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THESIS

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Master's Committee:

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Abstract

Acknowledgments

Acks.

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Chapter 1

Introduction

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 billard 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 (*****roberto pres links find*****).

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

Literature review

give first instance of triso/htgr/pebble bed, etc, then fast forward to today

first concept:

PBMR

- South-African pebble bed HTGR based on German HTGR reactor technology
- Designs had thermal power capacities 200+
- currently in "care and maintenance"
- various

NGNP

Cisneros

Xenergy (Xe-100,etc)

mention these briefly

https://www.sciencedirect.com/science/article/pii/S0306454918303748?casa_token=t58RGuIX6VAAAAAA:
2dcGCyANultpSMw7DSSIGGvmzdgpH3wr6fWw50j2awnpkBVItZ5zxoyOxQVGpGcIFNMRlPs

https://www.mdpi.com/1996-1073/8/12/13938

https://onlinelibrary.wiley.com/doi/full/10.1002/er.4542?casa_token=Q78UeM8i1XkAAAAA%3ArcPa5kUAo6c04Y
7WtlydJu1_PeVpr

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 [Leppänen] . 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.

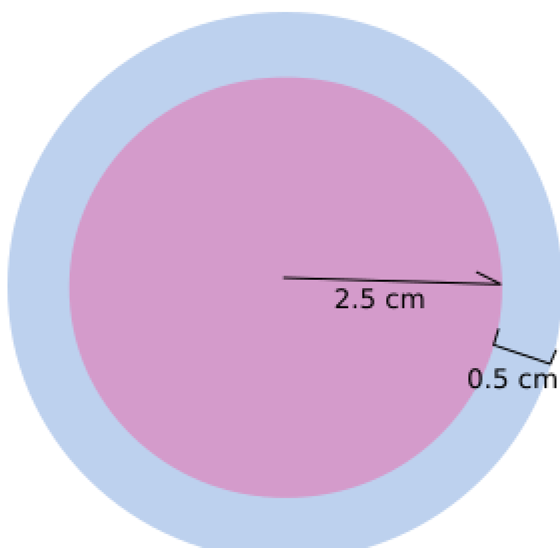


Figure 3.1: Pebble Zones

Fuel isotopic composition aside, the pebbles are identical in both reactor designs. Both reactors feature a 6-month

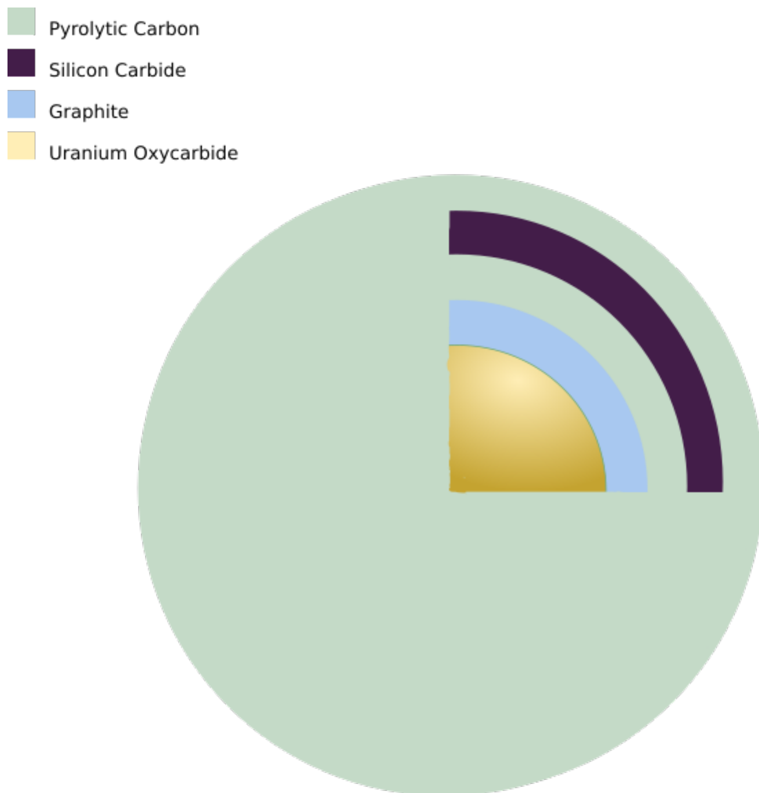


Figure 3.2: TRISO Particle Layers (not to scale)

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

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.

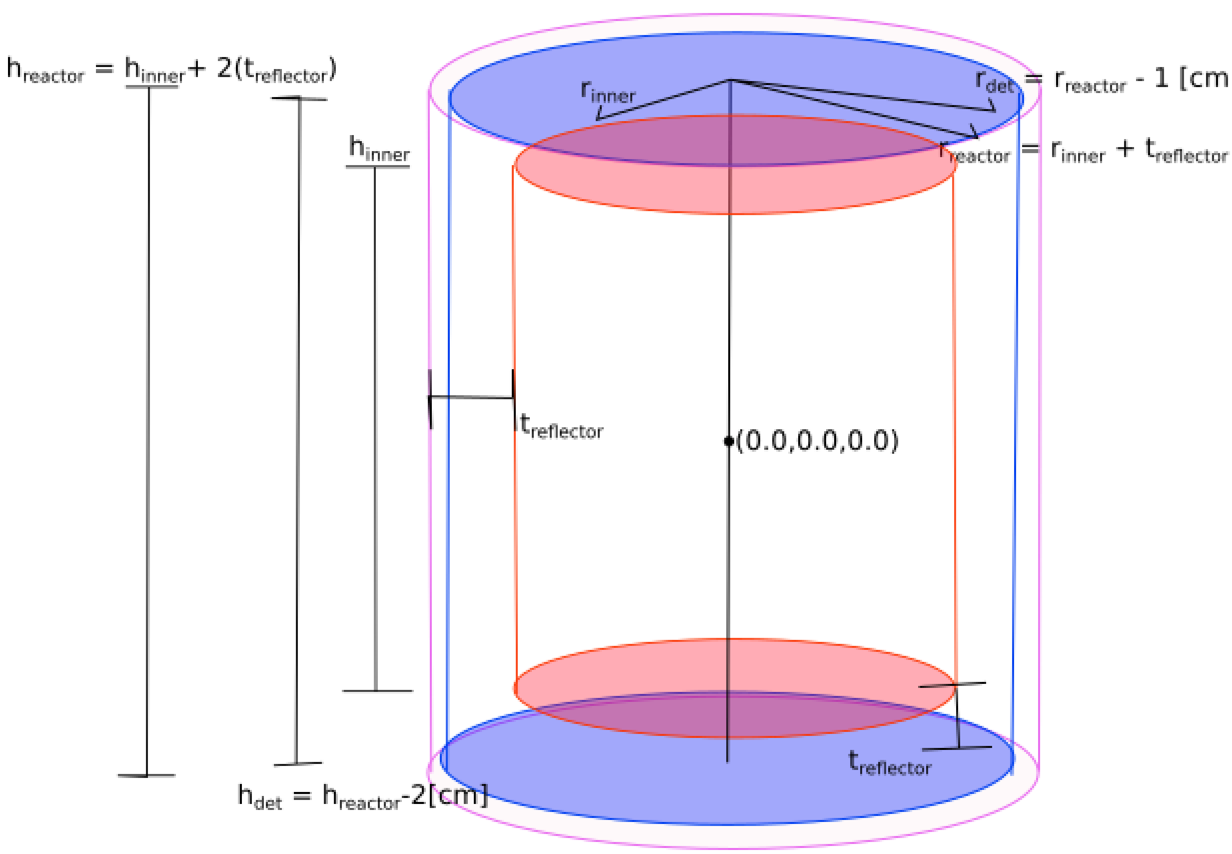


Figure 3.3: Detector Placement Inside Reflector

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 $\frac{\text{kW}}{\text{g fuel}}$ (*** 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

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

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

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

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

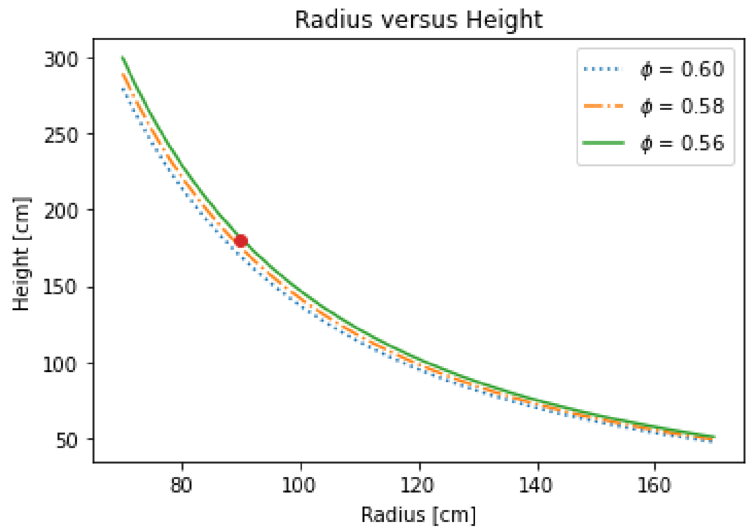


Figure 3.4: Curve of Possible Height and Radii by Packing Fraction

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

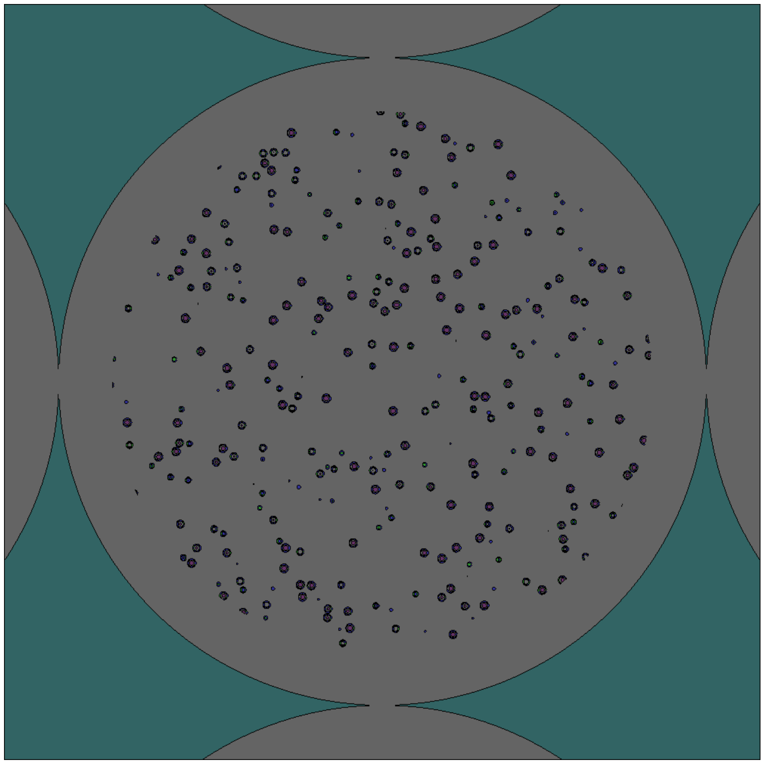


Figure 3.5: Geometry of the Single-Pebble Burnup Calculation: Sangamon20

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.

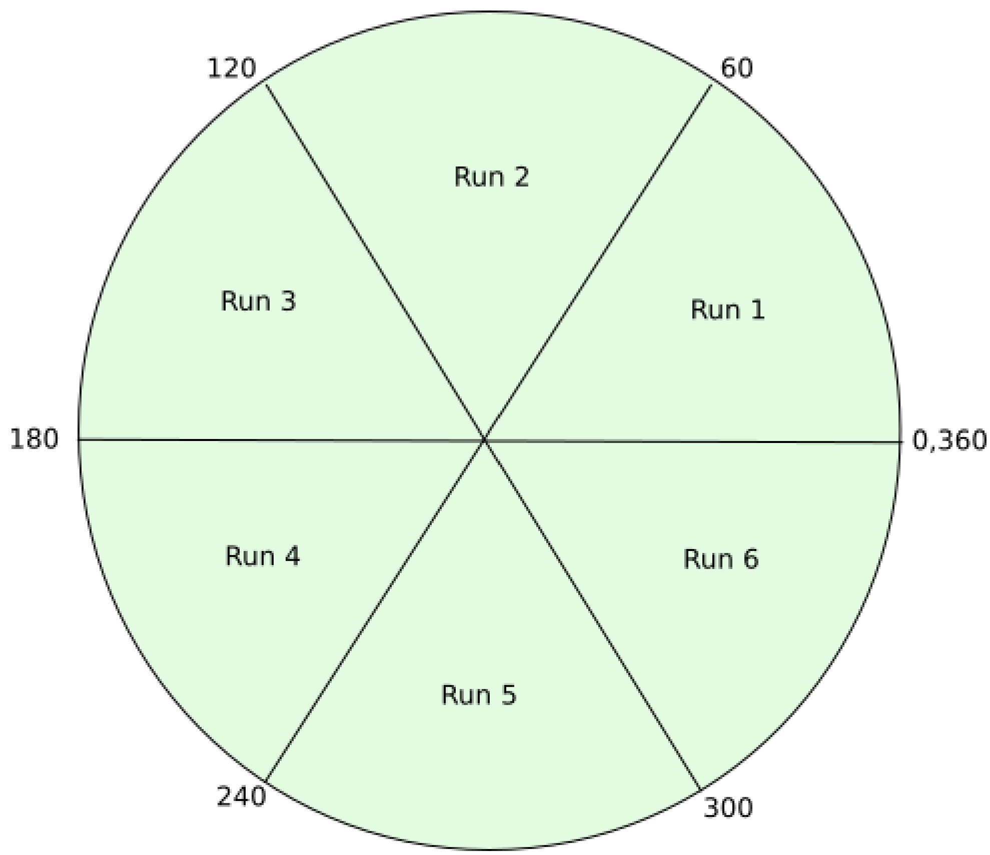
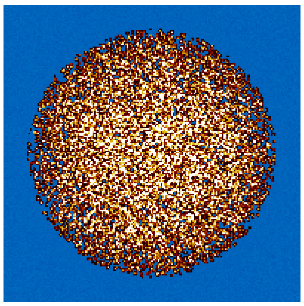


Figure 3.6: Symmetry Test Run Layouts

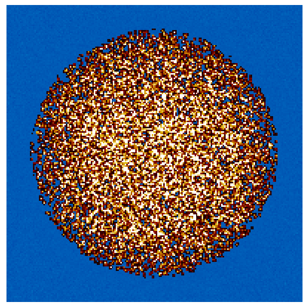
Chapter 4

Results

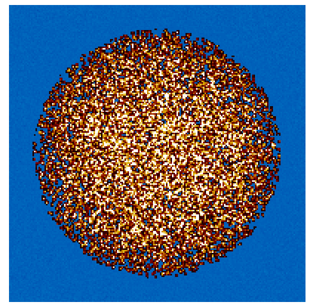
results



(a) Fresh

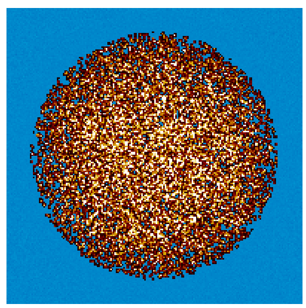


(b) One Pass

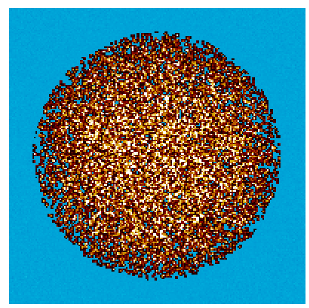


(c) Two Passes

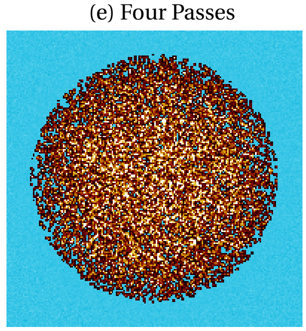
(d) Three Passes



(e) Four Passes

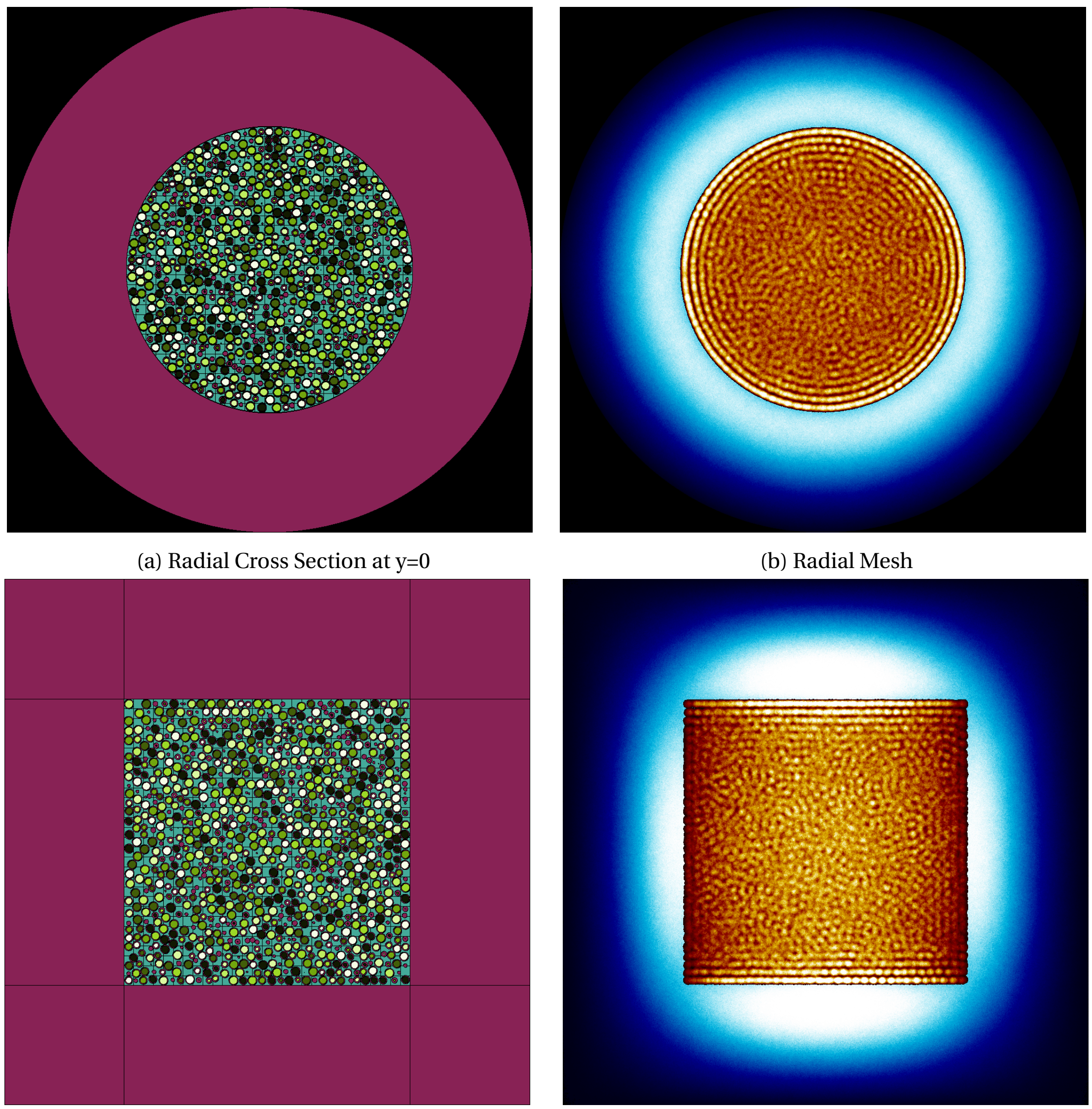


(f) Five Passes



(g) Six Passes

Figure 4.1: Mesh Figures For Single Pebble Burnup



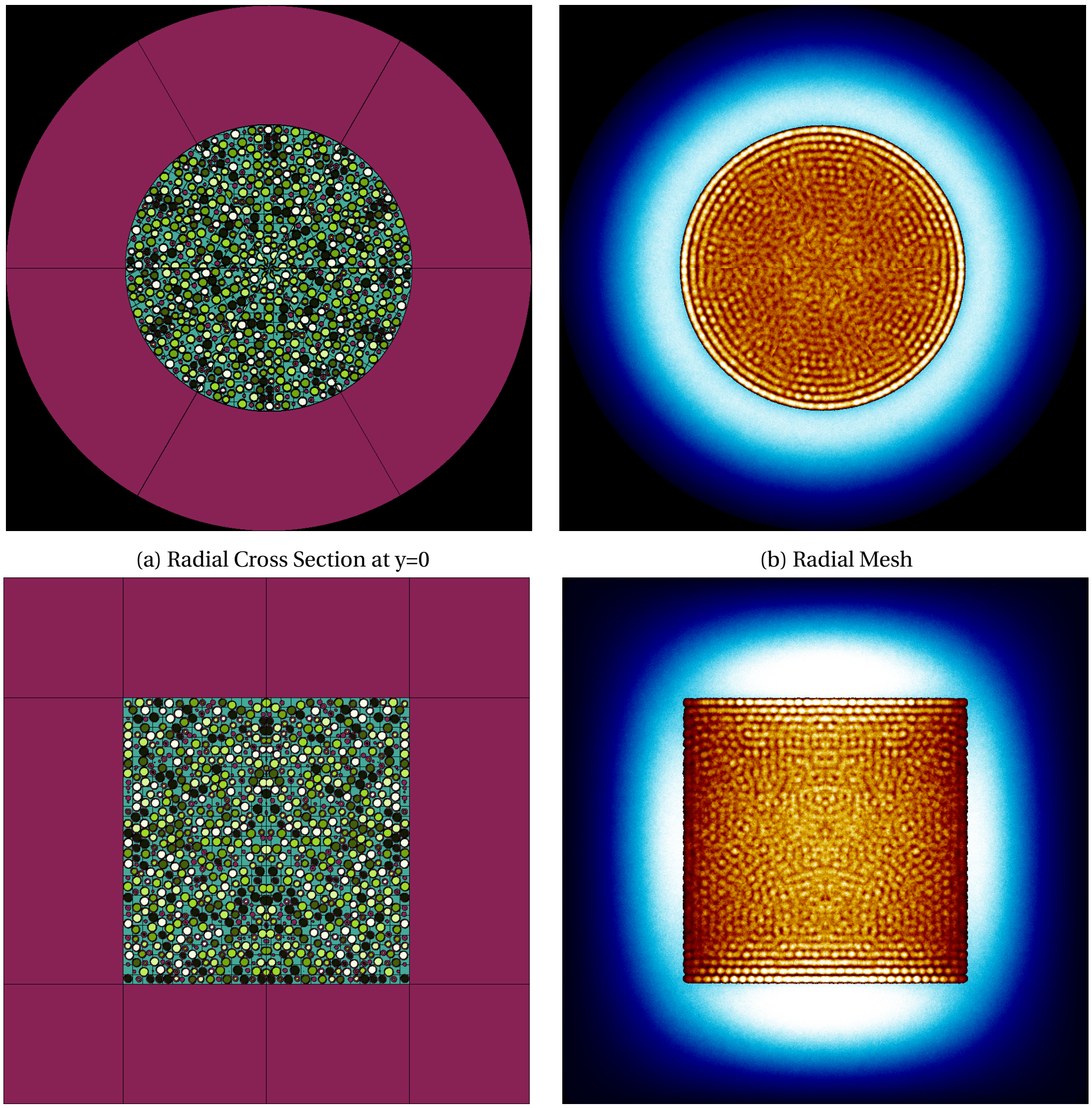
(a) Radial Cross Section at y=0

(b) Radial Mesh

(c) Axial Cross Section at z=0

(d) Axial Mesh

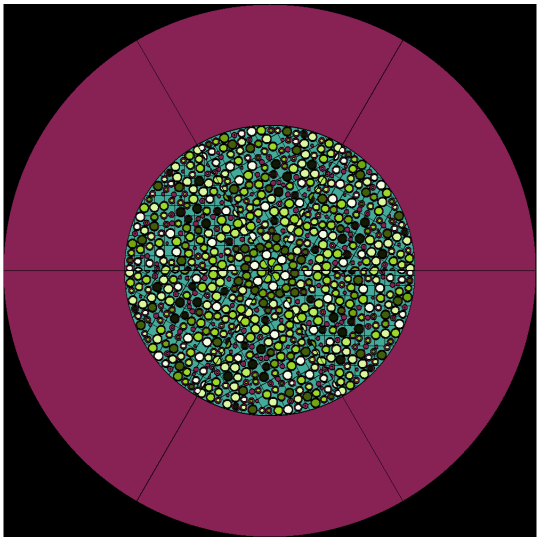
Figure 4.2: Full Core



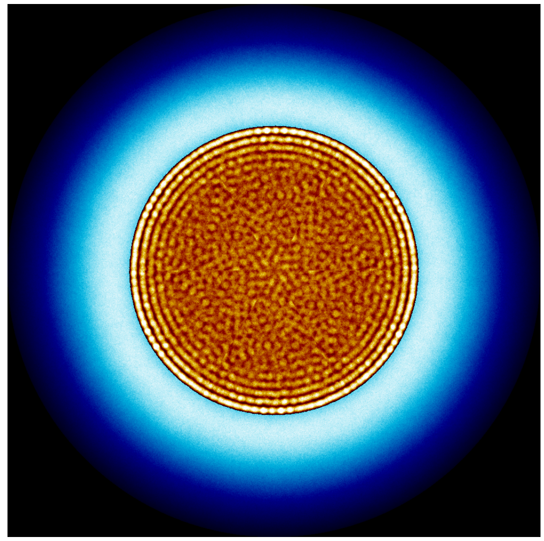
(a) Radial Cross Section at y=0 (b) Radial Mesh

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

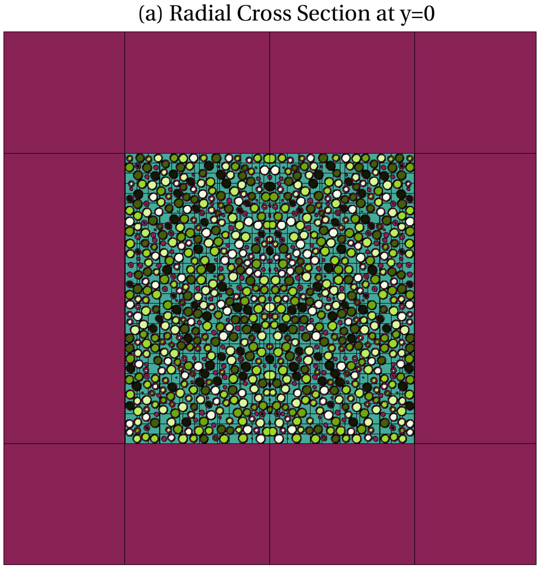
Figure 4.3: Sensitivity Analysis: 60° - 120°



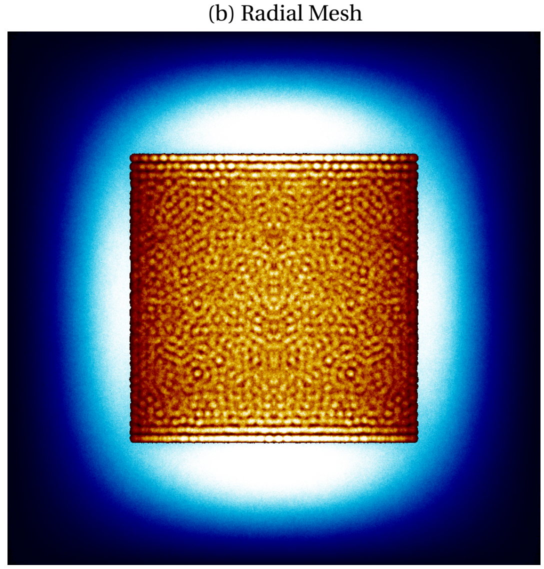
(a) Radial Cross Section at y=0



(b) Radial Mesh

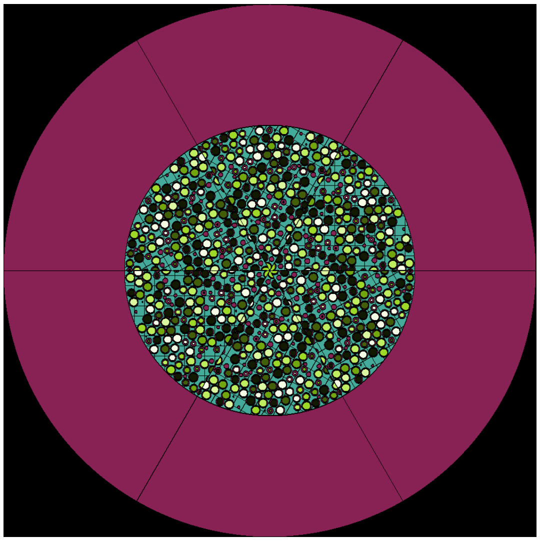


(c) Axial Cross Section at z=0

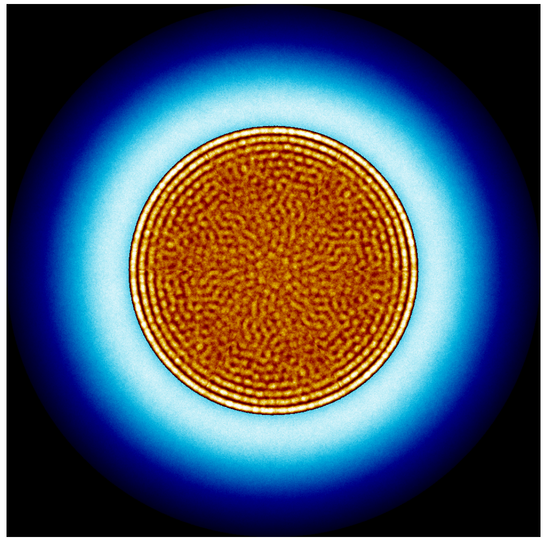


(d) Axial Mesh

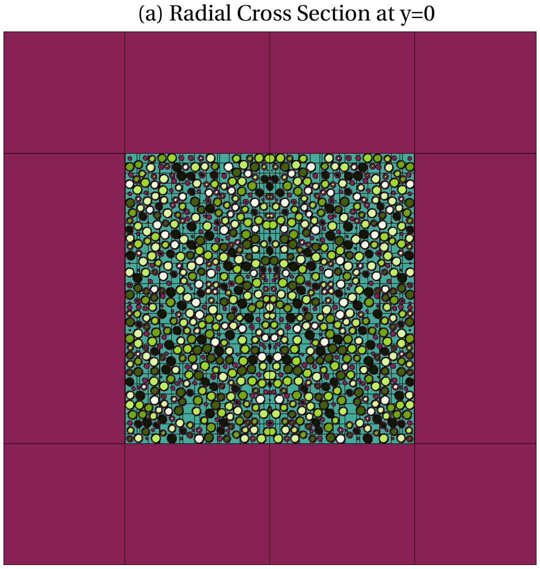
Figure 4.4: Sensitivity Analysis: 120° - 180°



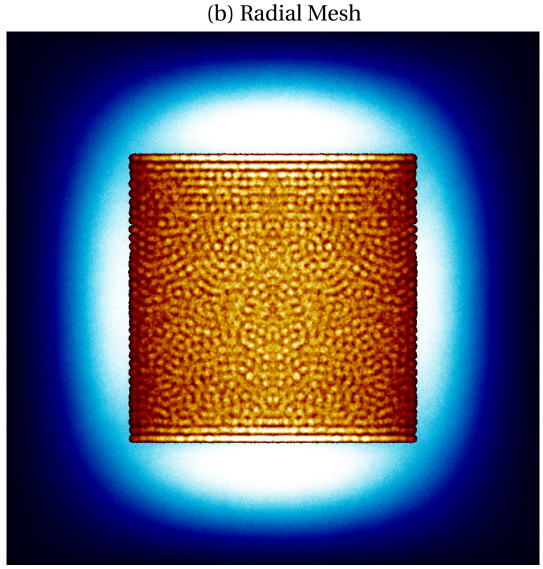
(a) Radial Cross Section at y=0



(b) Radial Mesh

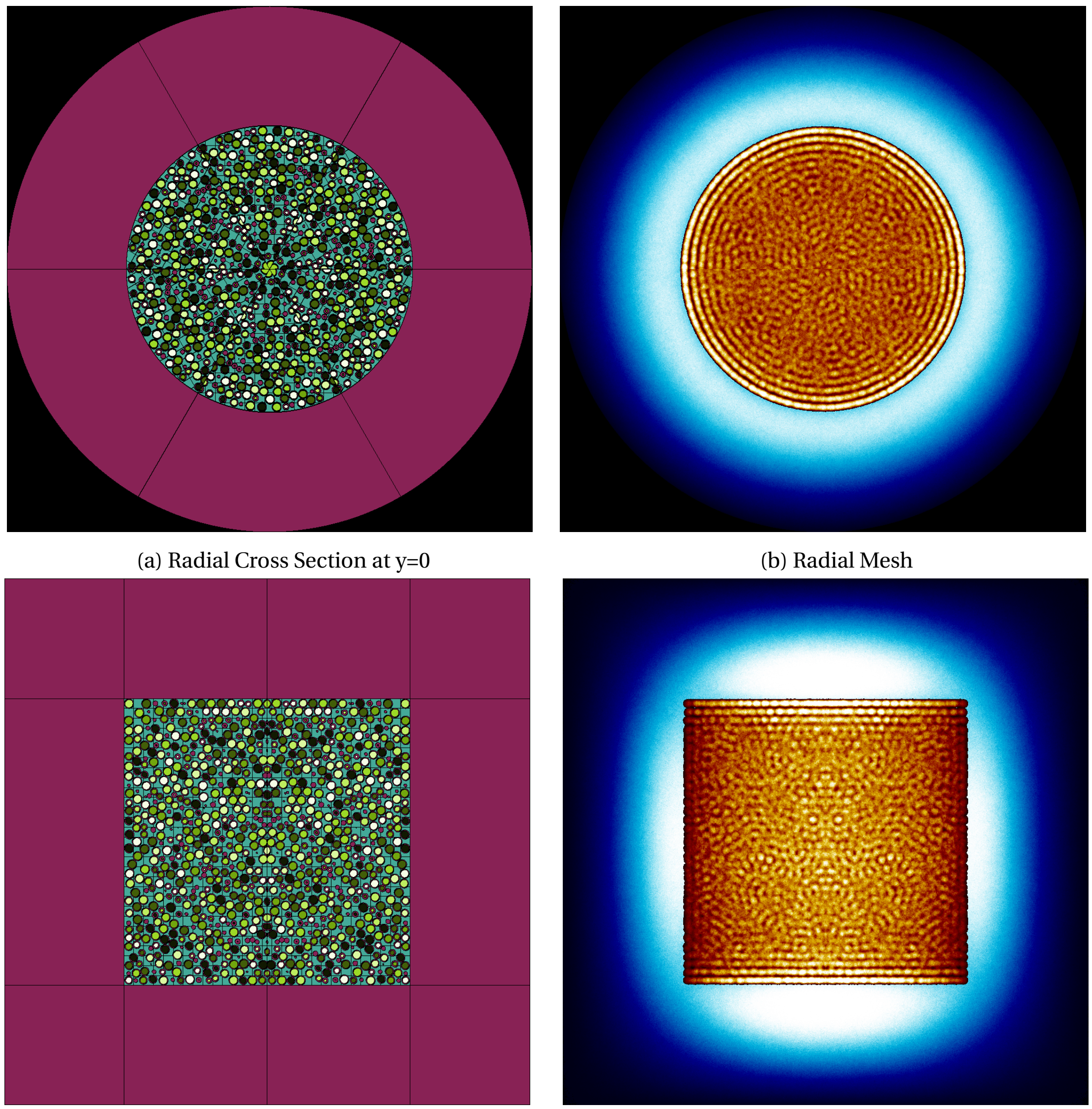


(c) Axial Cross Section at z=0



(d) Axial Mesh

Figure 4.5: Sensitivity Analysis: 180° - 240°



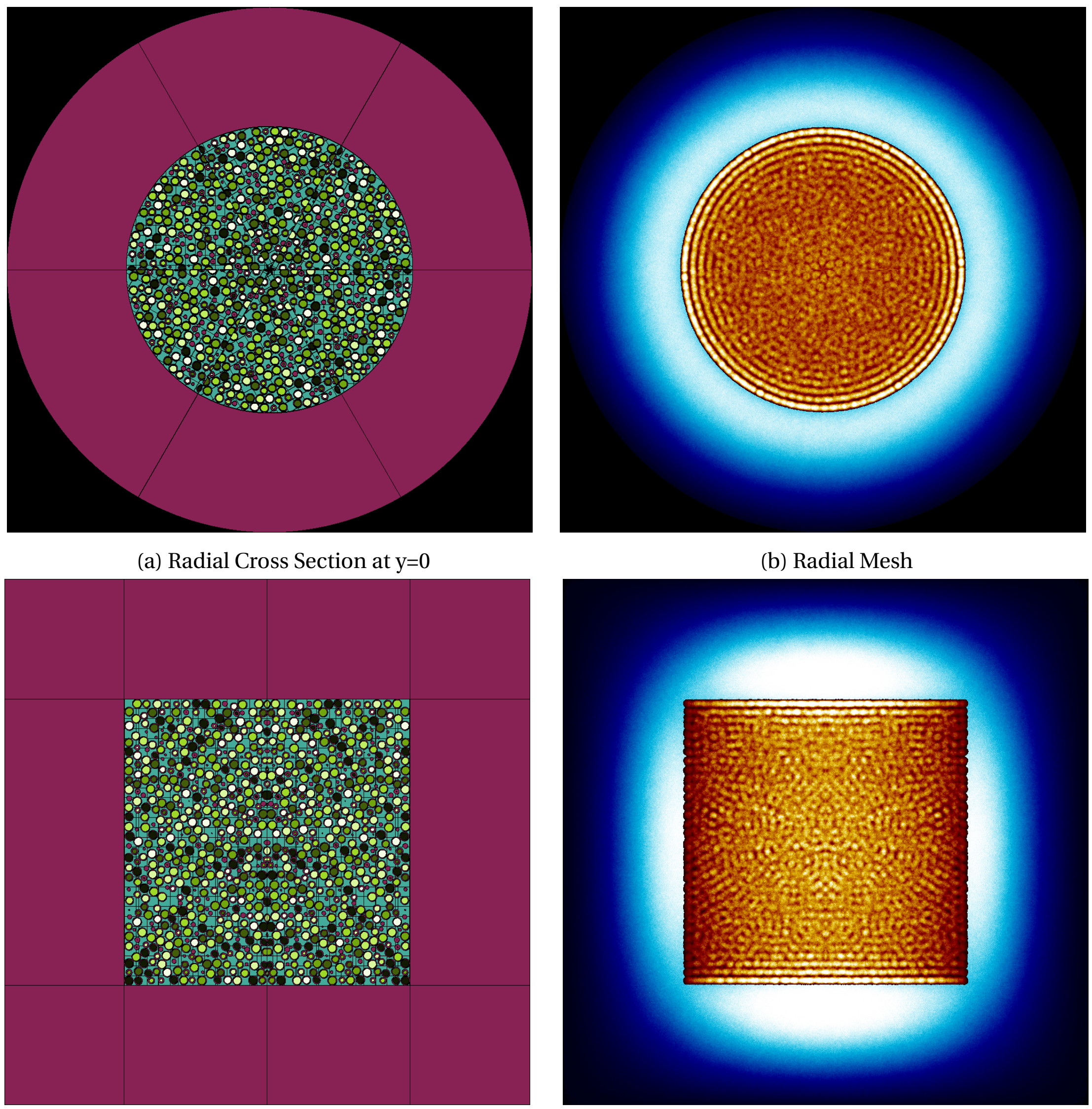
(a) Radial Cross Section at y=0

(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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