensitivity Tests

4.2.1 Effects of Symmetry Assumption

- 1/6 core symmetry
- uses the section of the core that is the 0-60 slice from the full core
- periodic boundary condition between core 'slices' vacuum outside
- the center cross section is slightly better to visualize the 'banding' or petal behavior of the pebbles, but the axial one is more representative of the banding patterns in the entire core. Remember, the line the axial image cuts through to give us this image lays on the boundary of a slice (the line corresponding to the horizontal one in the radial geom cross section) this means that the patterns seen in the axial geom here are repeated at the borders of every slice.
- as above, but the 120-180 degree slice
- as above, but the 180-140 degree slice
- as above, but the 240-300 degree slice
- as above, but the 300-360 degree slice

4.2.2 Effects of Fuel Composition Shuffling



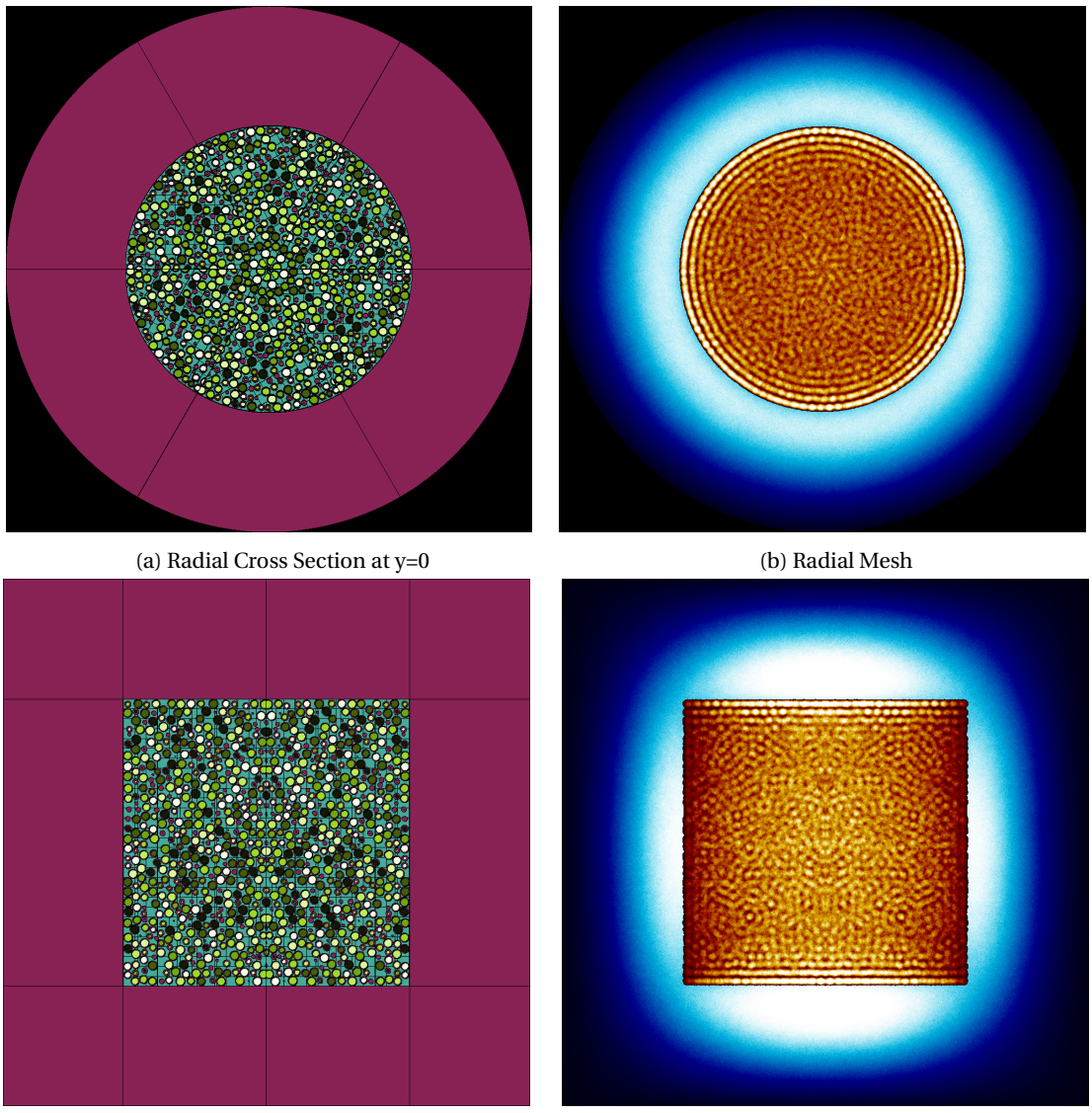
(a) Radial Cross Section at y=0

(b) Radial Mesh

(c) Axial Cross Section at z=0

(d) Axial Mesh

Figure 4.3: Sensitivity Analysis: 60° - 120°



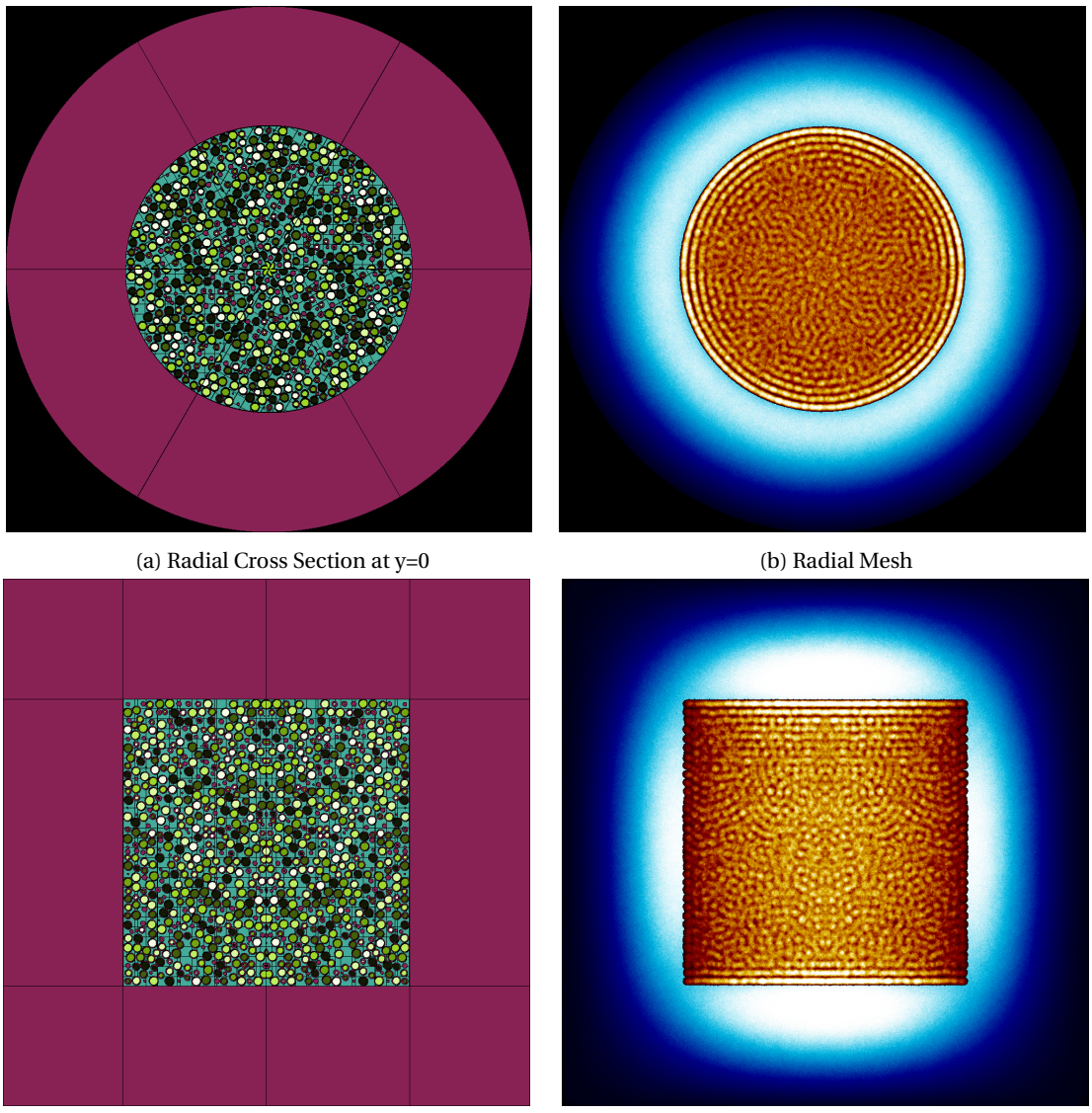
(a) Radial Cross Section at y=0

(b) Radial Mesh

(c) Axial Cross Section at z=0

(d) Axial Mesh

Figure 4.4: Sensitivity Analysis: 120° - 180°



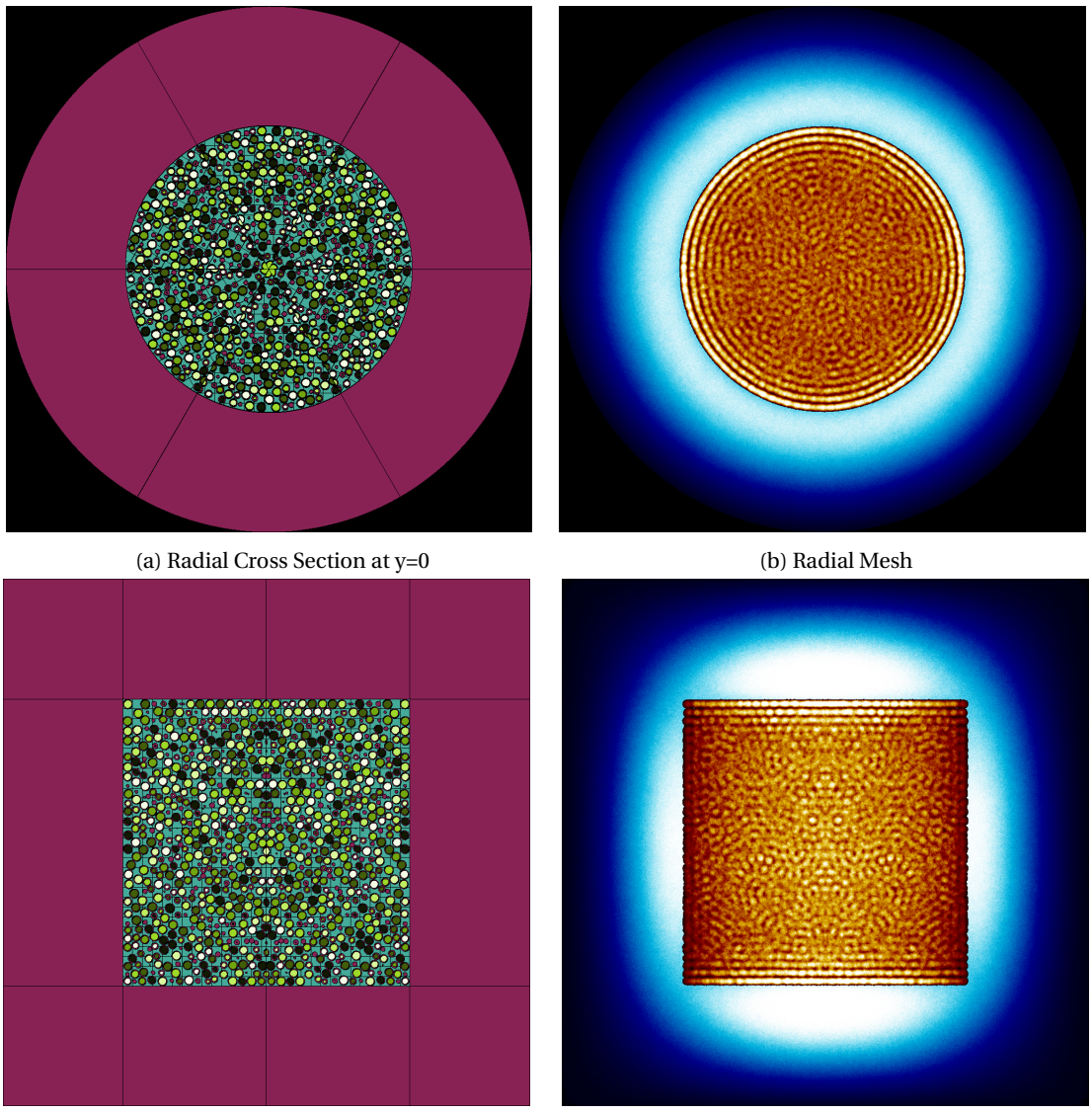
(a) Radial Cross Section at y=0

(b) Radial Mesh

(c) Axial Cross Section at z=0

(d) Axial Mesh

Figure 4.5: Sensitivity Analysis: 180° - 240°



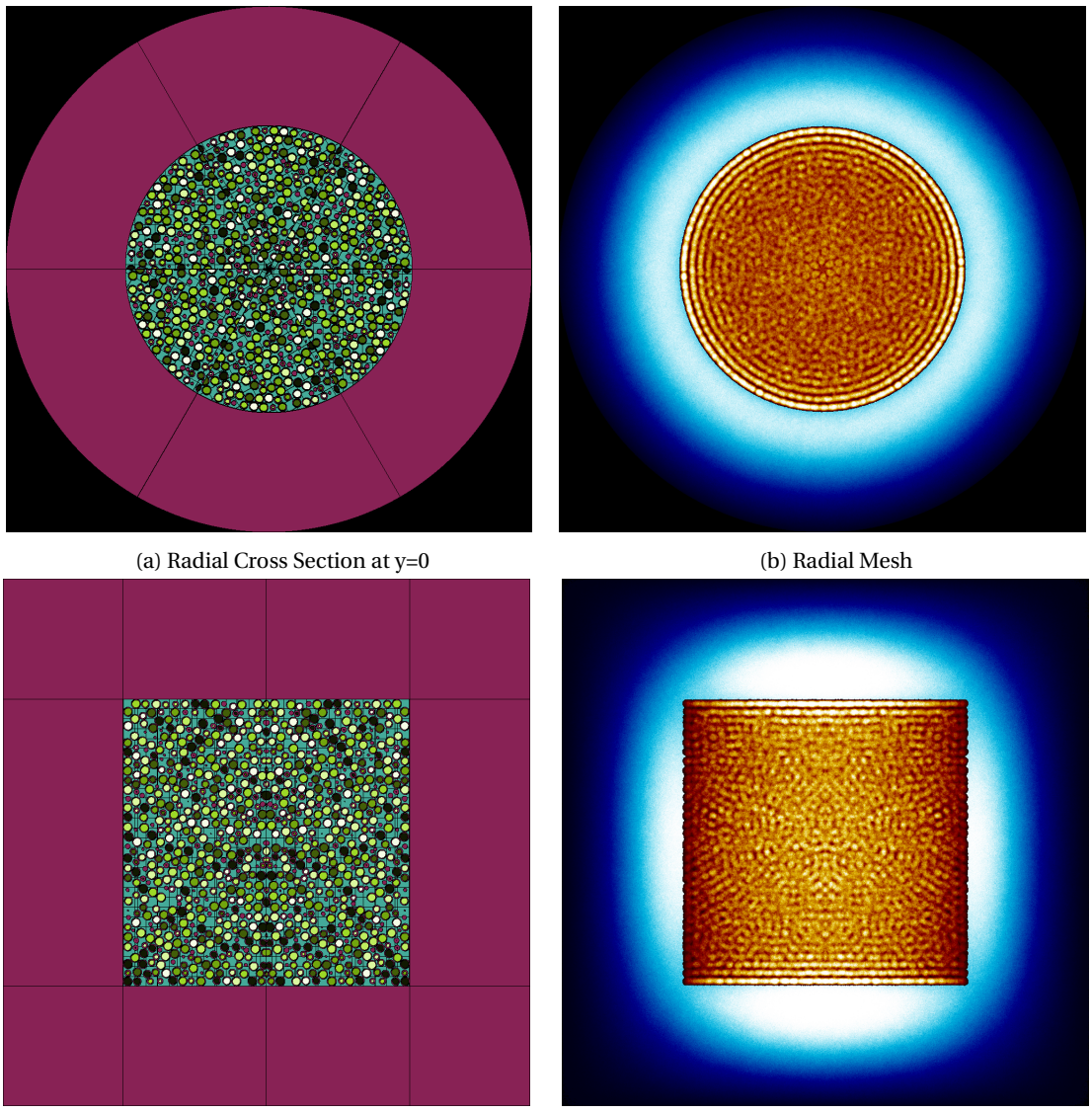
(a) Radial Cross Section at y=0

(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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