2018

MONTE CARLO SIMULATIONS OF THE THREE-DIMENSIONAL NEUTRON FLUX PROFILE INSIDE THE R.I.N.S.C. REACTOR

Benjamin Iannitelli
University of Rhode Island, biannitelli@gmail.com

Follow this and additional works at: <https://digitalcommons.uri.edu/theses>

Recommended Citation

Iannitelli, Benjamin, "MONTE CARLO SIMULATIONS OF THE THREE-DIMENSIONAL NEUTRON FLUX PROFILE INSIDE THE R.I.N.S.C. REACTOR" (2018). *Open Access Master's Theses*. Paper 1296.
<https://digitalcommons.uri.edu/theses/1296>

This Thesis is brought to you for free and open access by DigitalCommons@URI. It has been accepted for inclusion in Open Access Master's Theses by an authorized administrator of DigitalCommons@URI. For more information, please contact digitalcommons-group@uri.edu.

MONTE CARLO SIMULATIONS OF THE THREE-
DIMENSIONAL NEUTRON FLUX PROFILE INSIDE THE

R.I.N.S.C. REACTOR

BY

BENJAMIN IANNITELLI

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

MECHANICAL ENGINEERING AND APPLIED MECHANICS

UNIVERSITY OF RHODE ISLAND

2018

MASTER OF SCIENCE THESIS
OF
BENJAMIN IANNITELLI

APPROVED:

Thesis Committee:

Major Professor Bahram Nassersharif

Cameron Goodwin

Yana Reshetnyak

Nasser H. Zawia
DEAN OF THE GRADUATE SCHOOL

UNIVERSITY OF RHODE ISLAND
2018

ABSTRACT

This study sought the neutron flux profile inside of the Rhode Island Nuclear Science Center (RINSC) reactor. A computer model was made of the three-dimensional reactor core and simulations were run utilizing the Monte Carlo method and actual data specific to this reactor.

Heat map plots of the neutron flux show that the results for total fluence and thermal fluence are consistent with what the applicable physics would lead one to expect for the spatial profile of flux (or fluence) for either energy group. Moreover, the results for thermal fluence were parsed and rendered into 2D plots. This enabled comparison to the plots from the flux mapping measurements that followed the conversion to low-enriched uranium (LEU) fuel in 1992 at the RINSC research reactor.

The model developed as part of this work will form a foundation for future studies on the effects of fuel aging and burnup on flux characteristics within the experimental neutron irradiation facilities in the RINSC reactor.

ACKNOWLEDGMENTS

The central question of any thesis is not easy in the first place; on top of that life doesn't just make room for grad school. I would like to thank a substantial roster for this opportunity:

- my major professor, Dr. Nassersharif, for the travel support for the MCNP class, and for help and guidance throughout graduate school;
- Dr. Goodwin and the R.I.N.S.C. staff, for all kinds of support at relativistic speeds;
- Dr. Sai-Chi Mo of Argonne National Laboratory, for sharing his pre-existing model of the R.I.N.S.C. core;
- Jennifer Alwin of Los Alamos National Laboratory, for myriad pointers refining the model;
- Dr. Forrest Brown and Donna Pimentel of Los Alamos National Laboratory, for the opening in the MCNP Criticality Calculations class;
- my thesis committee: Drs. Nassersharif, Goodwin, and Reshetnyak, for hanging on despite the twists and turns;
- Ralph Kfoury, for guidance using PBS/Torque;
- Jim Byrnes, Engineering / IT Support for the Department of Mechanical, Industrial & Systems Engineering, for little downtime and plenty of computing power;
- and last but certainly not least my family, for more support than words can do justice, in more ways than can be counted, despite everything fate threw our way!

TABLE OF CONTENTS

ABSTRACT	ii
ACKNOWLEDGMENTS	iii
TABLE OF CONTENTS.....	iv
LIST OF TABLES	v
LIST OF FIGURES	vi
CHAPTER 1	1
INTRODUCTION	1
CHAPTER 2	6
METHODOLOGY.....	6
CHAPTER 3	18
FINDINGS	18
CHAPTER 4	48
CONCLUSIONS.....	48
APPENDICES	62
BIBLIOGRAPHY	126

LIST OF TABLES

TABLE	PAGE
Table 1: Percentage of fissions caused by neutrons of each group. “All energies” has been added for convenience; the rest of the content came directly from the simulation results.	45

LIST OF FIGURES

FIGURE	PAGE
Figure 1: Schematic of LEU Core 6 for the RINSC reactor ¹ . Regions of particular interest are cell D-5 and row 9.	2
Figure 2: RINSC LEU Core #2 ¹⁰	8
Figure 3: Scatter plot of a parameter study which varied two independent parameters: the binning of the tally mesh per the “z” direction (“Z_RES”), and the starting histories per cycle (“n/cyc”). The binning at all of the margins in all directions was set to match Z_RES. The data demonstrate that the finer the mesh, the slower the simulation will run (after controlling for starting histories per cycle). Also, the more starting histories per cycle the slower the simulation will run (after controlling for mesh resolution).	14
Figure 4: Scatter plot of a parameter study which varied two independent parameters: the side length of each core voxel per “x” and “y”, and the resolution of the mesh at its margins. Both of these contribute independently to the total number of voxels formed by the mesh, which is the independent variable depicted in this plot. (Resolution of the mesh per “z” within the core grid was set to 1 in this parameter study.) The data show that the finer the mesh is made, the slower the simulations run.	14
Figure 5: Scatter plot of a parameter study which varied two independent parameters: the side length of each core voxel per “x” and “y”, and the resolution of the mesh at its margins. (Resolution of the mesh per “z” within the core grid was set to 1 in this parameter study; this is the same study already depicted in Figure 4.) The data	

demonstrate in this plot that even after accounting for core voxel side length, the time cost incurred by the margins of the mesh can be substantial. For example, the finest margin resolution in this parameter study (70) counter-acted the coarsest core voxel side length (1 cm) so greatly that the time cost is almost equal to that of the finest core voxel side length (0.127 cm) and a margin resolution of 10. (The latter was faster than the former by about 4 seconds.) 15

Figure 6: Scatter plot of a parameter study which varied two independent parameters: the side length of each core voxel per “x” and “y”, and the resolution of the mesh at its margins. (Resolution of the mesh per “z” within the core grid was set to 1 in this parameter study; this is the same study already depicted in Figure 4 and Figure 5.) The data demonstrate in this plot that after accounting for margin resolution, finer and finer core voxels slow the simulations. 15

Figure 7: MCNP neutron flux type “B” mesh tally for all energies (total fluence per source particle history) for the RINSC reactor, in the form of a heat map. 20

Figure 8: MCNP neutron flux type “B” mesh tally for all energies (total fluence per source particle history) for the RINSC reactor, in the form of a heat map. 21

Figure 9: MCNP neutron flux type “B” mesh tally for all energies (total fluence per source particle history) for the RINSC reactor, in the form of a heat map. In this plot the regulating rod is visible to the left of center, reaching roughly halfway down..... 22

Figure 10: MCNP neutron flux type “B” mesh tally for all energies (total fluence per source particle history) for the RINSC reactor, in the form of a heat map. This plot shows shim safety blades 3 (left) and 4 (right). 23

Figure 11: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for all energies (relative error for total fluence per source particle history) for the RINSC reactor.	25
Figure 12: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for all energies (relative error for total fluence per source particle history) for the RINSC reactor.	26
Figure 13: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for all energies (relative error for total fluence per source particle history) for the RINSC reactor.	27
Figure 14: MCNP neutron flux type “B” mesh tally for thermal energies (thermal fluence per source particle history) for the RINSC reactor, in the form of a heat map.	29
Figure 15: MCNP neutron flux type “B” mesh tally for thermal energies (thermal fluence per source particle history) for the RINSC reactor, in the form of a heat map.	30
Figure 16: MCNP neutron flux type “B” mesh tally for thermal energies (thermal fluence per source particle history) for the RINSC reactor, in the form of a heat map.	31
Figure 17: MCNP neutron flux type “B” mesh tally for thermal energies (thermal fluence per source particle history) for the RINSC reactor, in the form of a heat map. This plot shows shim safety blades 3 (left) and 4 (right).	32
Figure 18: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for thermal energies (relative error for thermal fluence per source particle	

history) for the RINSC reactor. This plot shows column F, and the relative error is less than 10% everywhere of interest except for a small region at the top of F-9 (green)..	34
Figure 19: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for thermal energies (relative error for thermal fluence per source particle history) for the RINSC reactor. This plot shows row 9.	35
Figure 20: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for thermal energies (relative error for thermal fluence per source particle history) for the RINSC reactor. This plot shows column B.....	36
Figure 21: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for epithermal energies (relative error for epithermal fluence per source particle history) for the RINSC reactor.	38
Figure 22: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for epithermal energies (relative error for epithermal fluence per source particle history) for the RINSC reactor. This plot shows row 9.	39
Figure 23: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for epithermal energies (relative error for epithermal fluence per source particle history) for the RINSC reactor. This plot shows column D.....	40
Figure 24: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for fast energies (relative error for fast fluence per source particle history) for the RINSC reactor.	42
Figure 25: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for fast energies (relative error for fast fluence per source particle history) for the RINSC reactor.	43

Figure 26: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for fast energies (relative error for fast fluence per source particle history) for the RINSC reactor.	44
Figure 27: <i>keff</i> versus iteration cycle for the chain of simulations in this study.	46
Figure 28: Shannon entropy for the simulated neutron source versus iteration cycle for the chain of simulations in this study.	47
Figure 29: The results of this study along row 5 starting from the center of the grid, running toward and then through column A to the surrounding water, normalized by their maximum. For convenience, the horizontal increment is half of a grid unit.	49
Figure 30: Results of the 1992 flux mapping along the height of D5 of the core grid ¹² . Measurements (the crosses) were taken at various power levels, but are presented in this figure (from the original article) normalized to the power level of 2 MW ¹²	51
Figure 31: Measurements from the 1992 flux mapping of the RINSC core ¹² (blue) co-plotted with the results of this study (red). Each data set has been normalized to its respective maximum, allowing a comparison of spatial profiles. Both sets of data pertain to section D5 of the core grid.	52
Figure 32: Results of the 1992 flux mapping along the height of D9 of the core grid ¹² . Measurements (the crosses and squares) were taken at various power levels, but are presented in this figure (from the original article) normalized to the power level of 2 MW ¹²	53
Figure 33: Measurements from the 1992 flux mapping of the RINSC core ¹² (blue) co-plotted with the results of this study (red). Each data set has been normalized to its	

respective maximum, allowing a comparison of spatial profiles. Both sets of data pertain to section D9 of the core grid.....	54
Figure 34: Results of the 1992 flux mapping along row 5 of the reactor grid ¹² . The crosses represent measurements taken at low power; the dashed line represents the profile predicted by the mapping team; the solid vertical lines represent the boundaries of the LEU core ¹² . Measurements were taken at various power levels, but are presented in this figure (from the original article) normalized to the power level of 2 MW ¹²	55
Figure 35: Measurements from the 1992 flux mapping of the RINSC core ¹² (blue) co- plotted with the results of this study (red). Each data set has been normalized to its respective maximum, allowing a comparison of spatial profiles. Both sets of data pertain to row 5 of the core grid.....	56
Figure 36: Measurements from the 1992 flux mapping of the RINSC core ¹² (blue) co- plotted with the results of this study (red). Each data set has been normalized to its respective maximum, allowing a comparison of spatial profiles. Both sets of data pertain to row 5 of the core grid.....	56
Figure 37: Results of the 1992 flux mapping along column “D” of the reactor grid ¹² . The crosses represent measurements taken at low power; the dashed line represents the profile predicted by the mapping team; the solid vertical lines represent the boundaries of the LEU core ¹² . Measurements were taken at various power levels, but are presented in this figure (from the original article) normalized to the power level of 2 MW ¹²	57

Figure 38: Measurements from the 1992 flux mapping of the RINSC core ¹² (blue) co-plotted with the results of this study (red). Each data set has been normalized to its respective maximum, allowing a comparison of spatial profiles. Both sets of data pertain to column D of the core grid.	58
Figure 39: Measurements from the 1992 flux mapping of the RINSC core ¹² (blue) co-plotted with the results of this study (red). Each data set has been normalized to its respective maximum, allowing a comparison of spatial profiles. Both sets of data pertain to column D of the core grid.	58
Figure 40: “before” (left) and “after” (right) for an instance of the “water pillar” problem. The input decks resulting in these plots were made from the full model and then modified to isolate columns F and G of the core grid.	71
Figure 41: MCNP neutron flux type “B” mesh tally for all energies (total fluence per source particle history) for the RINSC reactor, in the form of a heat map. This plot shows row 9.	108
Figure 42: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for all energies (relative error for total fluence per source particle history) for the RINSC reactor. This plot shows column F.	109
Figure 43: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for all energies (relative error for total fluence per source particle history) for the RINSC reactor. This plot shows row 9.	110
Figure 44: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for all energies (relative error for total fluence per source particle history) for the RINSC reactor. This plot shows column D.	111

Figure 45: MCNP neutron flux type “B” mesh tally for thermal energies (thermal fluence per source particle history) for the RINSC reactor, in the form of a heat map. This plot shows row 9.	112
Figure 46: MCNP neutron flux type “B” mesh tally for thermal energies (thermal fluence per source particle history) for the RINSC reactor, in the form of a heat map. This plot shows column D.	113
Figure 47: MCNP neutron flux type “B” mesh tally for thermal energies (thermal fluence per source particle history) for the RINSC reactor, in the form of a heat map. This plot shows column B.	114
Figure 48: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for thermal energies (relative error for thermal fluence per source particle history) for the RINSC reactor.	115
Figure 49: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for thermal energies (relative error for thermal fluence per source particle history) for the RINSC reactor.	116
Figure 50: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for thermal energies (relative error for thermal fluence per source particle history) for the RINSC reactor.	117
Figure 51: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for thermal energies (relative error for thermal fluence per source particle history) for the RINSC reactor. This plot shows column D.	118

Figure 52: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for epithermal energies (relative error for epithermal fluence per source particle history) for the RINSC reactor.....	119
Figure 53: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for epithermal energies (relative error for epithermal fluence per source particle history) for the RINSC reactor.....	120
Figure 54: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for epithermal energies (relative error for epithermal fluence per source particle history) for the RINSC reactor. This plot shows column B.....	121
Figure 55: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for fast energies (relative error for fast fluence per source particle history) for the RINSC reactor.	122
Figure 56: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for fast energies (relative error for fast fluence per source particle history) for the RINSC reactor.	123
Figure 57: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for fast energies (relative error for fast fluence per source particle history) for the RINSC reactor. This plot shows column F.....	124
Figure 58: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for fast energies (relative error for fast fluence per source particle history) for the RINSC reactor. This plot shows row 9.....	125

CHAPTER 1

INTRODUCTION

A great many uses have been (and continue to be) devised for the reactor at RINSC; many of these uses rely on deliberately activating a material with neutrons. Often when one irradiates an object, one has a goal in mind, and often this ultimate goal creates an intermediate goal of using a certain amount of neutron flux. This study was conducted to determine the neutron flux profile inside of the Rhode Island Nuclear Science Center (RINSC) reactor. A computer model was made of the three-dimensional reactor core and simulations were run, utilizing the Monte Carlo simulation code MCNP6 and actual data specific to this reactor.

For projects which involve activating a specimen directly inside the core of RINSC's reactor, exposing the specimen to only a certain amount of neutron flux would require knowing that flux profile inside of the reactor and particularly in irradiation facilities at the center of the core, in the perimeter of the core, and at the bottom of the core. That radiation bombarding an arbitrary specimen, in the form of neutrons from fission, depends not only on the positioning of the control blades, but also on the geometry of the reactor. Suppose a plan is in place to irradiate a specimen at a certain height in a certain radiation basket, at a certain power level, based on a measurement recently made at that particular position in the core. Absent a reliable spatial flux profile, there is reason to wonder whether the same desired activation could be achieved at a different position using less power. There may even be reason

to question how well the shape of the irradiation target suits the desired outcome. Thus, the profile of the neutron flux in RINSC's reactor promised to be especially useful information for the many applications of neutron activation. Once able to account for the influence of geometry on neutron activation, designers of experiments or of applications would be able to optimize their use of the neutron radiation. This could guide where they place their items in the reactor (Figure 1).

Figure 1: Schematic of LEU Core 6 for the RINSC reactor¹. Regions of particular interest are cell D-5 and row 9.

Knowledge of the profile of the neutron flux would also help the RINSC staff. It would serve them in their safety and maintenance tasks to know how they should expect the radiation to be distributed, as the reactor is the largest single source of ionizing radiation in the entire facility. It may additionally benefit them while operating the reactor, as it may unexpectedly become relevant to an application of the reactor for neutron activation.

Deterministic treatments of neutron transport are well-suited to simple geometries: infinite fissile slabs, infinite fissile cylinders, *etc*²⁻⁴. Introducing reality means introducing boundary conditions and solving not one differential equation but a system thereof²⁻⁴. Some solutions are more approximate than others, and require additional efforts to ensure validity^{2,4}. The more complex (and realistic) the geometry, the more complex the neutron transport. With fuel pins, pellets, and wafers plausibly numbering in the hundreds and spanning only centimeters (or less) in some dimensions^{2,5}, the concerns of a purely calculus-based approach are substantive, inevitable, and inevitably complex.

Concerns like these motivated the invention of the Monte Carlo method, originally inspired by the need to simulate the behavior of fissionable materials^{6,7}. The Manhattan Project required a reliable probabilistic simulation of fission within the nuclear bomb to ensure a successful test of the prototype⁶. While the interactions of subatomic particles and nuclei can be described by an integro-differential equation, it happens that this governing equation does not lend itself to a purely deterministic approach. Often an analytical solution does not exist or does not fit the given conditions^{6,8}. For this reason, the Monte Carlo method introduces an element of

probabilistic methods. When a governing equation (in this case and the original, neutron transport) cannot indicate what should happen to one simulated particle of many, the computer makes a random choice guided by actual probabilistic data until it has enough inputs to make the remainder of its outputs based on the governing equation^{6,8}. In modeling neutron transport, Monte Carlo software will randomly choose whether each neutron in its simulations is absorbed or scattered by the next nucleus with which it collides (guided by actual probabilistic data), in the event of absorption it will then randomly choose when that nucleus decays, and after all random selections have been made it will calculate momentum and new positions for all of the particles⁶⁻⁸. Thus, the Monte Carlo method blends probabilistic and deterministic methods by beginning with one and finishing with the other.

Since 1986, Argonne National Laboratory (ANL) has helped model the RINSC reactor using MCNP^{9,10}. MCNP, short for “Monte Carlo N-Particle”, is a mature tool developed and maintained by Los Alamos National Laboratory, which claims most of the earliest pioneers both in radiation transport and in the Monte Carlo method itself^{6,7,11}. One of those many MCNP simulations, was a criticality projection in anticipation of the conversion to low-enrichment uranium (LEU) fuel¹⁰.

Shortly after the conversion of RINSC’s fuel elements from high-enrichment uranium (HEU) to LEU, a team formed of URI physicists and the Rhode Island Atomic Energy Commission mapped the flux profile with actual measurements, at multiple power levels¹². The flux mapping surveyed the reactor core and many immediate surroundings.

Later, with help from Brookhaven National Laboratory, RINSC staff simulated both the neutron flux and gamma radiation profile in the thermal column, which is used to irradiate samples outside the core⁹.

Early this century, a URI senior mapped the neutron flux in the dry irradiation room¹³.

This work, developing an MCNP model of the RINSC reactor to model the neutron flux inside the core, is new and had not been previously attempted.

CHAPTER 2

METHODOLOGY

The methodology of this study is summarized as follows:

- Model the reactor in MCNP.
- In the model, employ a “mesh tally” to get a flux score, broken into sub-regions by a mesh.
- Adjust the parameters of the model as appropriate until results converge in the regions of interest.

Modeling the reactor

The MCNP model used in this study is an adaptation of one originally completed in 1998 by Dr. Sai-Chi Mo of Argonne National Laboratory. Not long before work began on that version of the model, RINSC underwent a conversion from high-enrichment uranium fuel (HEU) to low-enrichment uranium fuel (LEU)¹⁰. This modification prompted further modifications to optimize the use of the LEU fuel, which was simulated using MCNP 4C¹⁰. The 1998 MCNP model used the then-available cross section data libraries corresponding to ENDF/B-VI data, and the model used MCNP’s KCODE feature to predict the effective multiplication factor, k_{eff} , of the RINSC reactor. That model compared the HEU core configuration with the proposed new LEU configurations¹⁰. The relevant geometry for the original simulation proved only to be the immediate three-dimensional region of the core assembly and nearest face of the thermal column of the reactor⁵.

Further development of the model had two basic aspects: 1) model changes for MCNP6 (released in 2013¹⁴), and 2) enhancing the model for neutron flux calculations. Since the time of the 1998 model, MCNP underwent significant changes. Version 4 was succeeded by Version 5, which was in turn succeeded by Version 6¹⁵. More accurately, Version 6 is a merger of the previously-separate forks of MCNP which had culminated in versions “5” and “X”, respectively¹⁵. This had many practical implications for modifying the 1998 model for use with the most recent available version at the time, *i.e.* MCNP6.1.0. Since MCNP is a mature program offered for all of the most commonly available computer platforms, hardware concerns were largely negligible and modification was largely a result of the software changes between ver. 4C and 6^{15,16}. The differences between versions 4C and 6.1.0 required many changes to the input model.

Thus the initial 2015 input model developed for this study was based on the 1998 MCNP4C model –a model of the 1998 core. But the 2015 core configuration had changed compared with the 1998 core^{1,10}. The 1998 model represented a configuration which RINSC designated “LEU Core 2”(see Figure 2), and RINSC had since moved on to LEU Core 6 (Figure 1)^{1,10}. Thus it was necessary to change the configuration in the MCNP model, and the initial 2015 MCNP model of the 1998 core began its evolution into the 2015 model of LEU Core 6. Accomplishing these configuration changes in the model comprised changing universe numbers in the fill assignments for the mid-level, lattice cells.

Figure 2: RINSC LEU Core #2¹⁰

While necessary that it use the 2015 configuration, the model was not truly “the 2015 model” until it asked the right question of MCNP. The 1998 model was made to find the steady-state effective multiplication factor of the reactor⁵; the goal of this project was to predict the spatial profile of the neutron flux for the reactor.

Changes to Implementation of Geometry

On the recommendation of Jennifer Alwin from Los Alamos, one change made to the model in a departure from the 1998 version was that the plane and infinite cylinder surfaces used in the model to define rectangular prisms and “finite” right cylinders were replaced with the equivalent macrobody surfaces: rectangular parallelepiped

(rpp), and right circular cylinder (rcc). This made the input deck simpler for a human being to parse. Macrobody surfaces provide the abstraction of being one finite, enclosed surface, which often renders the geometrical description of a cell much simpler than the equivalent using non-macrobody surfaces¹⁵. For example, the cell card for the very first wafer of fuel meat defined in the input deck was originally written⁵:

```
54 1 5.36392E-02 106 -107 +313 -314 +501 -502 trcl=0 u=1 imp:n=1
$meat 1
```

Substituting a macrobody surface (labeled “6”) leads to the following:

```
54 1 5.36392E-02 -6 trcl=0 u=1 imp:n=1 $meat 1
```

The difference is more substantial in the surface block. The original six surfaces corresponding to the aforementioned cell originally appeared as follows:

```
106 px 0.8445 $meat x plane 1
107 px 6.9275 $meat x plane 2
313 py 0.1801 $clad-meat 1
314 py 0.2309 $meat-clad 1
501 pz -0.00001 $fuel element z plane 1
502 pz 59.6900 $fuel element z plane 2
```

Whereas the macrobody replacement was:

```
6 rpp 0.8445 6.9275 0.1801 0.2309 -1e-005 59.69 $cell 54
```

Leveraging the macrobody feature of MCNP 6.1.0 enabled the reduction of the surface block of the input deck from 302 surface definitions to 185, for a net reduction of 117 lines.

Units

What the makers of MCNP refer to as a “flux tally” is more accurately a fluence tally; it is based on distance traveled by each particle where the formula for flux would use particle speed. Users are instructed to interpret the units of their results one way should their problem be steady-state, and another way otherwise¹⁵. Whichever kind of tallies the user employs (current, “flux”, heating, etc.), the steady-state modification is “per unit source time”¹⁵. For example, what is referred to as a “current tally” has units

of particles unless the problem is steady-state, in which case the units are particles per unit source time¹⁵. This raises the issue of what is meant by “unit of source time”. It depends on what the simulator meant for it to mean. If it is known beforehand that the simulation will correspond to a certain, fixed time rate of particles in a steady-state treatment, then the time unit in that time rate carries on to the final tallies; if instead a certain number of source particles are known to contribute to whatever transpires, then there is no unit of source time by which to divide the final results¹⁷. The KCODE feature of MCNP is derived from a steady-state case of Boltzmann neutron transport¹⁸. However, there was no time rate of particles nor a fixed total of source particles in the context of this study –nor should there have been. In general, the state of a reactor (k_{eff}) stipulates the ratio of one generation of neutrons to the preceding generation, not either generation. This study and its results are such that one can “just add time” in future studies. Thus the “flux tally”, despite its name, is fluence per starting particle. Fortunately, the central question was not “what is the flux” but “what is the spatial profile of the flux”, and it will be demonstrated that regardless of what a flux tally is or is not it has the same shape, and thus gives the shape.

Mesh Tally

Toward answering the new question, it proved necessary to utilize an MCNP feature known as a “mesh tally” -specifically superimposed mesh tally B, “fmesh”. Whereas the “normal” (non-mesh) tallies largely rely upon describing the region of interest in terms of the same cells or surfaces used in defining the geometry of the problem, mesh tallies require the user to define a mesh¹⁵. For mesh tallies in general the user has his or her choice of coordinate system from Cartesian, cylindrical, or

spherical, and the option to apply a coordinate transformation if doing such is more convenient in defining the mesh¹⁵. The definition of the mesh is independent of cell and surface labels¹⁵. Some users may find this independence more convenient than the protocol for “normal” tallies, especially if they think of the regions of interest for their tallies independently of the cell and surface labels.

The “fmesh” tool of MCNP offers as one of its features several choices for the format of the output of each mesh tally¹⁵. Each format has different advantages which lend themselves best to different use cases. For this study, the “CF” format was used. The advantage of “CF” over any of the “matrix/array” formats is that it is easy to parse for any researcher who has to “roll his own” post-processing scripts. The advantage over the default columnar format (“COL”) concerns two additional columns in “CF”, which are the only difference between these two formats¹⁵. The first of these additional columns is for the volume of each bin¹⁵. The second of these additional columns holds for each respective bin the product of the volume and the tally result¹⁵. A key step in generating tally results (of this kind) at each bin is to divide the pending result by bin volume^{15,17}. In some situations, *e.g.* comparing the results of this study to the results of others’ work, it later becomes necessary to un-do the division by bin volume. At best that would mean a careful employment of the “FM” tally multiplier card, if the need is known in advance. Otherwise it may require expending time and effort post-processing to un-do the normalization per bin volume, including the tedious effort of verifying and validating the post-processing. Worse yet, it may require re-running the problem with a different mesh definition. Thus the “CF” option saves human time and effort pre-processing and post-processing.

The mesh defined for the “fmesh” tally was not binned per time, as the focus of this study was the spatial profile. As for energy, the tally was binned for thermal, epithermal, fast, and total. The energy thresholds for these groups were borrowed from MCNP, in which they are hard-coded into the KCODE output: thermal 0.625 eV and less; epithermal from 0.625 eV to 100 keV; and fast 100 keV and higher.

For binning with respect to space the core grid was the main concern. Identical rectangular prism voxels were superimposed onto it, which were square with respect to “x” and “y”. The mesh for this study was extended around the rectangular prism of the core grid by a margin of one grid unit outward from the core grid in each direction. The subdivisions for the margin were copied from those for the core grid along “z”. The way that FMESH is implemented binning by space is normally a matter of specifying into how many bins an interval will be divided^{15,17}; instead in this study formulas were employed to specify voxel side length in centimeters and then convert it to the appropriate binning with respect to “x” and “y”.

Correction of model parameters

It is not obvious how thick the voxels of the mesh should be, nor how many total iteration cycles will be needed. Nor is it apparent how many of those iteration cycles should be discarded. Inevitably one must pick a number; one does not know which numbers to pick until one tries.

At first the mesh parameters were to be determined one direction at a time, but the decision to match the “x” dimension and the “y” dimension simplified the process into determining binning for “non-z” and then for “z”. For each of these two direction sets, intuitively non-taxing values were arbitrarily chosen for the parameters not of

immediate concern, and then a parameter study was performed on the binning for each direction set. The “non-z” parameter study also tested the impact of the binning options for the margin of the mesh. As source particle histories per cycle had not yet been decided, the “z” parameter study also varied the number of source particle histories per cycle, in case the parameter study data might lend themselves to extrapolation. Other parameter values set in these parameter studies would be unacceptable for estimating k_{eff} , but at this stage that was not the goal. Convergence did not matter in these mesh-refining parameter studies, as long as neutrons visited a broad-enough swath of the problem geometry to judge the mesh. Each case of each parameter study was concluded with plots of the mesh tally, and each parameter study was concluded with plots of the time cost of each test run (*e.g.*, Figure 3 through Figure 6). These enabled judgements of plot quality supplemented by time cost. The results of each parameter study were then combined to result in the final binning for the tally mesh. As part of the process for refining the mesh parameters, plot commands were produced and also refined for the sake of assessing the mesh, and these contributed greatly to the final set of commands used for the production run.

Figure 3: Scatter plot of a parameter study which varied two independent parameters: the binning of the tally mesh per the “z” direction (“Z_RES”), and the starting histories per cycle (“n/cyc”). The binning at all of the margins in all directions was set to match Z_RES. The data demonstrate that the finer the mesh, the slower the simulation will run (after controlling for starting histories per cycle). Also, the more starting histories per cycle the slower the simulation will run (after controlling for mesh resolution).

Figure 4: Scatter plot of a parameter study which varied two independent parameters: the side length of each core voxel per “x” and “y”, and the resolution of the mesh at its margins. Both of these contribute independently to the total number of voxels formed by the mesh, which is the independent variable depicted in this plot. (Resolution of the mesh per “z” within the core grid was set to 1 in this parameter study.) The data show that the finer the mesh is made, the slower the simulations run.

Figure 5: Scatter plot of a parameter study which varied two independent parameters: the side length of each core voxel per “x” and “y”, and the resolution of the mesh at its margins. (Resolution of the mesh per “z” within the core grid was set to 1 in this parameter study; this is the same study already depicted in Figure 4.) The data demonstrate in this plot that even after accounting for core voxel side length, the time cost incurred by the margins of the mesh can be substantial. For example, the finest margin resolution in this parameter study (70) counter-acted the coarsest core voxel side length (1 cm) so greatly that the time cost is almost equal to that of the finest core voxel side length (0.127 cm) and a margin resolution of 10. (The latter was faster than the former by about 4 seconds.)

Figure 6: Scatter plot of a parameter study which varied two independent parameters: the side length of each core voxel per “x” and “y”, and the resolution of the mesh at its margins. (Resolution of the mesh per “z” within the core grid was set to 1 in this parameter study; this is the same study already depicted in Figure 4 and Figure 5.) The data demonstrate in this plot that after accounting for margin resolution, finer and finer core voxels slow the simulations.

With the geometry finished, and the tally mesh defined, all that remained toward solving the problem was the KCODE card. The first parameter to be refined from its previous placeholder was the number of cycles to be discarded (hereafter labeled “ndiscard”, borrowed from Los Alamos for convenience¹⁸). In the course of pre-production efforts, *ndiscard* had been set to two hundred. If only the first fifty cycles needed to be discarded in a production run, discarding the next 150 cycles would constitute an appreciable waste. Thus, a parameter study was performed to test various values for *ndiscard* while leaving the other parameters at placeholder values. In addition to consulting convergence plots as Los Alamos recommends¹⁸, the source convergence information in each output file was directly consulted to directly check the effect of *ndiscard* on the Shannon entropy. With the other crucial parameters at placeholder values, there was a risk that production-run values for the other parameters would require a different *ndiscard* value than determined in this parameter study. Nevertheless, this parameter study would lend itself to extrapolation in that scenario. Also, wasted cycles in pre-production are undesirable if reasonably preventable. Thus *ndiscard* was the first to be refined, despite the risk of needing to re-refine it. Ultimately, one refinement proved adequate, and the final value for *ndiscard* was ten.

The next parameter to be refined was the number of source particle histories per iteration (“n_per_cyc” hereafter). For pre-production, Los Alamos recommends as little as one thousand or as many as five thousand for this parameter; in production runs they warn that more realistic values are from ten thousand to one hundred thousand –or even higher¹⁸. Here the risk of needing to re-refine the parameter was

more apparent than before, so the parameter study for n_per_cyc was done with extrapolation foremost in mind. The dependent variables of interest were running time, running time per total cycles, and running time per source particle. Plots for these quantities versus n_per_cyc showed appreciable noise, frustrating extrapolation. In hindsight, the extrapolation effort may not have been worthwhile for this study. Proper use of MCNP (and other Monte Carlo applications) requires that particles reach all the “nooks and crannies” enough not to miss relevant events which would transpire in those hard-to-reach regions^{8,15}. Thus, a test run which misses a hard-to-reach region only has so much in common with a production run in which particles reach everywhere, should the hard-to-reach region prove important. An effort such as this may still prove worthwhile to other users of MCNP working with simpler geometries. Ultimately, the value of ten thousand was settled upon for n_per_cyc . The total number of source particle histories is the product of n_per_cyc and the total number of active cycles¹, so more cycles can compensate for a low value of n_per_cyc .

No parameter study was needed for the initial guess of the criticality, as the iterative KCODE process of simulating neutron transport is self-correcting¹⁸. This was left at the very common value of 1. Similarly, no parameter study was needed for the total number of iterative cycles; the production run *is* “the parameter study”.

With production values for relevant input deck parameters settled, an initial simulation was run. This was followed by continuations with more iterative cycles until results reached acceptable precision.

¹ (total cycles) – ndiscard = (active cycles)

CHAPTER 3

FINDINGS

Scalar fluence is a scalar field with a three-dimensional domain. This document is a two-dimensional medium. As a text file, the full results are 1.3 gigabytes and 16,320,019 lines. Later drafts of this thesis are 17.9 megabytes, and a page of text and only text is 23 lines, double-spaced. Including those results as an appendix in this work would be to add 354,783 pages, single-spaced.

Fortunately, the results lend themselves to visualization in “heat map” form. The three-dimensional data was sliced into two-dimensional plots, with several points throughout the geometry serving as origins. Three plots were made at most of these points, each in one of the cardinal orientations of “xy”, “yz”, or “xz”. If all of the same heat maps used to assess the results were featured in this work, it would be a total of 124 pages of heat maps. Instead, only a select few will appear in this chapter, and several more will be included in an appendix.

MCNP predicts that the beryllium and graphite reflectors are substantial in concentrating the total fluence. Figure 7 shows a border running approximately through the center of the beryllium reflectors. In fact, these appear to be the greatest influence on the shape at all points exterior to them from the reference point of D5. In this way they appear to weigh heavily in explaining the fluence gradient in row 9, and in each radiation basket of row 9. If instead the fuel assemblies were most important, by a wide margin, one may have expected total fluence along row 9 to be most intense

in columns C and E with a slight dip in column D, and a more drastic decrease in intensity in columns B and F. Were the reflectors and fuel assemblies of approximately equal importance in determining the shape of the total fluence, one might have expected to see a compromise between the latter and the former. Instead, the reflectors appear to dominate. They dominate both outside and *inside*; the neutron fluence is very concentrated in D5 despite D5 lacking fuel. While source distribution matters, scattering helped the reflectors to “even out” the neutron transport. In other orientations the same phenomenon holds for total fluence, apparently because of the top and bottom reflectors. The control rods look like they are “squashing” the flux, when in fact they are “slurping it up” for largely the same effect on the shape.

Figure 7: MCNP neutron flux type “B” mesh tally for all energies (total fluence per source particle history) for the RINSC reactor, in the form of a heat map.

Figure 8: MCNP neutron flux type “B” mesh tally for all energies (total fluence per source particle history) for the RINSC reactor, in the form of a heat map.

Figure 9: MCNP neutron flux type “B” mesh tally for all energies (total fluence per source particle history) for the RINSC reactor, in the form of a heat map. In this plot the regulating rod is visible to the left of center, reaching roughly halfway down.

```

05/03/18 16:33:37
Ben's Adaptation of Dr. Mo's
Model of the RINSC Core

probid = 05/03/18 08:12:09
basis: YZ
( 0.000000, 1.000000, 0.000000)
( 0.000000, 0.000000, 1.000000)
origin:
( 43.49, 99.48, 68.36)
extent = ( 42.80, 42.80)

Mesh Tally 4
Spatial Profile of Neutron Flux
10000 n/cycle, .00077
210000 Core voxels (60 x 70 x
50),
each 1 cm square
Total Energy Bin
nps 10101442
runtpe = runtpe 10
dump

```

Figure 10: MCNP neutron flux type “B” mesh tally for all energies (total fluence per source particle history) for the RINSC reactor, in the form of a heat map. This plot shows shim safety blades 3 (left) and 4 (right).

It took more than ten million one hundred thousand starting particle histories to attain reliable results for total fluence in all of the regions of interest, as illustrated in Figure 11 through Figure 13.

Figure 11: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for all energies (relative error for total fluence per source particle history) for the RINSC reactor.

Figure 13: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for all energies (relative error for total fluence per source particle history) for the RINSC reactor.

For thermal fluence the beryllium and graphite reflectors influence the shape, as was the case in the plots for total fluence. However, the thermal fluence plots are consistent with absorption and moderation dominating the neutron transport above all else. The heat maps are “cold” with respect to thermal fluence in the fuel assemblies that consume the thermal neutrons for fission. Per “x” and “y”, the sleeves for the control rods are “hottest”. This is consistent with the influence of the beryllium reflectors. Also, it is consistent with the water in the control rod sleeves slowing faster neutrons incoming from elsewhere to thermal energies. With respect to “x” and “y”, the resulting profile is more spread-out than for total fluence. While D5 is bombarded with more thermal neutrons than row 9, the difference is less dramatic. Comparing the radiation baskets of row 9 to each other, the intra-row profile of the thermal fluence bears a strong resemblance to that for the total fluence. With respect to “z” the “slurping” effect of the shim safety blades is more dramatic for thermal fluence than for total fluence. The shape for total fluence resembles a nectarine with two sharp-cornered pieces cut from the top. Thermal fluence looks less like a nectarine and more like an apple.

Figure 14: MCNP neutron flux type “B” mesh tally for thermal energies (thermal fluence per source particle history) for the RINSC reactor, in the form of a heat map.

```

05/03/18 16:35:13
Ben's Adaptation of Dr. Mo's
Model of the RINSC Core

probid = 05/03/18 08:12:09
basis: xz
( 1.000000, 0.000000, 0.000000, 0.000000)
( 0.000000, 0.000000, 1.000000, 0.000000)
origin:
( 56.52, 99.48, 68.37)
extent = ( 42.80, 42.80)

Mesh Tally 4
Spatial Profile of Neutron Flux
10000 n/cycle, .00035
210000 Core voxels (60 x 70 x
50), .00026
each 1 cm square
Energy Range: 0 to 6.25-7 MeV
nps 10101442 .00017
runtpe = runtpe 10
dump
.000086
8.2-9

```

Figure 15: MCNP neutron flux type “B” mesh tally for thermal energies (thermal fluence per source particle history) for the RINSC reactor, in the form of a heat map.

Figure 16: MCNP neutron flux type “B” mesh tally for thermal energies (thermal fluence per source particle history) for the RINSC reactor, in the form of a heat map.

Figure 17: MCNP neutron flux type “B” mesh tally for thermal energies (thermal fluence per source particle history) for the RINSC reactor, in the form of a heat map. This plot shows shim safety blades 3 (left) and 4 (right).

It so happens that fluences of particular energy designations would require even more starting particle histories to attain the same precision as the total fluence. The green in some of the error plots requires arguing for or against a judgement call whereas the corresponding plots for total fluence are an objective matter of seeing only orange (5% or less) and cyan (5% to 10%). The results for thermal fluence are arguably “good enough”. The region covered reliably for thermal fluence was almost the same as that for total fluence, failing to meet it by a margin on the order of 1 cm (e.g. Figure 18). For many an application of the reactor, the imprecise (green) regions in Figure 18, Figure 19, and Figure 20 are irrelevant. It is implausible (if not impossible) to secure an object in those upper corners of B-9 and F-9, and unlikely to be desirable in the first place.

Figure 18: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for thermal energies (relative error for thermal fluence per source particle history) for the RINSC reactor. This plot shows column F, and the relative error is less than 10% everywhere of interest except for a small region at the top of F-9 (green).

Figure 20: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for thermal energies (relative error for thermal fluence per source particle history) for the RINSC reactor. This plot shows column B.

Results for epithermal fluence were less precise than for the aforementioned groups; the region of the center and fuel assemblies was reliably modeled but precision was lacking for row 9 of the grid. These problems are conveyed in Figure 21 through Figure 23. Figure 22 displays especially well the imprecision of the results for B-9 and F-9. The same figure shows that for each column in the remainder of row 9, an appreciable fraction is not precisely covered (though “appreciable” is subject to the context of applications).

Figure 22: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for epithermal energies (relative error for epithermal fluence per source particle history) for the RINSC reactor. This plot shows row 9.

Figure 23: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for epithermal energies (relative error for epithermal fluence per source particle history) for the RINSC reactor. This plot shows column D.

While adequately precise for the center and fuel assemblies, the relative error of the results for fast fluence was even more lacking in precision than for epithermal. The reasons for concern can be seen in Figure 24 through Figure 26. The same logic applies for the fast fluence results as for the epithermal; a comparison of the corresponding plots (e.g. Figure 19 against Figure 25) illustrates that the key difference is the extent of the precision problem. For fast fluence, useful precision does not extend as far from the center of the fuel assemblies as for epithermal.

Figure 24: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for fast energies (relative error for fast fluence per source particle history) for the RINSC reactor.

Figure 25: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for fast energies (relative error for fast fluence per source particle history) for the RINSC reactor.

Figure 26: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for fast energies (relative error for fast fluence per source particle history) for the RINSC reactor.

The pattern referenced in comparing precision of the fast flux tally to that of the epithermal extends to comparison amongst all of the energy designations. The larger pattern emerges that they can be ranked by the extent of precision from the center of the neutron source as follows, from least extent to furthest: fast, epithermal, thermal, and total. This coincides with the relative amount of each designation that one would

expect in the RINSC reactor or any simulation of it. This also agrees with the fissions attributed in the simulation to neutrons of each designation (Table 1).

Table 1: Percentage of fissions caused by neutrons of each group. “All energies” has been added for convenience; the rest of the content came directly from the simulation results.

Energy band	Percentage of fissions caused
fast (>100 kev)	1.17%
intermediate (0.625 ev - 100 kev)	7.60%
thermal (<0.625 ev)	91.23%
all energies	100.00%

Ignoring the blue in Figure 26 and instead addressing the yellow, much of the relative error for the fast flux tally reaches 25% in B-9. The standard deviation of a tally is treated as inversely proportional to the square root of the total number of particle histories, and the precision goal for a tally of this kind is 10% or less¹⁷. Getting satisfactorily precise results from MCNP in this case would likely require another 5.87 million starting particle histories in addition to the 10.1 million already simulated. If that is not “good enough” (by the justification already given in this study for the thermal fluence or perhaps by some other rationale), then one is not free to ignore the blue and from the plot the relative error reaches as high as 50%; more reliable fast fluence would require another 12.5 million starting particle histories in addition to the 10.1 million already simulated.

The convergence plots (Figure 27 and Figure 28) illustrate that whatever the concerns for the fluence of various groups, both k_{eff} and the Shannon entropy for the simulated neutron source converged long before the total fluence.

```

mcnp          6
probid:05/03/18 08:12:09
nps      10101442
runtime = runtime
dump      10
      kcode 16

```

Figure 27: k_{eff} versus iteration cycle for the chain of simulations in this study.

```

mcnp      6
probid:05/03/18 08:12:09
nps      10101442
runtime = runtime
dump     10
_____ kcode 6

```

Figure 28: Shannon entropy for the simulated neutron source versus iteration cycle for the chain of simulations in this study.

CHAPTER 4

CONCLUSIONS

Comparison to Differential-Equation-Based Modeling

Figure 29 shows the (normalized) results of this study along row 5, starting from the center of the grid, tracking toward and then through column A into the surrounding water. For convenience, the horizontal increment is half of a grid unit. Had the flux been modeled with the reactor equation in columns C, D, and E, and neutron diffusion elsewhere, the result would resemble Figure 29. The solution in columns C, D, and E would resemble the cosine curve of a bare reactor, widened overall and raised at the end of column C to accommodate the interface boundary conditions upon leaving the fuel-dominated region of the core. Between column C and column B, water dominates the transport as a moderator, partly aided by shim safety blades 3 and 4, which slow some neutrons despite absorbing others, overall causing thermal flux to rise nearer the beryllium reflectors of column B. In column B, the thermal neutrons would be expected to diffuse through the beryllium, necessitating a local maximum of thermal flux within column B to accommodate a decrease following an increase. The decrease would continue through column A, albeit more gradually, as the thermal neutron diffusion length for graphite is greater than that for beryllium in common operating conditions². After the graphite of column A, the remaining thermal neutrons reach water, and neutron diffusion theory would predict a rapid exponential decay of the thermal neutron flux, as the diffusion length for light water is much less than that for

graphite or beryllium². Thus, it is apparent that the results of this study are consistent with predictions from differential-equation-based theory.

Figure 29: The results of this study along row 5 starting from the center of the grid, running toward and then through column A to the surrounding water, normalized by their maximum. For convenience, the horizontal increment is half of a grid unit.

Comparison to Flux Mapping

Data from the flux mapping was only available in the form of 2D scatter plots (Figure 30, Figure 32, Figure 34, Figure 37), as opposed to heat maps or tables. This study was not immediately comparable to the flux mapping, and at first it appeared that comparison would require re-running the simulation. Fortunately, a work-around was devised.

In general, defining a new mesh would require re-running MCNP. However, in the special case that the newly desired mesh would amount to merely deleting some (not all) bin boundaries from the original (and not introducing any new boundaries), it is straightforward to filter and merge the results of the original run. Thus, 2D plots of the data from this study were obtained.

Subsequent to converting data into a 2D form, the problem remained of comparing flux to fluence per source particle. The former and the latter each were normalized by their respective maxima. This allowed a comparison of the spatial profile of one to the spatial profile of the other.

Thermal fluence through D5 as a function of height (Figure 31) was achieved by filtering out data external to D5 with respect to “x” and “y” and merging all remaining subsets of data with “z” in common into one datum per “z” bin. There is a resemblance along the height of the central irradiation basket. However, the two data sets differ at the top and bottom reflectors; the measurements were flat where instead the simulation curves up and then down. The simulation is consistent with diffusion theory²; the measurements (at the reflector heights) were not. The concurrence of diffusion theory with the simulation suggests that the flatness at the reflectors could be the symptom of a practical problem taking the measurements. One possible explanation for the difference is that foils placed at the height of the reflectors had to be placed beside them, as opposed to through them or in their place. Foils along the height of the radiation basket went inside the radiation basket, since it is hollow. This is impossible for the reflectors. The distance from the center line of the core grid to foils fixed beside the top and bottom reflectors may explain the discrepancy. Coordinates per “x” and “y” for the D5 measurements were not available at the time of this writing. In light of this, comparison to the measurements lends credence to the simulation.

Figure 30: Results of the 1992 flux mapping along the height of D5 of the core grid¹². Measurements (the crosses) were taken at various power levels, but are presented in this figure (from the original article) normalized to the power level of 2 MW¹².

Figure 31: Measurements from the 1992 flux mapping of the RINSC core¹² (blue) co-plotted with the results of this study (red). Each data set has been normalized to its respective maximum, allowing a comparison of spatial profiles. Both sets of data pertain to section D5 of the core grid.

For D9, all but one measurement was taken along the height of the radiation basket, which prevents conjecture on the reflector concerns previously described for D5. The distribution of the simulation results appears wider than that for the measurements; nevertheless a resemblance is apparent in Figure 33.

Figure 32: Results of the 1992 flux mapping along the height of D9 of the core grid¹². Measurements (the crosses and squares) were taken at various power levels, but are presented in this figure (from the original article) normalized to the power level of 2 MW¹².

Figure 33: Measurements from the 1992 flux mapping of the RINSC core¹² (blue) co-plotted with the results of this study (red). Each data set has been normalized to its respective maximum, allowing a comparison of spatial profiles. Both sets of data pertain to section D9 of the core grid.

The fact that the peaks with respect to height do not match exactly for D5 nor for D9 is not surprising, as it is likely that the constant control rod heights in this study do not match the time average of the control rod heights during the flux mapping measurements.

The results of this study were also filtered and merged for row 5 (Figure 35, Figure 36). These results resemble the calculations made by the mapping team (Figure 35), except at the core center –where instead they are closer to the mapping team’s actual measurements (Figure 36).

Figure 34: Results of the 1992 flux mapping along row 5 of the reactor grid¹². The crosses represent measurements taken at low power; the dashed line represents the profile predicted by the mapping team; the solid vertical lines represent the boundaries of the LEU core¹². Measurements were taken at various power levels, but are presented in this figure (from the original article) normalized to the power level of 2 MW¹².

Figure 35: Measurements from the 1992 flux mapping of the RINSC core¹² (blue) co-plotted with the results of this study (red). Each data set has been normalized to its respective maximum, allowing a comparison of spatial profiles. Both sets of data pertain to row 5 of the core grid.

Figure 36: Measurements from the 1992 flux mapping of the RINSC core¹² (blue) co-plotted with the results of this study (red). Each data set has been normalized to its respective maximum, allowing a comparison of spatial profiles. Both sets of data pertain to row 5 of the core grid.

Additionally, the results of this study were filtered and merged for column D (Figure 38, Figure 39). They are loyal to the measurements where there are

measurements (Figure 39), and the mapping team's calculations everywhere else (Figure 38).

Figure 37: Results of the 1992 flux mapping along column "D" of the reactor grid¹². The crosses represent measurements taken at low power; the dashed line represents the profile predicted by the mapping team; the solid vertical lines represent the boundaries of the LEU core¹². Measurements were taken at various power levels, but are presented in this figure (from the original article) normalized to the power level of 2 MW¹².

Figure 38: Measurements from the 1992 flux mapping of the RINSC core¹² (blue) co-plotted with the results of this study (red). Each data set has been normalized to its respective maximum, allowing a comparison of spatial profiles. Both sets of data pertain to column D of the core grid.

Figure 39: Measurements from the 1992 flux mapping of the RINSC core¹² (blue) co-plotted with the results of this study (red). Each data set has been normalized to its respective maximum, allowing a comparison of spatial profiles. Both sets of data pertain to column D of the core grid.

The thermal data from this study resemble those from the flux mapping conducted after the fuel element conversion, per the information available from the latter and simple variations on the mesh defined for the former.

Future Study

One idea for future study which was outside the scope of this study would be to employ the MCNP model to predict power generation. By necessity, the N in “Monte Carlo N -Particle” is orders of magnitude fewer than would be true; in typical usage millions of simulated particles represent moles of real particles¹⁸. What happens to each simulated particle will be a loyal representation (within reason) of what could happen to any single real particle⁷. Unfortunately, aggregated simulation results will inevitably understate real aggregate phenomena, owing to the dearth of particles contributing in the simulation. Fortunately, the former can compensate for the latter: simulated aggregate results will be proportional to the real aggregate phenomenon (Eq.1). For any desired quantity Q , the contribution per particle should be the same in both the simulation and reality. For this reason, tallies are normalized per starting particle history by default¹⁹. (In terms of Eq. 1, MCNP gives Q_{sim}/N_{sim} , as opposed to Q_{sim}).

$$\frac{Q_{sim}}{N_{sim}} = \frac{Q_{real}}{N_{real}} \quad 1$$

As this pertains to power generated by fission events in a reactor, the tally that one may colloquially refer to as a “power tally” does not predict the power which would have been generated in the reactor; it reports the volumetric density of the simulated power generation, normalized per simulated starting neutron. After the user (or MCNP, on the user’s behalf) converts the volumetric power density to power, the

results form the left-hand side of Eq. 2. If one wants to predict the real power, one must multiply the “power tally” by the real number of neutrons; if one wants the real number of neutrons, one must divide the real power by the “power tally”. MCNP supplies the left-hand side; the user must get the right-hand side some other way.

$$\frac{P_{sim}}{N_{sim}} = \frac{P_{real}}{N_{real}} \quad 2$$

Using data from RINSC’s control rod calibrations, one can ascertain the power in a real-world situation. One can simulate a change in power to correspond with this scenario, and then compare the power tally to the real power. The immediate result is that one has N_{real} for that scenario; the longer-term benefit is that one has the “gain” from the MCNP model to the reactor that it represents:

$$G = \frac{P_{real}}{P_{sim}} = \frac{N_{real}}{N_{sim}} \quad 3$$

Armed with the model-to-subject gain, one can put the model through arbitrary maneuvers, and then predict the corresponding power in the reactor.

Simulating a change from one state (k_{eff}) to another will require chaining together simulations in which the control rod heights are set to different positions, each run utilizing the “source tape” (“srctp”) file from the preceding run. If desired, the output can be “stitched” together to show power vs. time as the control rods are moved. To accomplish such a thing, there would be considerable computer scripting work to be done; computer hardware concerns would also need to be examined for feasibility.

With those concerns of “how” resolved, the “what” of model-to-subject gain would require a researcher to test either that the gain is constant or that it fits a pattern such that it could be used as proposed. Should such a practice be established to be

reliable, it would be a predictive tool for the RINSC staff that would free them to consider different parameters for proposed procedures by “tinkering” with them in simulations where before the cost of “tinkering” was too much to permit much of it (if any).

Another potential direction for future study would be to simulate burnup of RINSC’s fuel. As the fuel assemblies change, it is reasonable to expect a change in the spatial profile of the neutron flux. As to how would it change, one might employ MCNP toward making a prediction.

One of the surprises that emerged during this study was that the model’s response to the control rods does not match that of the actual reactor. At control rod heights for which the real reactor was critical when Core 6 began, the model is supercritical, in the interval $[1.04793, 1.04930]$ with 99% confidence. This difference is a compelling topic for future study.

Essentially, this study was a simulation of a flux mapping. In light of that, it is encouraging how closely it matched measurements. While MCNP modeling would never be a substitute for flux mapping, it shows tremendous promise as a supplement. Between mappings, RINSC will be empowered to make detailed predictions without burning uranium to make those predictions. More appreciable to the fiscally-minded, simulations will have lower labor costs than those of operating the reactor. Thus, while enjoying multiple kinds of economy, RINSC will gain a potent tool to compound their abilities in their mission to advance nuclear science and technology.

APPENDICES

The Challenges in Converting and Modifying an older input deck to a newer version program

Largely as a consequence of changes between versions 4C and 6.1.0 of MCNP, the model required modification merely to cease crashing. The necessary model changes ran a spectrum from things which prevented the model from running, to things which led to incorrect output, to things which led to inconveniently-presented output.

As mentioned earlier, in its specification of the materials for the simulation the original model used the cross-section data libraries available at the time corresponding to ENDF/B-VI data. It did not merely use these libraries by default; the original code explicitly specified their use⁵. That cross section data has not only been succeeded by more recent data but has been removed from the default library, so adaptation began with removing the library IDs, which referred to a cross section library no longer included in the basic MCNP package. This removal was merely to eliminate a fatal error² causing crashes, rather than to improve output per se, so selecting a more appropriate cross section library was deferred for future studies. In this study library IDs were omitted altogether, causing MCNP to use its default cross section data for each nuclide.

Thus fatal errors concerning missing cross section data were replaced by fatal errors stating that the source was rejected. Investigation of this problem uncovered a

² To be clear: “fatal error” is a term borrowed from the MCNP documentation to refer to any problem which will cause MCNP to crash, not to a life-or-death mishap¹⁵.

typo inherited from the version of the ANL model which had been shared with me. Specifically, that typo was that the surface reference defining cell 12 said “-20 21” (which translates out-of-context as “interior to surface 20 but exterior to surface 21”) where somebody must have meant “20 -21” (“exterior to surface 20 but interior to surface 21”). Thus a change was made from “-20 21” to “20 -21”³, and as a result the fuel assemblies were rendered in the geometry setup. It so happened that there would still be problems with the source definition, none of which would be diagnosable without first having solved the problem just described.

After this a blow-by-blow of the error messages and solutions in chronological order would be tedious and confusing. The account thus far should suffice to demonstrate that updating a program or model can unexpectedly deviate from the iterative debugging cycle that one might imagine beforehand. The refinement process meandered as new concerns were discovered while searches were ongoing for previous causes of concern. Some obstacles of note:

- (1) Some cells in universe 4 overlapped with cell 708. Inserting “#708” into each cell definition in universe 4 (except that of cell 708) solved this problem.
- (2) The KSRC point specifications in the 1998 (ver. 4C) model happened to be positioned in water near the fuel assemblies, in what are now invalid positions. In ver. 6, “[a]t least one point must be in a cell containing fissile material”¹⁵.

Changes explained thus far –other than removing cross section library IDs- suggest that version 4C employed “Do What I Mean” features, since apparently it was

³ This modification preceded the migration to macrobody surfaces.

less stringent in the input which it would accept than later versions. Interestingly, some of these features may have lived on in succeeding versions. At one point while experimenting with the input deck to address lost-neutron problems, KSRC was used to re-define the neutron source with one point in each wafer where a fuel assembly would sit if there were a fuel assembly at D5, and then this author forgot to change it back to how it had been defined previously (KSRC had previously been set so that the two centermost fuel wafers of every fuel assembly each had a KSRC point at their center). There is no fuel meat where these twenty-two points are, but KCODE refines the initially given source into a physically plausible source during its initial, discarded iteration cycles. Apparently the original “KSRC” problem was not a bad initial source, but a bad initial source that was also “un-fixable”, and despite the words of the User Manual the “fissile material” requirement can be violated by accident and sometimes the simulation will proceed.

The most appreciable way in which version 4C was apparently different from version 6.1.0 was in geometry specification. Despite changes already explained, the simulations continued to lose ten particles before the third KCODE cycle could be completed. On re-examining the model geometry and the output this author noticed that the lowest-level universes had space for which no cell was defined; all the space within each of the lowest-level universes which went on to fill a higher-level “window” cell had been assigned a cell in its original universe, but not all of the space inside these lowest-level universes had been assigned a cell⁵. These “incomplete” universes thusly found were then “completed” by defining additional cells of water occupying the remaining space in each. In other words, apparently in version 6.1.0

every universe must ascribe every point in its space to a cell –regardless of whether any higher-level cell will ever use that space! This was a surprising problem because the “undefined” space had no physical meaning. In this case the software’s requirements for the input exceeded those for a physically valid model; the crux of this lost-neutron problem was MCNP’s need for full context in each level of a model before navigating the various levels.

Issues like these teach a simulator to appreciate the tools employed in simulations, and of the sort of incidental differences that can emerge between one version of software and the next. Once the “incomplete universes” were remedied, the 2015 adaptation of the 1998 model had been brought to a state in which it would run to completion, completing all 2000 of its originally intended KCODE cycles.

Dealing with extremely slow runtimes

The emergence of slowness issues preceded even adapting the model to the needs of the new project. Symptoms of the problem so early in the timeline speak to its profundity, since the adaptations for this study would only add to the computational burden. One can only invest so much time in questions of time efficiency before defeating the purpose of those questions, but in the course of this project the investment proved worthwhile.

This project began on a laptop with 2 GB RAM and one dual-core processor. The earliest measure taken to address speed was to add 4 GB RAM to the laptop. Soon thereafter the need for even greater speed became apparent, and the project was migrated to a desktop computer at RINSC employing a quad-core processor. Early versions of the model took days to run on the original platform, and the same models

took six hours on the new platform. Unfortunately, remote access to the RINSC desktop became a project of its own. This author has no experience maintaining or configuring a server, which left the project dependent at the time on ready-made solutions. Of the ready-made remote access solutions, options were further limited by the project budget to those that were free-of-charge. Fortunately, an account was established on the seven-node Beowulf cluster (one head and six computing nodes) housed at Tyler Hall on the main campus of URI. Migrating to the Tyler Hall cluster also reduced remote access from a project of its own to the most minor of problems, rapidly solved with a free-of-charge SSH client.

Addressing speed concerns was not limited to hardware; usage of the cluster was optimized with respect to time. Migration to a computer cluster also presented the opportunity to build MCNP for Open MPI, so it was decided to test notions of how to optimize the speed –notions relating both to Open MPI and to MCNP. Unfortunately the MPI build of MCNP ultimately proved slower at running the model than the sequential build. Fortunately, the sequential build includes OMP threading, which lent itself greatly to speeding calculations inside of or outside of the PBS/Torque environment available on the cluster. In the course of these speed tests it became clear that the optimal way to run MCNP with respect to speed of calculation was: to submit each job to only one of the computing nodes –never running one job across multiple nodes; to assign each job as many cores as the assigned node had, while telling MCNP to run that many tasks; and also to queue each job on any node to wait for any preceding jobs assigned to the same node to complete. In other words the optimal

method of computing was to submit jobs to run one job at a time per computing node, running on all their respective nodes' cores.

Where have all the neutrons gone?

A recurring problem while refining the model was that MCNP would “lose” neutrons during a simulation. This problem began to present itself in the early stages of adaptation from version 4C to 6.1.0 (due to “incomplete” low-level universes), and persisted after updating the core configuration. The default behavior is for MCNP to continue a simulation until a total of ten transported particles (neutrons, in this case) are lost¹⁵. By way of the Lost Particle Control card (LOST), the default lost particle threshold can be overridden, but LANL discourages doing such: “Losing more than 10 particles is rarely justifiable”¹⁵. Regardless of how many particles are lost in a run LANL advises MCNP users to understand why exactly a particle was lost.

Before pursuing other measures, a geometry check was performed in the manner recommended by LANL in section 2.12 of the manual, “Geometry Errors”¹⁵. To summarize that geometry check: one bombards one's model from all directions with an inward, spherical source and anyplace in the model that a particle is lost is in need of attention¹⁵. The stronger the source, the less likely for a false negative result to occur¹⁵. Ultimately this “inward sphere” check was employed multiple times, often with useful results.

In multiple sections of the MCNP user manual, LANL advises the reader that a good diagnostic tool is to train the geometry plotter on the last known position of a lost particle¹⁵. (An occasionally useful variant of this technique is to point the plotter at the last few locations, not merely the very last). Understanding the loss of neutrons

proved challenging nonetheless because details of the event log encumber its interoperability with the plotter. A side effect of the “multi-universe” architecture of the model was that the event log for a lost neutron would reference a non-unique label for the last relevant cell and surface. The final position of the particle was always given in the event log with respect to the local coordinate system of the deepest applicable universe. Meanwhile the geometry plotter takes coordinates as inputs strictly with respect to the global coordinate system. In theory, one can make all of the necessary conversions to the global coordinate system, though unfortunately the increment used throughout the event log was coarser than that used to define the geometry of the model. At times that proved relevant, but ultimately plotting the last-known whereabouts was tremendously helpful.

While the ideal scenario is to plot the last known whereabouts of a lost neutron and see red dotted lines¹⁵, plots that show no apparent problem can also be informative. Instead patterns provide hints, as was the case in this study. The very last cause of lost-neutron problems to be rooted out was only rooted out because this author caught on from the (flawless-looking) plots that the problem was consistently happening near the shim safety blades, and then this author remembered that each shim safety blade was rendered in its own universe (at the time), which in turn filled a “real-world” window cell. The shim safety blades were promoted to universe 0 (“the real world”), and the model entirely ceased to lose neutrons.

Side Effects of Complexity

The anecdote at the end of the previous appendix may bother an experienced MCNP user, who may wonder why such a basic usage of universes and filling would

cause the program to lose track of neutrons. It would seem that such a defect would defeat the purpose of that feature. There is a missing piece to that puzzle: while simulating transport, MCNP distinguishes between surfaces to a resolution of 1.0e-3 cm and no finer²⁰. The detail in the model was so fine near the shim safety blades that it prevented MCNP from recognizing when it was supposed to switch from “the real world” to each blade’s universe.

Another interesting challenge during the refinement of the model was that MCNP needed help filling out the grid; specifically, some of the grid elements at extremes of lattices failed to appear as specified in the input deck (*e.g.* radiation basket, corner post) and instead were water, top to bottom. Ironically, the workaround to realize the intended geometry was more complexity, not less. Several new universes were introduced, in which each previously-intended universe was repeated endlessly per “x” and “y” in a new lattice, and the fill entry for that previously-intended universe in each original lattice was replaced with a reference to the new purpose-made lattice for that universe. For example, the lattice definition for columns F and G had been:

```
2  0  -10188881 u=101 lat=1
    fill=0:1 0:8 0:0
    12(3) 3(3) $ROW 1
    3(3) 3(3) $ROW 2
    3(3) 2(3) $ROW 3
    3(3) 2(3) $ROW 4
    3(3) 2(3) $ROW 5
    3(3) 2(3) $ROW 6
    3(3) 2(3) $ROW 7
    3(3) 3(3) $ROW 8
    12(3) 11(3) $ROW 9
c    G          c F
```

Universe 11 corresponds to a radiation basket, and one would expect the transformation applied to all of the other universes in the other lattice entries (“3”, in each entry written above in the format “[universe_index](3)”,) to do its job as it already did seventeen times previously. Strangely, the eighteenth lattice segment is

filled with the correct universe but without the transformation applied (left-hand side of Figure 40). What actually worked was to introduce a new universe in the lattice definition:

```
2  0  -10188881 u=101 imp:n=1 lat=1
    fill=0:1 0:8 0:0
    12(3) 3(3) $ROW 1
    3(3) 3(3) $ROW 2
    3(3) 2(3) $ROW 3
    3(3) 2(3) $ROW 4
    3(3) 2(3) $ROW 5
    3(3) 2(3) $ROW 6
    3(3) 2(3) $ROW 7
    3(3) 3(3) $ROW 8
    12(3) 1100 $ROW 9
c   G       c F
```

This new lattice definition required an additional universe, as already explained:

```
264 0 -10188881 fill=11(3) lat=1 imp:n=1 u=1100 $inspired by pp.4, 6 of
adv. geom
```

One theory as to why this was necessary is that perhaps the problem setup component(s) of MCNP can only hold a bank of so many object references, and perhaps the input deck with the “water pillar” problem required too many object references in one rendering. Further, the lattice workaround herein described may have circumvented that limit through an object reference inside one bank making reference to another bank. A container ship cannot turn as tightly as a speedboat, but if it “zigs” one way before it “zags” the other, it can navigate more difficult circumstances than were obvious; this “water pillar” problem and its solution appear to be analogous to that.

Figure 40: “before” (left) and “after” (right) for an instance of the “water pillar” problem. The input decks resulting in these plots were made from the full model and then modified to isolate columns F and G of the core grid.

Both of these problems –and their solutions- demonstrate that it is paramount to appreciate the complexity of advanced tools.

Templates (and Kinds) of Input Decks

An MCNP input deck is a computer model -depending on what one is doing, and how. In the context of this project, not one input deck of the input decks used may be regarded on its own as “the model”.

From one perspective the binary restart file is the actual model in any single run of MCNP, and the input deck is its “source code” with MCNP serving as the compiler. However, that simple assertion is based on several assumptions: (1) there is only one input deck, necessarily an “initiate” deck; (2) the particle source is adequately defined inside the “initiate” deck; and (3) the user needs only final results from MCNP, not intermediate results of any kind. After removing these assumptions the most general case is that the binary restart file, and as many source tape files⁴ as necessary together constitute the actual model; the “initiate” deck, together with as many “continue” decks as necessary, also combined with any source subroutine files (“source” and possibly “srcdx”), and even further combined with any accessory files incidentally needed at the outset as input by programs or scripts are the source code⁵.

Whittling the general case back down to this study, the “initiate” deck adequately introduced the computer to the problem to be solved (geometry, source definition, etc.), but it took several “continue” runs, each with its own “continue” deck, to finish the job. The “initiate” deck could have done the job entirely on its own, if only this author happened to correctly guess how many iterations it would take for

⁴ or source definition files, e.g. “wxxa” or “rssa”,

⁵ Supplementary programs or scripts become “pre-compilers” in this analogy. Perhaps some of the accessory files fit better in the analogy as header files.

results to satisfactorily converge. Any of the intermediate “continue” runs could have been omitted, if only the second guess for how many iterations had been correct. For planning purposes, an MCNP user will never correctly guess how many iterations are needed -not on the first guess, not on the one-hundred-thirty-first guess. The thing to do is start with an “initiate” run to rule out any flaws in the model, and follow it with reasonably-spaced “continue” runs until the user finds that convergence and other requirements have been met. Also, many a user uses intermediate results to extrapolate when the latest run might finish, or try to discern a pattern with regard to iterations and their temporal cost. A revised “initiate” deck would sufficiently characterize the model, but in deference to the actual procedure the model will be shared in two parts: the “initiate” deck which introduces the computer to the problem, and the final version of the “continue” deck.

Also shared are template input decks of both kinds (“initiate” and “continue”). The “initiate” template is meant to be fed to `mcnp_pstudy`, which in turn results in a proper MCNP input deck. What appears at first to be a one-case parameter study can be reimagined as an input deck only better: input parameters can be clearly labeled by the user, and the user can adjust incidental details of the input deck (e.g. the value of a parameter).

This second benefit deserves emphasis: small changes in the user’s mental model generally are not small changes to the (traditional) input deck. An example is how one adjusts the control rod heights. The naïve approach would be to adjust the surfaces –but not before: checking which surfaces to adjust; checking that the object one wants to move has no surfaces in common with something that one does not want

to move; nor checking which other surfaces must be adjusted to prevent a geometry error. Suppose that adjustment is unsatisfactory, and the user wants to move any of the control rods again. The same tedious work as before must be repeated entirely, lest the user introduce a geometry error. The advantage of an `mcnp_pstudy` template in this situation is that the user can render a unique surface adjustable once, finding and solving whatever conflicts emerge, and thereafter adjust one parameter value without re-investing time and energy in avoiding conflicts.

Another approach would be to assign a unique transformation to each cell one wishes to move, as has been done in other studies modeling other reactors²¹. This also requires assigning the objects of interest their own universes, and “window” cells to be filled with those universes^{21,22}. Experience in this study suggests that such a strategy carries the risk that physically valid input may not successfully run (see “Where have all the neutrons gone?”). Particle loss concerns aside, this approach would also benefit from the usage of `mcnp_pstudy` templating; one can update comments at the top of the file and then adjust the positions on the next line, without diving into the data block to adjust one data card with a somewhat abstract name. (This also applies to the previous approach.)

Whether moving control rods or adjusting material compositions, readers who may wish to extend this study may save themselves much frustration by regarding a re-usable, adjustable template for an input deck as “the model”.

The “continue” template is not meant for `mcnp_pstudy`; instead any user is advised to directly copy from the template and then edit the copy directly.

"Initiate" Deck for the Model

```
Ben's Adaptation of Dr. Mo's Model of the RINSC Core
c RINSC Core #6 - Fresh Fuel
c Comments are of my making, unless specifically attributed to Dr. Mo. -Ben
c
c   -Core #6
c       The mesh tally for the flux profile is divided on the core:
c           along x into 60 intervals, each 1 cm long;
c           along y into 70 intervals, each 1 cm long;
c           along z into 50 intervals, each 1.1938 cm long;
c           for a total of 210000 3-D voxels throughout the core.
c       That same mesh is divided into 4080000 voxels overall.
c           (core voxels / overall voxels = 0.0514705882352941)
c           (See tally cards directly for more details as to how it's
divided
c           over the rest of the non-void space.)
c       This problem is running 10000 neutrons in each cycle
c       My initial k_eff guess is 1.0
c       Running for 100 active cycles after discarding the first 10
c       -which will result in 1000000 source particle histories.
c       All the shim safety blades are raised 40.64 cm, while the
c       regulating rod is at 27.0764 cm.
c
c           ~~~~~+
c           CELL BLOCK
c           ~~~~~-
c
c Universe Zero
c
c 1 0 -9001 imp:n=1 fill=101
c
c 11 0 -9004 imp:n=1 fill=103
c
c 21 0 -9007 imp:n=1 fill=105
c
c 27 2 0.0602684 -9013 imp:n=1 $x left side -Dr. Mo
c 28 3 0.100292 9013 -9025 imp:n=1 $x left side -Dr. Mo
c 29 3 0.100292 -9008 imp:n=1 $x left water -Dr. Mo
c
c 30 2 0.0602684 -9014 imp:n=1 $x right side -Dr. Mo
c 31 3 0.100292 9014 -9026 imp:n=1 $x right side -Dr. Mo
c 32 3 0.100292 -9011 imp:n=1 $x right water -Dr. Mo
c
c 33 2 0.0602684 -9012 imp:n=1 $y bottom Al -Dr. Mo
c 34 3 0.100292 9012 -9027 imp:n=1 $y bottom water -Dr. Mo
c 35 3 0.100292 -9015 imp:n=1 $y bottom water -Dr. Mo
c
c 36 2 0.0602684 -9010 imp:n=1 $y top Al -Dr. Mo
c 37 3 0.100292 9010 -9028 imp:n=1 $y top water -Dr. Mo
c 38 3 0.100292 -9009 imp:n=1 $y top water -Dr. Mo
c
c 39 10 0.08023 -9020 imp:n=1 imp:n=1 $graphite -Dr. Mo
c 40 2 0.0602684 -9021 imp:n=1 $TC1 clad -Dr. Mo
c 41 10 0.08023 -9029 imp:n=1 $graphite -Dr. Mo
c 42 2 0.0602684 9029 -9016 imp:n=1 $TC2 clad -Dr. Mo
c
c 43 9 0.032962 -9017 imp:n=1 $lead shield -Dr. Mo
c 44 2 0.0602684 9017 -9018 imp:n=1 $lead shield -Dr. Mo
c
c 45 3 0.100292 9020 9021 9016 9018 -9019 imp:n=1 $water reflec -Dr. Mo
c
c 46 3 0.100292 -9022 imp:n=1 $water reflec -Dr. Mo
c 47 3 0.100292 -9024 imp:n=1 $water reflec -Dr. Mo
c 48 3 0.100292 -9023 imp:n=1 $water reflec -Dr. Mo
c
c 49 0 9030 imp:n=0 $outside void -Dr. Mo
c
c Control Blade 1 (formerly universe 5)
c
```

```

751 7 0.088221 -5001 imp:n=1 $absorber -Dr. Mo
752 2 0.0602684 5001 -5002 imp:n=1 $al clad -Dr. Mo
753 3 0.100292 5002 -5003 imp:n=1 $water -Dr. Mo
754 2 0.0602684 5003 -5004 -9006 imp:n=1 $al guid -Dr. Mo
755 3 0.100292 5004 -5005 -9006 imp:n=1 $h2o gap -Dr. Mo
c held off on re-making cell 758 -Ben
759 4 0.0842826 -5006 -9006 imp:n=1 $grid support -Dr. Mo
760 5 0.0911399 -5007 -9006 imp:n=1 $bottom reflect -Dr. Mo
c held off on re-making cell 762 -Ben
763 3 0.100292 5005 5006 5007 -9006 imp:n=1
    $Finishes control blade region! -Ben
c
c Control Blade 2 (formerly universe 6)
c
801 7 0.088221 -6001 -9005 imp:n=1 $absorber -Dr. Mo
802 2 0.0602684 6001 -6002 -9005 imp:n=1 $al clad -Dr. Mo
803 3 0.100292 6002 -6003 -9005 imp:n=1 $water -Dr. Mo
804 2 0.0602684 6003 -6004 -9005 imp:n=1 $al guid -Dr. Mo
805 3 0.100292 6004 -6005 -9005 imp:n=1 $h2o gap -Dr. Mo
c held off on re-making cell 808 -Ben
809 4 0.0842826 -6006 -9005 imp:n=1 $grid support -Dr. Mo
810 5 0.0911399 -6007 -9005 imp:n=1 $bottom reflect -Dr. Mo
c
c held off on re-making cell 812 -Ben
813 3 0.100292 6005 6006 6007 -9005 imp:n=1
    $Finishes control blade region! -Ben
c
c Control Blade 3 (formerly universe 7)
c
851 7 0.088221 -7001 -9002 imp:n=1 $absorber -Dr. Mo
852 2 0.0602684 7001 -7002 -9002 imp:n=1 $al clad -Dr. Mo
853 3 0.100292 7002 -7003 -9002 imp:n=1 $water -Dr. Mo
854 2 0.0602684 7003 -7004 -9002 imp:n=1 $al guid -Dr. Mo
855 3 0.100292 7004 -7005 -9002 imp:n=1 $h2o gap -Dr. Mo
c held off on re-making cell 858 -Ben
859 4 0.0842826 -7006 -9002 imp:n=1 $grid support -Dr. Mo
860 5 0.0911399 -7007 -9002 imp:n=1 $bottom reflect -Dr. Mo
c held off on re-making cell 862 -Ben
863 3 0.100292 7005 7006 7007 -9002 imp:n=1
    $Finishes control blade region! -Ben
c
c Control Blade 4 (formerly universe 8)
c
901 7 0.088221 -8001 -9003 imp:n=1 $absorber -Dr. Mo
902 2 0.0602684 8001 -8002 -9003 imp:n=1 $al clad -Dr. Mo
903 3 0.100292 8002 -8003 -9003 imp:n=1 $water -Dr. Mo
904 2 0.0602684 8003 -8004 -9003 imp:n=1 $al guid -Dr. Mo
905 3 0.100292 8004 -8005 -9003 imp:n=1 $h2o gap -Dr. Mo
906 3 0.100292 8005 8006 8007 -9003 imp:n=1
    $Finishes control blade region! -Ben
c held off on re-making cell 908 -Ben
909 4 0.0842826 -8006 -9003 imp:n=1 $grid support -Dr. Mo
910 5 0.0911399 -8007 -9003 imp:n=1 $bottom reflect -Dr. Mo
c held off on re-making cell 912 -Ben
c
c Mid-Level Universes
c
2 0 -10188881 u=101 imp:n=1 lat=1
    fill=0:1 0:8 0:0
    12(3) 3(3) $ROW 1
    3(3) 3(3) $ROW 2
    3(3) 2(3) $ROW 3
    3(3) 2(3) $ROW 4
    3(3) 2(3) $ROW 5
    3(3) 2(3) $ROW 6
    3(3) 2(3) $ROW 7
    3(3) 3(3) $ROW 8
    12(3) 1100
    $ROW 9 $Notice I no longer reference u11 directly here. -Ben
c G F
c
12 0 -10388881 u=103 lat=1 imp:n=1

```



```

fill=-1:1 -4:4 0:0
3(2) 3(2) 3(2) $ROW 1
2(2) 4(2) 2(2) $ROW 2
19 19 19 $ROW 3 $I've replaced "1(2)" with "19" -Ben
19 19 19 $ROW 4
19 10(2) 19 $ROW 5
19 19 19 $ROW 6
19 19 19 $ROW 7
2(2) 2(2) 2(2) $ROW 8
1101 1101 1101
$ROW 9 $Notice I no longer reference u11 directly here. -Ben
c   E   D   C
c
c
22  0   -10588881 u=105 lat=1 imp:n=1
fill=0:1 0:8 0:0
$Notice I no longer reference u12 directly in what follows. -Ben
3(6) 1202 $ROW 1
3(6) 3(6) $ROW 2
2(6) 3(6) $ROW 3
2(6) 3(6) $ROW 4
2(6) 3(6) $ROW 5
2(6) 3(6) $ROW 6
2(6) 3(6) $ROW 7
3(6) 3(6) $ROW 8
11(6) 1202 $ROW 9
c   B   A
c
c
c Ground Floor (and Additional) Universes
c
266 0 -10388881 fill=1(2) lat=1 imp:n=1 u=19
c
50  3 0.100292 2 -1 u=1 imp:n=1 vol=43.24
c
51 2 6.02684E-02 -3 u=1 imp:n=1 $sideplate l -Dr. Mo
52 2 6.02684E-02 -4 u=1 imp:n=1 $sideplate r -Dr. Mo
53 3 1.00292E-01 -5 u=1 imp:n=1 $h20 1 -Dr. Mo
c
54  1 0.0536392 -6 u=1 imp:n=1 $meat 1 -Dr. Mo
c
55 2 6.02684E-02 6 -7 u=1 imp:n=1 $clad 1 -Dr. Mo
c
56 3 1.00292E-01 -8 u=1 imp:n=1 $h2o 2 -Dr. Mo
57  1 0.0536392 -14 u=1 imp:n=1
58 2 6.02684E-02 14 -15 u=1 imp:n=1
c
59  3 1.00292E-01 -9 u=1 imp:n=1
60  1 0.0536392 -16 u=1 imp:n=1
61 2 6.02684E-02 16 -17 u=1 imp:n=1
c
62  3 1.00292E-01 -18 u=1 imp:n=1
63  1 0.0536392 -19 u=1 imp:n=1
64 2 6.02684E-02 19 -20 u=1 imp:n=1
c
65  3 1.00292E-01 -21 u=1 imp:n=1
66  1 0.0536392 -22 u=1 imp:n=1
67 2 6.02684E-02 22 -23 u=1 imp:n=1
c
68  3 1.00292E-01 -24 u=1 imp:n=1
69  1 0.0536392 -25 u=1 imp:n=1
70 2 6.02684E-02 25 -26 u=1 imp:n=1
c
71  3 1.00292E-01 -27 u=1 imp:n=1
72  1 0.0536392 -28 u=1 imp:n=1
73 2 6.02684E-02 28 -29 u=1 imp:n=1
c
74  3 1.00292E-01 -30 u=1 imp:n=1
75  1 0.0536392 -31 u=1 imp:n=1
76 2 6.02684E-02 31 -32 u=1 imp:n=1
c
77  3 1.00292E-01 -33 u=1 imp:n=1
78  1 0.0536392 -34 u=1 imp:n=1
79 2 6.02684E-02 34 -35 u=1 imp:n=1

```

```

c
80 3 1.00292E-01 -36 u=1 imp:n=1
81 1 0.0536392 -37 u=1 imp:n=1
82 2 6.02684E-02 37 -38 u=1 imp:n=1
c
83 3 1.00292E-01 -39 u=1 imp:n=1
84 1 0.0536392 -40 u=1 imp:n=1
85 2 6.02684E-02 40 -41 u=1 imp:n=1
c
86 3 1.00292E-01 -42 u=1 imp:n=1
87 1 0.0536392 -43 u=1 imp:n=1
88 2 6.02684E-02 43 -44 u=1 imp:n=1
c
89 3 1.00292E-01 -45 u=1 imp:n=1
90 1 0.0536392 -46 u=1 imp:n=1
91 2 6.02684E-02 46 -47 u=1 imp:n=1
c
92 3 1.00292E-01 -48 u=1 imp:n=1
93 1 0.0536392 -49 u=1 imp:n=1
94 2 6.02684E-02 49 -50 u=1 imp:n=1
c
95 3 1.00292E-01 -51 u=1 imp:n=1
96 1 0.0536392 -52 u=1 imp:n=1
97 2 6.02684E-02 52 -53 u=1 imp:n=1
c
98 3 1.00292E-01 -54 u=1 imp:n=1
99 1 0.0536392 -55 u=1 imp:n=1
100 2 6.02684E-02 55 -56 u=1 imp:n=1
c
101 3 1.00292E-01 -57 u=1 imp:n=1
102 1 0.0536392 -58 u=1 imp:n=1
103 2 6.02684E-02 58 -59 u=1 imp:n=1
c
104 3 1.00292E-01 -60 u=1 imp:n=1
105 1 0.0536392 -61 u=1 imp:n=1
106 2 6.02684E-02 61 -62 u=1 imp:n=1
c
107 3 1.00292E-01 -63 u=1 imp:n=1
108 1 0.0536392 -64 u=1 imp:n=1
109 2 6.02684E-02 64 -65 u=1 imp:n=1
c
110 3 1.00292E-01 -66 u=1 imp:n=1
111 1 0.0536392 -67 u=1 imp:n=1
112 2 6.02684E-02 67 -68 u=1 imp:n=1
c
113 3 1.00292E-01 -69 u=1 imp:n=1
114 1 0.0536392 -70 u=1 imp:n=1
115 2 6.02684E-02 70 -71 u=1 imp:n=1
c
116 3 1.00292E-01 -72 u=1 imp:n=1
117 1 0.0536392 -73 u=1 imp:n=1
118 2 6.02684E-02 73 -74 u=1 imp:n=1
c
119 3 1.00292E-01 -10 u=1 imp:n=1 $h2o end -Dr. Mo
c held off on re-making cell 120 -Ben
121 4 0.0842826 -11 u=1 imp:n=1 $grid support -Dr. Mo
122 5 0.0911399 -12 u=1 imp:n=1 $bottom reflect -Dr. Mo
c
123 5 0.0911399 -13 u=1 imp:n=1 $top reflector -Dr. Mo
c held off on re-making cell 124 -Ben
125 3 0.100292 1 11 12 13 u=1 imp:n=1 vol=1 $Finishes universe! -Ben
c
501 3 0.100292 -2001 u=2 imp:n=1
502 11 0.12364 2001 -2002 u=2 imp:n=1
503 3 0.100292 2002 -2003 u=2 imp:n=1
504 3 0.100292 2003 2004 2005 2006 u=2 imp:n=1
$Finishes universe! -Ben
c held off on re-making cell 508 -Ben
509 4 0.0842826 -2004 u=2 imp:n=1 $grid support -Dr. Mo
510 5 0.0911399 -2005 u=2 imp:n=1 $bottom reflect -Dr. Mo
c
511 5 0.0911399 -2006 u=2 imp:n=1 $top reflector -Dr. Mo

```

```

c held off on re-making cell 512 -Ben
c
531 10 0.08023 -3001 u=3 imp:n=1 $Graphite block -Dr. Mo
532 2 0.0602684 3001 -3002 u=3 imp:n=1 $al box -Dr. Mo
533 3 0.100292 3002 -3003 u=3 imp:n=1 $water gap -Dr. Mo
c held off on re-making cell 538 -Ben
539 4 0.0842826 -3004 u=3 imp:n=1 $grid support -Dr. Mo
540 5 0.0911399 -3005 u=3 imp:n=1 $bottom reflect -Dr. Mo
541 5 0.0911399 -3006 u=3 imp:n=1 $stop reflector -Dr. Mo
c held off on re-making cell 542 -Ben
543 3 0.100292 3003 3004 3005 3006 u=3 imp:n=1 $Finishes universe! -Ben
c
708 2 0.0602684 -4001 u=4 imp:n=1 $central rod -Dr. Mo
709 8 0.0877738 -4002 u=4 imp:n=1 $x-left absorber -Dr. Mo
710 2 0.0602684 4002 -4003 u=4 imp:n=1 $x-left clad -Dr. Mo
711 8 0.0877738 -4004 u=4 imp:n=1 $x-left absorber -Dr. Mo
712 2 0.0602684 4004 -4005 u=4 imp:n=1 $x-left clad -Dr. Mo
713 8 0.0877738 -4006 u=4 imp:n=1 $y-bottom absorber -Dr. Mo
714 2 0.0602684 4006 -4007 u=4 imp:n=1 $y-bottom clad -Dr. Mo
c
715 2 0.0602684 -4008 u=4 imp:n=1 $y-top clad -Dr. Mo
c
716 3 0.100292 4001 4003 4005 4007 4008 -4009 u=4 imp:n=1
c
701 2 0.0602684 -4010 u=4 imp:n=1 $x-left guide -Dr. Mo
703 2 0.0602684 -4011 u=4 imp:n=1 $x-right guide -Dr. Mo
705 2 0.0602684 -4012 u=4 imp:n=1 $y-bottom guide -Dr. Mo
707 2 0.0602684 -4013 u=4 imp:n=1 $y-bottom guide -Dr. Mo
718 3 0.100292 4009 4010 4011 4012 4013 -4014 u=4 imp:n=1
$water gap -Dr. Mo
c held off on re-making cell 721 -Ben
722 4 0.0842826 -4015 u=4 imp:n=1 $grid support -Dr. Mo
723 5 0.0911399 -4016 u=4 imp:n=1 $bottom reflect -Dr. Mo
724 5 0.0911399 4009 -4017 u=4 imp:n=1 $stop reflector -Dr. Mo
c held off on re-making cell 725 -Ben
726 3 0.100292 4014 4015 4016 4017 u=4 imp:n=1 $Finishes universe! -Ben
c
201 3 0.100292 -1001 u=10 imp:n=1
202 11 0.12364 1001 -1002 u=10 imp:n=1
203 3 0.100292 1002 -1003 u=10 imp:n=1
204 11 0.12364 1003 -1004 u=10 imp:n=1
205 3 0.100292 1004 -1005 u=10 imp:n=1
c held off on re-making cell 208 -Ben
209 4 0.0842826 -1006 u=10 imp:n=1 $grid support -Dr. Mo
210 5 0.0911399 -1007 u=10 imp:n=1 $bottom reflect -Dr. Mo
c
211 5 0.0911399 -1008 u=10 imp:n=1 $stop reflector -Dr. Mo
c held off on re-making cell 212 -Ben
213 3 0.100292 1005 1006 1007 1008 u=10 imp:n=1
$Finishes universe! -Ben
c
251 2 0.0602684 1101 -1102 u=11 imp:n=1 $Al -Dr. Mo
252 3 0.100292 -1103 #251 u=11 imp:n=1 $water -Dr. Mo
253 2 0.0602684 1103 -1104 u=11 imp:n=1
254 3 0.100292 -1105 #251 #252 #253 u=11 imp:n=1
c held off on re-making cell 258 -Ben
259 4 0.0842826 -1106 u=11 imp:n=1 $grid support -Dr. Mo
260 5 0.0911399 -1107 u=11 imp:n=1 $bottom reflect -Dr. Mo
c
261 5 0.0911399 -1108 u=11 imp:n=1 $stop reflector -Dr. Mo
c held off on re-making cell 262 -Ben
263 3 0.100292 1105 1106 1107 1108 u=11 imp:n=1
$Finishes universe! -Ben
c
c "Tiling" of universe 11
264 0 -10188881 fill=11(3) lat=1 imp:n=1 u=1100
$inspired by pp.4, 6 of adv. geom -Ben
265 0 -10388881 fill=11(2) lat=1 imp:n=1 u=1101
$inspired by pp.4, 6 of adv. geom -Ben
c
c Back to Ground Floor...
c

```

```

301 6 0.08027975 -1201 imp:n=1 u=12 $post -Dr. Mo
302 3 0.100292 1201 -1202 imp:n=1 u=12 $ -Ben
c
304 3 0.100292 1202 1203 1204 1205 imp:n=1 u=12
$Finishes universe! -Ben
309 4 0.0842826 -1203 imp:n=1 u=12 $grid support -Dr. Mo
310 5 0.0911399 -1204 imp:n=1 u=12 $bottom reflect -Dr. Mo
311 5 0.0911399 -1205 imp:n=1 u=12 $top reflector -Dr. Mo
c
c "Tiling" of universe 12
312 0 -10588881 fill=12(6) lat=1 imp:n=1 u=1202

c ~~~~~
c SURFACE BLOCK
c ~~~~~
c
c Universe Zero
c four-digit labels,
c leading with "9" bc there is no "universe 9".
9001 rpp 26.77301 42.316999 64.51001 134.45799 0 160 $cell 1
9002 rpp 42.316999 44.857001 64.51001 99.484 0 160 $cell 5
9003 rpp 42.316999 44.857001 99.484 134.45799 0 160 $cell 8
9004 rpp 44.857001 68.172999 64.51001 134.45799 0 160 $cell 11
9005 rpp 68.172999 70.713001 64.51001 99.484 0 160 $cell 15
9006 rpp 68.172999 70.713001 99.484 134.45799 0 160 $cell 18
9007 rpp 70.713001 86.256999 64.51001 134.45799 0 160 $cell 21
9008 rpp 26.72 26.77301 64.457 134.511 0 160 $cell 29
9009 rpp 26.77301 86.256999 134.45799 134.511 0 160 $cell 38
9010 rpp 26.72 86.31 134.511 135.146 26.22 110.51 $cell 36
9011 rpp 86.256999 86.31 64.457 134.511 0 160 $cell 32
9012 rpp 26.72 86.31 63.822 64.457 26.22 110.51 $cell 33
9013 rpp 26.085 26.72 63.822 135.146 26.22 110.51 $cell 27
9014 rpp 86.31 86.945 63.822 135.146 26.22 110.51 $cell 30
9015 rpp 26.77301 86.256999 64.457 64.51001 0 160 $cell 35
9016 rpp 11.43 101.6 29.527 52.387 28.45 117.35 $cell 42
9017 rpp 27.94 85.09 53.977 61.597 34.16 96.0725 $cell 43
9018 rpp 11.43 101.6 52.387 63.187 28.45 117.35 $cell 44
9019 rpp 0 120 0 63.822 0 160 $ext. of cell 45
9020 rpp 0 113.03 0 26.987 0 158.94 $cell 39
9021 rpp 0 113.03 26.987 29.527 0 158.94 $cell 40
9022 rpp 0 26.085 63.822 160 0 160 $cell 46
9023 rpp 26.085 86.945 135.146 160 0 160 $cell 48
9024 rpp 86.945 120 63.822 160 0 160 $cell 47
9025 rpp 26.085 26.72 63.822 135.146 0 160 $cell 28
9026 rpp 86.31 86.945 63.822 135.146 0 160 $ext. of cell 31
9027 rpp 26.72 86.31 63.822 64.457 0 160 $cell 34
9028 rpp 26.72 86.31 134.511 135.146 0 160 $cell 37
9029 rpp 13.96 99.06 29.527 49.847 29.72 116.08 $cell 41
9030 rpp 0 120 0 160 0 160 $ext. of cell 49
c
c Lattice Surfaces
c
10188881 rpp 26.773 34.545 64.51 72.282 0 0 $infinite in z -Ben
c [xmin of 10188881 is] corner element G1 -Dr. Mo
c
10388881 rpp 52.629 60.401 95.598 103.37 0 0 $infinite in z -Ben
c [xmin of 10388881 is] central element flux trap -Dr. Mo
c
10588881 rpp 70.713 78.485 64.51 72.282 0 0 $infinite in z -Ben
c [xmax of 10588881 is] element B2 -Dr. Mo
c
c Universe One
c
1 rcc 3.886 3.886 -1e-005 0 0 59.69001 11 $ext. of Cell 50
2 rpp 0.019 7.753 0.02774 7.74426 -1e-005 59.69 $int. of cell 50
3 rpp 0.019 0.494 0.02774 7.74426 -1e-005 59.69 $cell 51
4 rpp 7.278 7.753 0.02774 7.74426 -1e-005 59.69 $cell 52
5 rpp 0.494 7.278 0.02774 0.142 -1e-005 59.69 $cell 53
6 rpp 0.8445 6.9275 0.1801 0.2309 -1e-005 59.69 $cell 54
7 rpp 0.494 7.278 0.142 0.269 -1e-005 59.69 $ext. of cell 55
8 rpp 0.494 7.278 0.269 0.4926 -1e-005 59.69 $cell 56
9 rpp 0.494 7.278 0.6196 0.8431 -1e-005 59.69 $cell 59

```

10 rpp 0.494 7.278 7.63 7.74426 -1e-005 59.69 \$cell 119
11 rcc 3.886 3.886 -29.07 0 0 19.54 11 \$cell 121
12 rcc 3.886 3.886 -1e-005 0 0 -9.52999 11 \$cell 122
13 rcc 3.886 3.886 59.69 0 0 15.07001 11 \$cell 123
14 rpp 8.44500000e-01 6.92750000e+00 5.30700000e-01
5.81500000e-01 -1.00000000e-05 5.96900000e+01 \$cell 57
15 rpp 4.94000000e-01 7.27800000e+00 4.92600000e-01
6.19600000e-01 -1.00000000e-05 5.96900000e+01 \$ext. of cell 58
16 rpp 8.44500000e-01 6.92750000e+00 8.81200000e-01
9.32000000e-01 -1.00000000e-05 5.96900000e+01 \$cell 60
17 rpp 4.94000000e-01 7.27800000e+00 8.43100000e-01
9.70100000e-01 -1.00000000e-05 5.96900000e+01 \$ext. of cell 61
18 rpp 4.94000000e-01 7.27800000e+00 9.70100000e-01
1.19360000e+00 -1.00000000e-05 5.96900000e+01 \$cell 62
19 rpp 8.44500000e-01 6.92750000e+00 1.23170000e+00
1.28250000e+00 -1.00000000e-05 5.96900000e+01 \$cell 63
20 rpp 4.94000000e-01 7.27800000e+00 1.19360000e+00
1.32060000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 64
21 rpp 4.94000000e-01 7.27800000e+00 1.32060000e+00
1.54410000e+00 -1.00000000e-05 5.96900000e+01 \$cell 65
22 rpp 8.44500000e-01 6.92750000e+00 1.58220000e+00
1.63300000e+00 -1.00000000e-05 5.96900000e+01 \$cell 66
23 rpp 4.94000000e-01 7.27800000e+00 1.54410000e+00
1.67110000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 67
24 rpp 4.94000000e-01 7.27800000e+00 1.67110000e+00
1.89460000e+00 -1.00000000e-05 5.96900000e+01 \$cell 68
25 rpp 8.44500000e-01 6.92750000e+00 1.93270000e+00
1.98350000e+00 -1.00000000e-05 5.96900000e+01 \$cell 69
26 rpp 4.94000000e-01 7.27800000e+00 1.89460000e+00
2.02160000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 70
27 rpp 4.94000000e-01 7.27800000e+00 2.02160000e+00
2.24520000e+00 -1.00000000e-05 5.96900000e+01 \$cell 71
28 rpp 8.44500000e-01 6.92750000e+00 2.28330000e+00
2.33410000e+00 -1.00000000e-05 5.96900000e+01 \$cell 72
29 rpp 4.94000000e-01 7.27800000e+00 2.24520000e+00
2.37220000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 73
30 rpp 4.94000000e-01 7.27800000e+00 2.37220000e+00
2.59570000e+00 -1.00000000e-05 5.96900000e+01 \$cell 74
31 rpp 8.44500000e-01 6.92750000e+00 2.63380000e+00
2.68460000e+00 -1.00000000e-05 5.96900000e+01 \$cell 75
32 rpp 4.94000000e-01 7.27800000e+00 2.59570000e+00
2.72270000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 76
33 rpp 4.94000000e-01 7.27800000e+00 2.72270000e+00
2.94620000e+00 -1.00000000e-05 5.96900000e+01 \$cell 77
34 rpp 8.44500000e-01 6.92750000e+00 2.98430000e+00
3.03510000e+00 -1.00000000e-05 5.96900000e+01 \$cell 78
35 rpp 4.94000000e-01 7.27800000e+00 2.94620000e+00
3.07320000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 79
36 rpp 4.94000000e-01 7.27800000e+00 3.07320000e+00
3.29670000e+00 -1.00000000e-05 5.96900000e+01 \$cell 80
37 rpp 8.44500000e-01 6.92750000e+00 3.33480000e+00
3.38560000e+00 -1.00000000e-05 5.96900000e+01 \$cell 81
38 rpp 4.94000000e-01 7.27800000e+00 3.29670000e+00
3.42370000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 82
39 rpp 4.94000000e-01 7.27800000e+00 3.42370000e+00
3.64720000e+00 -1.00000000e-05 5.96900000e+01 \$cell 83
40 rpp 8.44500000e-01 6.92750000e+00 3.68530000e+00
3.73610000e+00 -1.00000000e-05 5.96900000e+01 \$cell 84
41 rpp 4.94000000e-01 7.27800000e+00 3.64720000e+00
3.77420000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 85
42 rpp 4.94000000e-01 7.27800000e+00 3.77420000e+00
3.99780000e+00 -1.00000000e-05 5.96900000e+01 \$cell 86
43 rpp 8.44500000e-01 6.92750000e+00 4.03590000e+00
4.08670000e+00 -1.00000000e-05 5.96900000e+01 \$cell 87
44 rpp 4.94000000e-01 7.27800000e+00 3.99780000e+00
4.12480000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 88
45 rpp 4.94000000e-01 7.27800000e+00 4.12480000e+00
4.34830000e+00 -1.00000000e-05 5.96900000e+01 \$cell 89
46 rpp 8.44500000e-01 6.92750000e+00 4.38640000e+00
4.43720000e+00 -1.00000000e-05 5.96900000e+01 \$cell 90
47 rpp 4.94000000e-01 7.27800000e+00 4.34830000e+00
4.47530000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 91

```

48 rpp 4.94000000e-01 7.27800000e+00 4.47530000e+00
    4.69880000e+00 -1.00000000e-05 5.96900000e+01 $cell 92
49 rpp 8.44500000e-01 6.92750000e+00 4.73690000e+00
    4.78770000e+00 -1.00000000e-05 5.96900000e+01 $cell 93
50 rpp 4.94000000e-01 7.27800000e+00 4.69880000e+00
    4.82580000e+00 -1.00000000e-05 5.96900000e+01 $ext. of cell 94
51 rpp 4.94000000e-01 7.27800000e+00 4.82580000e+00
    5.04930000e+00 -1.00000000e-05 5.96900000e+01 $cell 95
52 rpp 8.44500000e-01 6.92750000e+00 5.08740000e+00
    5.13820000e+00 -1.00000000e-05 5.96900000e+01 $cell 96
53 rpp 4.94000000e-01 7.27800000e+00 5.04930000e+00
    5.17630000e+00 -1.00000000e-05 5.96900000e+01 $ext. of cell 97
54 rpp 4.94000000e-01 7.27800000e+00 5.17630000e+00
    5.39980000e+00 -1.00000000e-05 5.96900000e+01 $cell 98
55 rpp 8.44500000e-01 6.92750000e+00 5.43790000e+00
    5.48870000e+00 -1.00000000e-05 5.96900000e+01 $cell 99
56 rpp 4.94000000e-01 7.27800000e+00 5.39980000e+00
    5.52680000e+00 -1.00000000e-05 5.96900000e+01 $ext. of cell 100
57 rpp 4.94000000e-01 7.27800000e+00 5.52680000e+00
    5.75040000e+00 -1.00000000e-05 5.96900000e+01 $cell 101
58 rpp 8.44500000e-01 6.92750000e+00 5.78850000e+00
    5.83930000e+00 -1.00000000e-05 5.96900000e+01 $cell 102
59 rpp 4.94000000e-01 7.27800000e+00 5.75040000e+00
    5.87740000e+00 -1.00000000e-05 5.96900000e+01 $ext. of cell 103
60 rpp 4.94000000e-01 7.27800000e+00 5.87740000e+00
    6.10090000e+00 -1.00000000e-05 5.96900000e+01 $cell 104
61 rpp 8.44500000e-01 6.92750000e+00 6.13900000e+00
    6.18980000e+00 -1.00000000e-05 5.96900000e+01 $cell 105
62 rpp 4.94000000e-01 7.27800000e+00 6.10090000e+00
    6.22790000e+00 -1.00000000e-05 5.96900000e+01 $ext. of cell 106
63 rpp 4.94000000e-01 7.27800000e+00 6.22790000e+00
    6.45140000e+00 -1.00000000e-05 5.96900000e+01 $cell 107
64 rpp 8.44500000e-01 6.92750000e+00 6.48950000e+00
    6.54030000e+00 -1.00000000e-05 5.96900000e+01 $cell 108
65 rpp 4.94000000e-01 7.27800000e+00 6.45140000e+00
    6.57840000e+00 -1.00000000e-05 5.96900000e+01 $ext. of cell 109
66 rpp 4.94000000e-01 7.27800000e+00 6.57840000e+00
    6.80190000e+00 -1.00000000e-05 5.96900000e+01 $cell 110
67 rpp 8.44500000e-01 6.92750000e+00 6.84000000e+00
    6.89080000e+00 -1.00000000e-05 5.96900000e+01 $cell 111
68 rpp 4.94000000e-01 7.27800000e+00 6.80190000e+00
    6.92890000e+00 -1.00000000e-05 5.96900000e+01 $ext. of cell 112
69 rpp 4.94000000e-01 7.27800000e+00 6.92890000e+00
    7.15240000e+00 -1.00000000e-05 5.96900000e+01 $cell 113
70 rpp 8.44500000e-01 6.92750000e+00 7.19050000e+00
    7.24130000e+00 -1.00000000e-05 5.96900000e+01 $cell 114
71 rpp 4.94000000e-01 7.27800000e+00 7.15240000e+00
    7.27940000e+00 -1.00000000e-05 5.96900000e+01 $ext. of cell 115
72 rpp 4.94000000e-01 7.27800000e+00 7.27940000e+00
    7.50300000e+00 -1.00000000e-05 5.96900000e+01 $cell 116
73 rpp 8.44500000e-01 6.92750000e+00 7.54110000e+00
    7.59190000e+00 -1.00000000e-05 5.96900000e+01 $cell 117
74 rpp 4.94000000e-01 7.27800000e+00 7.50300000e+00
    7.63000000e+00 -1.00000000e-05 5.96900000e+01 $ext. of cell 118
c
c Other Universes, labeled "[u number][padding of zeroes][unique index]" in
c   four-digit labels
c
2001 rcc 3.886 3.886 -1e-005 0 0 59.69001 0.635
2002 rpp 0.02333 7.69667 0.02333 7.69667 -1e-005 59.69
2003 rcc 3.886 3.886 -1e-005 0 0 59.69001 11
2004 rcc 3.886 3.886 -29.07 0 0 19.54 11
2005 rcc 3.886 3.886 -1e-005 0 0 -9.52999 11
2006 rcc 3.886 3.886 59.69 0 0 15.07001 11
c
3001 rpp 0.43795 7.33405 0.43795 7.33405 -1e-005 59.69
3002 rpp 0.28555 7.48645 0.28555 7.48645 -1e-005 59.69
3003 rcc 3.886 3.886 -1e-005 0 0 59.69001 11
3004 rcc 3.886 3.886 -29.07 0 0 19.54 11
3005 rcc 3.886 3.886 -1e-005 0 0 -9.52999 11
3006 rcc 3.886 3.886 59.69 0 0 15.07001 11
c

```

```

c 4001 rcc 3.886 3.886 59.69 0 0 15.07001 0.7145
4001 rcc 3.886 3.886 27.0764 0 0 47.68361 0.7145
4002 rpp 1.28885 1.72065 1.28885 5.84815 59.69 74.76001
4003 rpp 1.18725 1.82225 1.18725 5.94975 59.69 74.76001
4004 rpp 6.05135 6.48315 1.92385 6.48315 59.69 74.76001
4005 rpp 5.94975 6.58475 1.82225 6.58475 59.69 74.76001
4006 rpp 1.92385 6.48315 1.28885 1.72065 59.69 74.76001
4007 rpp 1.82225 6.58475 1.18725 1.82225 59.69 74.76001
4008 rpp 1.18725 5.94975 5.94975 6.58475 59.69 74.76001
4009 rpp 0.75545 7.01655 0.75545 7.01655 -1e-005 74.76001
4010 rpp 0.12045 0.75545 0.12045 7.65155 -1e-005 59.69
4011 rpp 7.01655 7.65155 0.12045 7.65155 -1e-005 59.69
4012 rpp 0.75545 7.01655 0.12045 0.75545 -1e-005 59.69
4013 rpp 0.75545 7.01655 7.01655 7.65155 -1e-005 59.69
4014 rcc 3.886 3.886 -1e-005 0 0 59.69001 11
4015 rcc 3.886 3.886 -29.07 0 0 19.54 11
4016 rcc 3.886 3.886 -1e-005 0 0 -9.52999 11
4017 rcc 3.886 3.886 59.69 0 0 15.07001 11
c
c 5001 15 rpp 0.9462 1.5939 2.0231 28.7691 67.564 74.76001
5001 15 rpp 0.9462 1.5939 2.0231 28.7691 40.64 74.76001
c [z_min of rpp for 5001 is] cr height from active fuel bottom -Dr. Mo
c 5002 15 rpp 0.79405 1.74605 1.8709 28.9212 67.564 74.76001
5002 15 rpp 0.79405 1.74605 1.8709 28.9212 40.64 74.76001
5003 15 rpp 0.31755 2.22255 1.3944 29.3977 -1e-005 74.76001
5004 15 rpp 0.01905 2.52105 5e-005 34.974 -1e-005 74.76001
5005 15 rcc 1.27 17.484 -1e-005 0 0 74.76002 36
5006 15 rcc 1.27 17.484 -29.07 0 0 19.54 36
5007 15 rcc 1.27 17.484 -1e-005 0 0 -9.52999 36
c
c 6001 5 rpp 0.9462 1.5939 6.2051 32.9511 67.564 74.76001
6001 5 rpp 0.9462 1.5939 6.2051 32.9511 40.64 74.76001
c [z_min of rpp for 6001 is] cr height from active fuel bottom -Dr. Mo
c 6002 5 rpp 0.79405 1.74605 6.0554 33.1032 67.564 74.76001
6002 5 rpp 0.79405 1.74605 6.0554 33.1032 40.64 74.76001
6003 5 rpp 0.31755 2.22255 5.5764 33.5797 -1e-005 74.76001
6004 5 rpp 0.01905 2.52105 5e-005 34.974 -1e-005 74.76001
6005 5 rcc 1.27 17.484 -1e-005 0 0 74.76002 36
6006 5 rcc 1.27 17.484 -29.07 0 0 19.54 36
6007 5 rcc 1.27 17.484 -1e-005 0 0 -9.52999 36
c
c 7001 4 rpp 0.9462 1.5939 6.2051 32.9511 67.564 74.76001
7001 4 rpp 0.9462 1.5939 6.2051 32.9511 40.64 74.76001
c [z_min of rpp for 7001 is] cr height from active fuel bottom -Dr. Mo
c 7002 4 rpp 0.79405 1.74605 6.0554 33.1032 67.564 74.76001
7002 4 rpp 0.79405 1.74605 6.0554 33.1032 40.64 74.76001
7003 4 rpp 0.31755 2.22255 5.5764 33.5797 -1e-005 74.76001
7004 4 rpp 0.01905 2.52105 5e-005 34.974 -1e-005 74.76001
7005 4 rcc 1.27 17.484 -1e-005 0 0 74.76002 36
7006 4 rcc 1.27 17.484 -29.07 0 0 19.54 36
7007 4 rcc 1.27 17.484 -1e-005 0 0 -9.52999 36 $-9.53 0 0 9.52999 36
c
c 8001 14 rpp 0.9462 1.5939 2.0231 28.7691 67.564 74.76001
8001 14 rpp 0.9462 1.5939 2.0231 28.7691 40.64 74.76001
c [z_min of rpp for 801 is] cr height from active fuel bottom -Dr. Mo
c 8002 14 rpp 0.79405 1.74605 1.8709 28.9212 67.564 74.76001
8002 14 rpp 0.79405 1.74605 1.8709 28.9212 40.64 74.76001
8003 14 rpp 0.31755 2.22255 1.3944 29.3977 0 74.76001
8004 14 rpp 0.01905 2.52105 5e-005 34.974 -1e-005 74.76001
8005 14 rcc 1.27 17.484 -1e-005 0 0 74.76002 36
8006 14 rcc 1.27 17.484 -29.07 0 0 19.54 36
8007 14 rcc 1.27 17.484 -1e-005 0 0 -9.52999 36
c
1001 rcc 3.886 3.886 -1e-005 0 0 59.69001 0.23876
1002 rcc 3.886 3.886 -1e-005 0 0 59.69001 1.98374
1003 rcc 3.886 3.886 -1e-005 0 0 59.69001 2.06375
1004 rpp 0.02333 7.69667 0.02333 7.69667 -1e-005 59.69
1005 rcc 3.886 3.886 -1e-005 0 0 59.69001 11
1006 rcc 3.886 3.886 -29.07 0 0 19.54 11
1007 rcc 3.886 3.886 -1e-005 0 0 -9.52999 11
1008 rcc 3.886 3.886 59.69 0 0 15.07001 11
c

```

```

1101 rcc 3.886 3.886 -1e-005 0 0 59.69001 2.3749
1102 rcc 3.886 3.886 -1e-005 0 0 59.69001 2.54
1103 rpp 0.45446 7.31754 0.45446 7.31754 -1e-005 59.69
1104 rpp 0.13696 7.63504 0.13696 7.63504 -1e-005 59.69
1105 rcc 3.886 3.886 -1e-005 0 0 59.69001 11
1106 rcc 3.886 3.886 -29.07 0 0 19.54 11
1107 rcc 3.886 3.886 -1e-005 0 0 -9.52999 11
1108 rcc 3.886 3.886 59.69 0 0 15.07001 11
c
1201 rpp -1e-005 7.77201 -1e-005 7.77201 -1e-005 59.69
1202 rcc 3.886 3.886 -1e-005 0 0 59.69001 11
1203 rcc 3.886 3.886 -29.07 0 0 19.54 11
1204 rcc 3.886 3.886 -1e-005 0 0 -9.52999 11
1205 rcc 3.886 3.886 59.69 0 0 15.07001 11
c

c ~~~~~
c DATA BLOCK
c ~~~~~
c
mode n
kcode 10000 1.0 10 110
ksrc 5.6705E+01 9.5805E+01 6.5595E+01
5.7576E+01 9.6152E+01 6.5595E+01
5.7555E+01 9.6504E+01 6.5595E+01
5.7582E+01 9.6856E+01 6.5595E+01
5.7514E+01 9.7208E+01 6.5595E+01
5.7611E+01 9.7556E+01 6.5595E+01
5.7497E+01 9.7904E+01 6.5595E+01
5.7711E+01 9.8255E+01 6.5595E+01
5.7995E+01 9.8607E+01 6.5595E+01
5.7670E+01 9.8959E+01 6.5595E+01
5.7555E+01 9.9311E+01 6.5595E+01
5.7488E+01 9.9659E+01 6.5595E+01
5.7678E+01 1.0001E+02 6.5595E+01
5.7611E+01 1.0036E+02 6.5595E+01
5.4285E+01 1.0071E+02 6.5595E+01
5.5249E+01 1.0106E+02 6.5595E+01
5.5158E+01 1.0141E+02 6.5595E+01
5.4974E+01 1.0177E+02 6.5595E+01
5.5047E+01 1.0211E+02 6.5595E+01
5.5120E+01 1.0247E+02 6.5595E+01
5.4912E+01 1.0282E+02 6.5595E+01
5.5384E+01 1.0316E+02 6.5595E+01
c
ksen1 xs
c
ksen2 xs erg=0 0.000000625 0.1 1.00E+36
c
c 1/meat 2/clad 3/h2o 4/grid plate 5/Bot ref 6/Top ref
c 7/Shim Rod 8/Reg Rod 9/Pb 10/Graphite 11/Be -Dr. Mo
c
m1 92234. 5.6795e-009
92235. 0.00175523 92236. 7.1358e-009 92238. 0.00704193
13027. 0.0388984 14000. 0.00594365
c
m2 13027. 0.0602669
5010. 2.98636e-007 5011. 1.21115e-006
c
m3 1001. 0.066861
8016. 0.0334305
mt3 lwtr.01t
c
m4 1001. 0.040117
13027. 0.024107 8016. 0.020058 5010. 1.1945e-007
5011. 4.8446e-007
mt4 lwtr.01t
c
m5 1001. 0.05155
13027. 0.013064 14000. 0.00071537 12000. 3.5418e-005
5010. 1.5873e-008 5011. 6.4373e-008 8016. 0.025775
mt5 lwtr.01t

```



```

c
m6      1001.      0.033431
      13027.      0.030133 8016.      0.016715 5010.      1.4932e-007
      5011.      6.0557e-007
mt6      lwtr.01t
c
m7      5010.      0.007566
      5011.      0.030685 6012.      0.01158 13027.      0.03839
mt7      grph.01t
c
m8      14000.      0.0017147
      24000.      0.017598 25055.      0.0017532 26000.      0.058505
      28000.      0.0082029
c
m9      82000.      0.032962
c
m10     6012.      0.08023
mt10     grph.01t
c
m11     4009.      0.12364
mt11     be.01t
c
tr2     52.629 95.598 35.75
tr3     26.773 64.51 35.75
tr4     42.317 64.51 35.75
tr14    42.317 99.484 35.75
tr5     68.173 64.51 35.75
tr15    68.173 99.484 35.75
tr6     70.713 64.51 35.75
c
c      Debugging
c
RAND GEN 4 seed=5520000000000000007
LOST 10
DBCN 4J 6000
c
c      Tallies!
c
FC04 Spatial Profile of Neutron Flux
      10000 n/cycle,
      210000 Core voxels (60 x 70 x 50),
      each 1 cm square
      with a height of 1.1938 cm
fmesh04:n geom=xyz origin 18.948 56.685 26.22
imesh 26.72 86.31 94.082 iints 50 60 50
jmesh 64.457 134.511 142.283 jints 50 70 50
kmesh 35.75 95.44 110.51 kints 50 50 50
emesh 0.000000625 0.1 1.00E+36
out cf
print

```

“Continue” Deck for the Model

```

continue
c See Section 9.1.2 in User Manual for details of input deck format.
c
3/18/2018
c      Running for 1010 total KCODE cycles
kcode 10000 1.0 10 1010

```

Template “Continue” Deck

```

continue
c See Section 9.1.2 in User Manual for details of input deck format.
c
3/18/2018
c      Running for TOTAL_CYC total KCODE cycles

```

kcode 10000 1.0 10 TOTAL_CYC

Template "Initiate" Deck

Ben's Adaptation of Dr. Mo's Model of the RINSC Core

```
c RINSC Core #6 - Fresh Fuel
c Comments are of my making, unless specifically attributed to Dr. Mo. -Ben
c
c -Core #6
c @@@ NEAR_X = 26.72
c @@@ FAR_X = 86.31
c @@@ NEAR_Y = 64.457
c @@@ FAR_Y = 134.511
c @@@ tied = NEAR_X FAR_X NEAR_Y FAR_Y
c @@@ X_NMRTR = (FAR_X - NEAR_X)
c @@@ Y_NMRTR = (FAR_Y - NEAR_Y)
c @@@ X_BIN_LEN = 1
c @@@ Y_BIN_LEN = 1
c @@@ X_RES = (int((FAR_X - NEAR_X)/X_BIN_LEN+0.5))
c @@@ Y_RES = (int((FAR_Y - NEAR_Y)/Y_BIN_LEN+0.5))
c @@@ NEAR_Z = 35.75
c @@@ FAR_Z = 95.44
c @@@ Z_RES = 50
c @@@ tied = X_BIN_LEN Y_BIN_LEN Z_RES
c @@@ Z_BIN_LEN = ((FAR_Z - NEAR_Z)/Z_RES)
c @@@ RES = (X_RES*Y_RES*Z_RES)
c
c The mesh tally for the flux profile is divided on the core:
c along x into X_RES intervals, each X_BIN_LEN cm long;
c along y into Y_RES intervals, each Y_BIN_LEN cm long;
c along z into Z_RES intervals, each Z_BIN_LEN cm long;
c for a total of RES 3-D voxels throughout the core.
c @@@ X1 = (NEAR_X - 7.772)
c @@@ X_01 = (Z_RES)
c @@@ X_23 = (X_01)
c @@@ X3 = (FAR_X + 7.772)
c @@@ Y1 = (NEAR_Y - 7.772)
c @@@ Y_01 = (X_01)
c @@@ Y_23 = (Y_01)
c @@@ Y3 = (FAR_Y + 7.772)
c @@@ Z2 = 26.22
c @@@ Z_23 = (X_01)
c @@@ Z_45 = (Z_23)
c @@@ Z5 = 110.51
c @@@ TOTAL_VOXELS = ((X_01+X_RES+X_23)*(Y_01+Y_RES+Y_23)*(Z_23+Z_RES+Z_45))
c That same mesh is divided into TOTAL_VOXELS voxels overall.
c @@@ RATIO = (RES/TOTAL_VOXELS)
c (core voxels / overall voxels = RATIO)
c (See tally cards directly for more details as to how it's
divided
c over the rest of the non-void space.)
c @@@ N_PER_CYCLE = 10000
c This problem is running N_PER_CYCLE neutrons in each cycle
c @@@ K_GUESS = 1.0
c My initial k_eff guess is K_GUESS
c @@@ DISCARD_CYC = 10
c @@@ ACTIVE_CYC = 100
c @@@ TOTAL_CYC = (DISCARD_CYC + ACTIVE_CYC)
c Running for ACTIVE_CYC active cycles after discarding the
first DISCARD_CYC
c @@@ SOURCE_STRENGTH = (N_PER_CYCLE*ACTIVE_CYC)
c -which will result in SOURCE_STRENGTH source particle
histories.
c @@@ BLADE_IN = 16.00
c @@@ RR_IN = 10.66
c @@@ tied = BLADE_IN RR_IN
c @@@ IN_2_CM = 2.540000
c @@@ BLADE1_HEIGHT = (BLADE_IN*IN_2_CM)
c @@@ BLADE2_HEIGHT = BLADE1_HEIGHT
c @@@ BLADE3_HEIGHT = BLADE1_HEIGHT
c @@@ BLADE4_HEIGHT = BLADE1_HEIGHT
```

```

c   @@@ REG_ROD_BASE = (RR_IN*IN_2_CM)
c   @@@ REG_ROD_LENGTH = (15.07001 + 59.69 - REG_ROD_BASE)
c       All the shim safety blades are raised BLADE1_HEIGHT cm, while the
c       regulating rod is at REG_ROD_BASE cm.
c
c       ~~~~~+
c       CELL BLOCK
c       ~~~~~-
c
c Universe Zero
c
c 1 0 -9001 imp:n=1 fill=101
c
c 11 0 -9004 imp:n=1 fill=103
c
c 21 0 -9007 imp:n=1 fill=105
c
c 27 2 0.0602684 -9013 imp:n=1 $x left side -Dr. Mo
c 28 3 0.100292 9013 -9025 imp:n=1 $x left side -Dr. Mo
c 29 3 0.100292 -9008 imp:n=1 $x left water -Dr. Mo
c
c 30 2 0.0602684 -9014 imp:n=1 $x right side -Dr. Mo
c 31 3 0.100292 9014 -9026 imp:n=1 $x right side -Dr. Mo
c 32 3 0.100292 -9011 imp:n=1 $x right water -Dr. Mo
c
c 33 2 0.0602684 -9012 imp:n=1 $y bottom Al -Dr. Mo
c 34 3 0.100292 9012 -9027 imp:n=1 $y bottom water -Dr. Mo
c 35 3 0.100292 -9015 imp:n=1 $y bottom water -Dr. Mo
c
c 36 2 0.0602684 -9010 imp:n=1 $y top Al -Dr. Mo
c 37 3 0.100292 9010 -9028 imp:n=1 $y top water -Dr. Mo
c 38 3 0.100292 -9009 imp:n=1 $y top water -Dr. Mo
c
c 39 10 0.08023 -9020 imp:n=1 imp:n=1 $graphite -Dr. Mo
c 40 2 0.0602684 -9021 imp:n=1 $TC1 clad -Dr. Mo
c 41 10 0.08023 -9029 imp:n=1 $graphite -Dr. Mo
c 42 2 0.0602684 9029 -9016 imp:n=1 $TC2 clad -Dr. Mo
c
c 43 9 0.032962 -9017 imp:n=1 $lead shield -Dr. Mo
c 44 2 0.0602684 9017 -9018 imp:n=1 $lead shield -Dr. Mo
c
c 45 3 0.100292 9020 9021 9016 9018 -9019 imp:n=1 $water reflec -Dr. Mo
c
c 46 3 0.100292 -9022 imp:n=1 $water reflec -Dr. Mo
c 47 3 0.100292 -9024 imp:n=1 $water reflec -Dr. Mo
c 48 3 0.100292 -9023 imp:n=1 $water reflec -Dr. Mo
c
c 49 0 9030 imp:n=0 $outside void -Dr. Mo
c
c Control Blade 1 (formerly universe 5)
c
c 751 7 0.088221 -5001 imp:n=1 $absorber -Dr. Mo
c 752 2 0.0602684 5001 -5002 imp:n=1 $al clad -Dr. Mo
c 753 3 0.100292 5002 -5003 imp:n=1 $water -Dr. Mo
c 754 2 0.0602684 5003 -5004 -9006 imp:n=1 $al guid -Dr. Mo
c 755 3 0.100292 5004 -5005 -9006 imp:n=1 $h2o gap -Dr. Mo
c held off on re-making cell 758 -Ben
c 759 4 0.0842826 -5006 -9006 imp:n=1 $grid support -Dr. Mo
c 760 5 0.0911399 -5007 -9006 imp:n=1 $bottom reflect -Dr. Mo
c held off on re-making cell 762 -Ben
c 763 3 0.100292 5005 5006 5007 -9006 imp:n=1 $Finishes control blade
region! -Ben
c
c Control Blade 2 (formerly universe 6)
c
c 801 7 0.088221 -6001 -9005 imp:n=1 $absorber -Dr. Mo
c 802 2 0.0602684 6001 -6002 -9005 imp:n=1 $al clad -Dr. Mo
c 803 3 0.100292 6002 -6003 -9005 imp:n=1 $water -Dr. Mo
c 804 2 0.0602684 6003 -6004 -9005 imp:n=1 $al guid -Dr. Mo
c 805 3 0.100292 6004 -6005 -9005 imp:n=1 $h2o gap -Dr. Mo
c held off on re-making cell 808 -Ben
c 809 4 0.0842826 -6006 -9005 imp:n=1 $grid support -Dr. Mo

```

```

810 5 0.0911399 -6007 -9005 imp:n=1 $bottom reflect -Dr. Mo
c
c held off on re-making cell 812 -Ben
813 3 0.100292 6005 6006 6007 -9005 imp:n=1 $Finishes control blade
region! -Ben
c
c Control Blade 3 (formerly universe 7)
c
851 7 0.088221 -7001 -9002 imp:n=1 $absorber -Dr. Mo
852 2 0.0602684 7001 -7002 -9002 imp:n=1 $al clad -Dr. Mo
853 3 0.100292 7002 -7003 -9002 imp:n=1 $water -Dr. Mo
854 2 0.0602684 7003 -7004 -9002 imp:n=1 $al guid -Dr. Mo
855 3 0.100292 7004 -7005 -9002 imp:n=1 $h2o gap -Dr. Mo
c held off on re-making cell 858 -Ben
859 4 0.0842826 -7006 -9002 imp:n=1 $grid support -Dr. Mo
860 5 0.0911399 -7007 -9002 imp:n=1 $bottom reflect -Dr. Mo
c held off on re-making cell 862 -Ben
863 3 0.100292 7005 7006 7007 -9002 imp:n=1 $Finishes control blade
region! -Ben
c
c Control Blade 4 (formerly universe 8)
c
901 7 0.088221 -8001 -9003 imp:n=1 $absorber -Dr. Mo
902 2 0.0602684 8001 -8002 -9003 imp:n=1 $al clad -Dr. Mo
903 3 0.100292 8002 -8003 -9003 imp:n=1 $water -Dr. Mo
904 2 0.0602684 8003 -8004 -9003 imp:n=1 $al guid -Dr. Mo
905 3 0.100292 8004 -8005 -9003 imp:n=1 $h2o gap -Dr. Mo
906 3 0.100292 8005 8006 8007 -9003 imp:n=1 $Finishes control blade
region! -Ben
c held off on re-making cell 908 -Ben
909 4 0.0842826 -8006 -9003 imp:n=1 $grid support -Dr. Mo
910 5 0.0911399 -8007 -9003 imp:n=1 $bottom reflect -Dr. Mo
c held off on re-making cell 912 -Ben
c
c Mid-Level Universes
c
2 0 -10188881 u=101 imp:n=1 lat=1
fill=0:1 0:8 0:0
12(3) 3(3) $ROW 1
3(3) 3(3) $ROW 2
3(3) 2(3) $ROW 3
3(3) 2(3) $ROW 4
3(3) 2(3) $ROW 5
3(3) 2(3) $ROW 6
3(3) 2(3) $ROW 7
3(3) 3(3) $ROW 8
12(3) 1100 $ROW 9 $Notice I no longer reference u11 directly here. -Ben
c G F
c
12 0 -10388881 u=103 lat=1 imp:n=1
fill=-1:1 -4:4 0:0
3(2) 3(2) 3(2) $ROW 1
2(2) 4(2) 2(2) $ROW 2
19 19 19 $ROW 3 $I've replaced "1(2)" with "19" -Ben
19 19 19 $ROW 4
19 10(2) 19 $ROW 5
19 19 19 $ROW 6
19 19 19 $ROW 7
2(2) 2(2) 2(2) $ROW 8
1101 1101 1101 $ROW 9 $Notice I no longer reference u11 directly here.
-Ben
c E D C
c
22 0 -10588881 u=105 lat=1 imp:n=1
fill=0:1 0:8 0:0 $Notice I no longer reference u12 directly in what
follows. -Ben
3(6) 1202 $ROW 1
3(6) 3(6) $ROW 2
2(6) 3(6) $ROW 3
2(6) 3(6) $ROW 4
2(6) 3(6) $ROW 5
2(6) 3(6) $ROW 6

```

```

2(6) 3(6) $ROW 7
3(6) 3(6) $ROW 8
11(6) 1202 $ROW 9
c   B   A
c
c Ground Floor (and Additional) Universes
c
266 0 -10388881 fill=1(2) lat=1 imp:n=1 u=19
c
50 3 0.100292 2 -1 u=1 imp:n=1 vol=43.24
c
51 2 6.02684E-02 -3 u=1 imp:n=1 $sideplate l -Dr. Mo
52 2 6.02684E-02 -4 u=1 imp:n=1 $sideplate r -Dr. Mo
53 3 1.00292E-01 -5 u=1 imp:n=1 $h20 1 -Dr. Mo
c
54 1 0.0536392 -6 u=1 imp:n=1 $meat 1 -Dr. Mo
c
55 2 6.02684E-02 6 -7 u=1 imp:n=1 $clad 1 -Dr. Mo
c
56 3 1.00292E-01 -8 u=1 imp:n=1 $h2o 2 -Dr. Mo
57 1 0.0536392 -14 u=1 imp:n=1
58 2 6.02684E-02 14 -15 u=1 imp:n=1
c
59 3 1.00292E-01 -9 u=1 imp:n=1
60 1 0.0536392 -16 u=1 imp:n=1
61 2 6.02684E-02 16 -17 u=1 imp:n=1
c
62 3 1.00292E-01 -18 u=1 imp:n=1
63 1 0.0536392 -19 u=1 imp:n=1
64 2 6.02684E-02 19 -20 u=1 imp:n=1
c
65 3 1.00292E-01 -21 u=1 imp:n=1
66 1 0.0536392 -22 u=1 imp:n=1
67 2 6.02684E-02 22 -23 u=1 imp:n=1
c
68 3 1.00292E-01 -24 u=1 imp:n=1
69 1 0.0536392 -25 u=1 imp:n=1
70 2 6.02684E-02 25 -26 u=1 imp:n=1
c
71 3 1.00292E-01 -27 u=1 imp:n=1
72 1 0.0536392 -28 u=1 imp:n=1
73 2 6.02684E-02 28 -29 u=1 imp:n=1
c
74 3 1.00292E-01 -30 u=1 imp:n=1
75 1 0.0536392 -31 u=1 imp:n=1
76 2 6.02684E-02 31 -32 u=1 imp:n=1
c
77 3 1.00292E-01 -33 u=1 imp:n=1
78 1 0.0536392 -34 u=1 imp:n=1
79 2 6.02684E-02 34 -35 u=1 imp:n=1
c
80 3 1.00292E-01 -36 u=1 imp:n=1
81 1 0.0536392 -37 u=1 imp:n=1
82 2 6.02684E-02 37 -38 u=1 imp:n=1
c
83 3 1.00292E-01 -39 u=1 imp:n=1
84 1 0.0536392 -40 u=1 imp:n=1
85 2 6.02684E-02 40 -41 u=1 imp:n=1
c
86 3 1.00292E-01 -42 u=1 imp:n=1
87 1 0.0536392 -43 u=1 imp:n=1
88 2 6.02684E-02 43 -44 u=1 imp:n=1
c
89 3 1.00292E-01 -45 u=1 imp:n=1
90 1 0.0536392 -46 u=1 imp:n=1
91 2 6.02684E-02 46 -47 u=1 imp:n=1
c
92 3 1.00292E-01 -48 u=1 imp:n=1
93 1 0.0536392 -49 u=1 imp:n=1
94 2 6.02684E-02 49 -50 u=1 imp:n=1
c
95 3 1.00292E-01 -51 u=1 imp:n=1

```

```

96 1 0.0536392 -52 u=1 imp:n=1
97 2 6.02684E-02 52 -53 u=1 imp:n=1
c
98 3 1.00292E-01 -54 u=1 imp:n=1
99 1 0.0536392 -55 u=1 imp:n=1
100 2 6.02684E-02 55 -56 u=1 imp:n=1
c
101 3 1.00292E-01 -57 u=1 imp:n=1
102 1 0.0536392 -58 u=1 imp:n=1
103 2 6.02684E-02 58 -59 u=1 imp:n=1
c
104 3 1.00292E-01 -60 u=1 imp:n=1
105 1 0.0536392 -61 u=1 imp:n=1
106 2 6.02684E-02 61 -62 u=1 imp:n=1
c
107 3 1.00292E-01 -63 u=1 imp:n=1
108 1 0.0536392 -64 u=1 imp:n=1
109 2 6.02684E-02 64 -65 u=1 imp:n=1
c
110 3 1.00292E-01 -66 u=1 imp:n=1
111 1 0.0536392 -67 u=1 imp:n=1
112 2 6.02684E-02 67 -68 u=1 imp:n=1
c
113 3 1.00292E-01 -69 u=1 imp:n=1
114 1 0.0536392 -70 u=1 imp:n=1
115 2 6.02684E-02 70 -71 u=1 imp:n=1
c
116 3 1.00292E-01 -72 u=1 imp:n=1
117 1 0.0536392 -73 u=1 imp:n=1
118 2 6.02684E-02 73 -74 u=1 imp:n=1
c
119 3 1.00292E-01 -10 u=1 imp:n=1 $h2o end -Dr. Mo
c held off on re-making cell 120 -Ben
121 4 0.0842826 -11 u=1 imp:n=1 $grid support -Dr. Mo
122 5 0.0911399 -12 u=1 imp:n=1 $bottom reflect -Dr. Mo
c
123 5 0.0911399 -13 u=1 imp:n=1 $top reflector -Dr. Mo
c held off on re-making cell 124 -Ben
125 3 0.100292 1 11 12 13 u=1 imp:n=1 vol=1 $Finishes universe! -Ben
c
501 3 0.100292 -2001 u=2 imp:n=1
502 11 0.12364 2001 -2002 u=2 imp:n=1
503 3 0.100292 2002 -2003 u=2 imp:n=1
504 3 0.100292 2003 2004 2005 2006 u=2 imp:n=1 $Finishes universe! -Ben
c held off on re-making cell 508 -Ben
509 4 0.0842826 -2004 u=2 imp:n=1 $grid support -Dr. Mo
510 5 0.0911399 -2005 u=2 imp:n=1 $bottom reflect -Dr. Mo
c
511 5 0.0911399 -2006 u=2 imp:n=1 $top reflector -Dr. Mo
c held off on re-making cell 512 -Ben
c
531 10 0.08023 -3001 u=3 imp:n=1 $Graphite block -Dr. Mo
532 2 0.0602684 3001 -3002 u=3 imp:n=1 $al box -Dr. Mo
533 3 0.100292 3002 -3003 u=3 imp:n=1 $water gap -Dr. Mo
c held off on re-making cell 538 -Ben
539 4 0.0842826 -3004 u=3 imp:n=1 $grid support -Dr. Mo
540 5 0.0911399 -3005 u=3 imp:n=1 $bottom reflect -Dr. Mo
541 5 0.0911399 -3006 u=3 imp:n=1 $top reflector -Dr. Mo
c held off on re-making cell 542 -Ben
543 3 0.100292 3003 3004 3005 3006 u=3 imp:n=1 $Finishes universe! -Ben
c
708 2 0.0602684 -4001 u=4 imp:n=1 $central rod -Dr. Mo
709 8 0.0877738 -4002 u=4 imp:n=1 $x-left absorber -Dr. Mo
710 2 0.0602684 4002 -4003 u=4 imp:n=1 $x-left clad -Dr. Mo
711 8 0.0877738 -4004 u=4 imp:n=1 $x-left absorber -Dr. Mo
712 2 0.0602684 4004 -4005 u=4 imp:n=1 $x-left clad -Dr. Mo
713 8 0.0877738 -4006 u=4 imp:n=1 $y-bottom absorber -Dr. Mo
714 2 0.0602684 4006 -4007 u=4 imp:n=1 $y-bottom clad -Dr. Mo
c
715 2 0.0602684 -4008 u=4 imp:n=1 $y-top clad -Dr. Mo
c
716 3 0.100292 4001 4003 4005 4007 4008 -4009 u=4 imp:n=1

```



```

9008 rpp 26.72 26.77301 64.457 134.511 0 160 $cell 29
9009 rpp 26.77301 86.256999 134.45799 134.511 0 160 $cell 38
9010 rpp 26.72 86.31 134.511 135.146 26.22 110.51 $cell 36
9011 rpp 86.256999 86.31 64.457 134.511 0 160 $cell 32
9012 rpp 26.72 86.31 63.822 64.457 26.22 110.51 $cell 33
9013 rpp 26.085 26.72 63.822 135.146 26.22 110.51 $cell 27
9014 rpp 86.31 86.945 63.822 135.146 26.22 110.51 $cell 30
9015 rpp 26.77301 86.256999 64.457 64.51001 0 160 $cell 35
9016 rpp 11.43 101.6 29.527 52.387 28.45 117.35 $cell 42
9017 rpp 27.94 85.09 53.977 61.597 34.16 96.0725 $cell 43
9018 rpp 11.43 101.6 52.387 63.187 28.45 117.35 $cell 44
9019 rpp 0 120 0 63.822 0 160 $ext. of cell 45
9020 rpp 0 113.03 0 26.987 0 158.94 $cell 39
9021 rpp 0 113.03 26.987 29.527 0 158.94 $cell 40
9022 rpp 0 26.085 63.822 160 0 160 $cell 46
9023 rpp 26.085 86.945 135.146 160 0 160 $cell 48
9024 rpp 86.945 120 63.822 160 0 160 $cell 47
9025 rpp 26.085 26.72 63.822 135.146 0 160 $cell 28
9026 rpp 86.31 86.945 63.822 135.146 0 160 $ext. of cell 31
9027 rpp 26.72 86.31 63.822 64.457 0 160 $cell 34
9028 rpp 26.72 86.31 134.511 135.146 0 160 $cell 37
9029 rpp 13.96 99.06 29.527 49.847 29.72 116.08 $cell 41
9030 rpp 0 120 0 160 0 160 $ext. of cell 49
c
c Lattice Surfaces
c
10188881 rpp 26.773 34.545 64.51 72.282 0 0 $infinite in z -Ben
c [xmin of 10188881 is] corner element G1 -Dr. Mo
c
10388881 rpp 52.629 60.401 95.598 103.37 0 0 $infinite in z -Ben
c [xmin of 10388881 is] central element flux trap -Dr. Mo
c
10588881 rpp 70.713 78.485 64.51 72.282 0 0 $infinite in z -Ben
c [xmax of 10588881 is] element B2 -Dr. Mo
c
c Universe One
c
1 rcc 3.886 3.886 -1e-005 0 0 59.69001 11 $ext. of Cell 50
2 rpp 0.019 7.753 0.02774 7.74426 -1e-005 59.69 $int. of cell 50
3 rpp 0.019 0.494 0.02774 7.74426 -1e-005 59.69 $cell 51
4 rpp 7.278 7.753 0.02774 7.74426 -1e-005 59.69 $cell 52
5 rpp 0.494 7.278 0.02774 0.142 -1e-005 59.69 $cell 53
6 rpp 0.8445 6.9275 0.1801 0.2309 -1e-005 59.69 $cell 54
7 rpp 0.494 7.278 0.142 0.269 -1e-005 59.69 $ext. of cell 55
8 rpp 0.494 7.278 0.269 0.4926 -1e-005 59.69 $cell 56
9 rpp 0.494 7.278 0.6196 0.8431 -1e-005 59.69 $cell 59
10 rpp 0.494 7.278 7.63 7.74426 -1e-005 59.69 $cell 119
11 rcc 3.886 3.886 -29.07 0 0 19.54 11 $cell 121
12 rcc 3.886 3.886 -1e-005 0 0 -9.52999 11 $cell 122
13 rcc 3.886 3.886 59.69 0 0 15.07001 11 $cell 123
14 rpp 8.44500000e-01 6.92750000e+00 5.30700000e-01
5.81500000e-01 -1.00000000e-05 5.96900000e+01 $cell 57
15 rpp 4.94000000e-01 7.27800000e+00 4.92600000e-01
6.19600000e-01 -1.00000000e-05 5.96900000e+01 $ext. of cell 58
16 rpp 8.44500000e-01 6.92750000e+00 8.81200000e-01
9.32000000e-01 -1.00000000e-05 5.96900000e+01 $cell 60
17 rpp 4.94000000e-01 7.27800000e+00 8.43100000e-01
9.70100000e-01 -1.00000000e-05 5.96900000e+01 $ext. of cell 61
18 rpp 4.94000000e-01 7.27800000e+00 9.70100000e-01
1.19360000e+00 -1.00000000e-05 5.96900000e+01 $cell 62
19 rpp 8.44500000e-01 6.92750000e+00 1.23170000e+00
1.28250000e+00 -1.00000000e-05 5.96900000e+01 $cell 63
20 rpp 4.94000000e-01 7.27800000e+00 1.19360000e+00
1.32060000e+00 -1.00000000e-05 5.96900000e+01 $ext. of cell 64
21 rpp 4.94000000e-01 7.27800000e+00 1.32060000e+00
1.54410000e+00 -1.00000000e-05 5.96900000e+01 $cell 65
22 rpp 8.44500000e-01 6.92750000e+00 1.58220000e+00
1.63300000e+00 -1.00000000e-05 5.96900000e+01 $cell 66
23 rpp 4.94000000e-01 7.27800000e+00 1.54410000e+00
1.67110000e+00 -1.00000000e-05 5.96900000e+01 $ext. of cell 67
24 rpp 4.94000000e-01 7.27800000e+00 1.67110000e+00
1.89460000e+00 -1.00000000e-05 5.96900000e+01 $cell 68

```


25 rpp 8.44500000e-01 6.92750000e+00 1.93270000e+00
 1.98350000e+00 -1.00000000e-05 5.96900000e+01 \$cell 69
 26 rpp 4.94000000e-01 7.27800000e+00 1.89460000e+00
 2.02160000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 70
 27 rpp 4.94000000e-01 7.27800000e+00 2.02160000e+00
 2.24520000e+00 -1.00000000e-05 5.96900000e+01 \$cell 71
 28 rpp 8.44500000e-01 6.92750000e+00 2.28330000e+00
 2.33410000e+00 -1.00000000e-05 5.96900000e+01 \$cell 72
 29 rpp 4.94000000e-01 7.27800000e+00 2.24520000e+00
 2.37220000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 73
 30 rpp 4.94000000e-01 7.27800000e+00 2.37220000e+00
 2.59570000e+00 -1.00000000e-05 5.96900000e+01 \$cell 74
 31 rpp 8.44500000e-01 6.92750000e+00 2.63380000e+00
 2.68460000e+00 -1.00000000e-05 5.96900000e+01 \$cell 75
 32 rpp 4.94000000e-01 7.27800000e+00 2.59570000e+00
 2.72270000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 76
 33 rpp 4.94000000e-01 7.27800000e+00 2.72270000e+00
 2.94620000e+00 -1.00000000e-05 5.96900000e+01 \$cell 77
 34 rpp 8.44500000e-01 6.92750000e+00 2.98430000e+00
 3.03510000e+00 -1.00000000e-05 5.96900000e+01 \$cell 78
 35 rpp 4.94000000e-01 7.27800000e+00 2.94620000e+00
 3.07320000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 79
 36 rpp 4.94000000e-01 7.27800000e+00 3.07320000e+00
 3.29670000e+00 -1.00000000e-05 5.96900000e+01 \$cell 80
 37 rpp 8.44500000e-01 6.92750000e+00 3.33480000e+00
 3.38560000e+00 -1.00000000e-05 5.96900000e+01 \$cell 81
 38 rpp 4.94000000e-01 7.27800000e+00 3.29670000e+00
 3.42370000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 82
 39 rpp 4.94000000e-01 7.27800000e+00 3.42370000e+00
 3.64720000e+00 -1.00000000e-05 5.96900000e+01 \$cell 83
 40 rpp 8.44500000e-01 6.92750000e+00 3.68530000e+00
 3.73610000e+00 -1.00000000e-05 5.96900000e+01 \$cell 84
 41 rpp 4.94000000e-01 7.27800000e+00 3.64720000e+00
 3.77420000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 85
 42 rpp 4.94000000e-01 7.27800000e+00 3.77420000e+00
 3.99780000e+00 -1.00000000e-05 5.96900000e+01 \$cell 86
 43 rpp 8.44500000e-01 6.92750000e+00 4.03590000e+00
 4.08670000e+00 -1.00000000e-05 5.96900000e+01 \$cell 87
 44 rpp 4.94000000e-01 7.27800000e+00 3.99780000e+00
 4.12480000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 88
 45 rpp 4.94000000e-01 7.27800000e+00 4.12480000e+00
 4.34830000e+00 -1.00000000e-05 5.96900000e+01 \$cell 89
 46 rpp 8.44500000e-01 6.92750000e+00 4.38640000e+00
 4.43720000e+00 -1.00000000e-05 5.96900000e+01 \$cell 90
 47 rpp 4.94000000e-01 7.27800000e+00 4.34830000e+00
 4.47530000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 91
 48 rpp 4.94000000e-01 7.27800000e+00 4.47530000e+00
 4.69880000e+00 -1.00000000e-05 5.96900000e+01 \$cell 92
 49 rpp 8.44500000e-01 6.92750000e+00 4.73690000e+00
 4.78770000e+00 -1.00000000e-05 5.96900000e+01 \$cell 93
 50 rpp 4.94000000e-01 7.27800000e+00 4.69880000e+00
 4.82580000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 94
 51 rpp 4.94000000e-01 7.27800000e+00 4.82580000e+00
 5.04930000e+00 -1.00000000e-05 5.96900000e+01 \$cell 95
 52 rpp 8.44500000e-01 6.92750000e+00 5.08740000e+00
 5.13820000e+00 -1.00000000e-05 5.96900000e+01 \$cell 96
 53 rpp 4.94000000e-01 7.27800000e+00 5.04930000e+00
 5.17630000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 97
 54 rpp 4.94000000e-01 7.27800000e+00 5.17630000e+00
 5.39980000e+00 -1.00000000e-05 5.96900000e+01 \$cell 98
 55 rpp 8.44500000e-01 6.92750000e+00 5.43790000e+00
 5.48870000e+00 -1.00000000e-05 5.96900000e+01 \$cell 99
 56 rpp 4.94000000e-01 7.27800000e+00 5.39980000e+00
 5.52680000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 100
 57 rpp 4.94000000e-01 7.27800000e+00 5.52680000e+00
 5.75040000e+00 -1.00000000e-05 5.96900000e+01 \$cell 101
 58 rpp 8.44500000e-01 6.92750000e+00 5.78850000e+00
 5.83930000e+00 -1.00000000e-05 5.96900000e+01 \$cell 102
 59 rpp 4.94000000e-01 7.27800000e+00 5.75040000e+00
 5.87740000e+00 -1.00000000e-05 5.96900000e+01 \$ext. of cell 103
 60 rpp 4.94000000e-01 7.27800000e+00 5.87740000e+00
 6.10090000e+00 -1.00000000e-05 5.96900000e+01 \$cell 104

```

61 rpp 8.44500000e-01 6.92750000e+00 6.13900000e+00
    6.18980000e+00 -1.00000000e-05 5.96900000e+01 $cell 105
62 rpp 4.94000000e-01 7.27800000e+00 6.10090000e+00
    6.22790000e+00 -1.00000000e-05 5.96900000e+01 $ext. of cell 106
63 rpp 4.94000000e-01 7.27800000e+00 6.22790000e+00
    6.45140000e+00 -1.00000000e-05 5.96900000e+01 $cell 107
64 rpp 8.44500000e-01 6.92750000e+00 6.48950000e+00
    6.54030000e+00 -1.00000000e-05 5.96900000e+01 $cell 108
65 rpp 4.94000000e-01 7.27800000e+00 6.45140000e+00
    6.57840000e+00 -1.00000000e-05 5.96900000e+01 $ext. of cell 109
66 rpp 4.94000000e-01 7.27800000e+00 6.57840000e+00
    6.80190000e+00 -1.00000000e-05 5.96900000e+01 $cell 110
67 rpp 8.44500000e-01 6.92750000e+00 6.84000000e+00
    6.89080000e+00 -1.00000000e-05 5.96900000e+01 $cell 111
68 rpp 4.94000000e-01 7.27800000e+00 6.80190000e+00
    6.92890000e+00 -1.00000000e-05 5.96900000e+01 $ext. of cell 112
69 rpp 4.94000000e-01 7.27800000e+00 6.92890000e+00
    7.15240000e+00 -1.00000000e-05 5.96900000e+01 $cell 113
70 rpp 8.44500000e-01 6.92750000e+00 7.19050000e+00
    7.24130000e+00 -1.00000000e-05 5.96900000e+01 $cell 114
71 rpp 4.94000000e-01 7.27800000e+00 7.15240000e+00
    7.27940000e+00 -1.00000000e-05 5.96900000e+01 $ext. of cell 115
72 rpp 4.94000000e-01 7.27800000e+00 7.27940000e+00
    7.50300000e+00 -1.00000000e-05 5.96900000e+01 $cell 116
73 rpp 8.44500000e-01 6.92750000e+00 7.54110000e+00
    7.59190000e+00 -1.00000000e-05 5.96900000e+01 $cell 117
74 rpp 4.94000000e-01 7.27800000e+00 7.50300000e+00
    7.63000000e+00 -1.00000000e-05 5.96900000e+01 $ext. of cell 118
c
c Other Universes, labeled "[u number][padding of zeroes][unique index]" in
c   four-digit labels
c
2001 rcc 3.886 3.886 -1e-005 0 0 59.69001 0.635
2002 rpp 0.02333 7.69667 0.02333 7.69667 -1e-005 59.69
2003 rcc 3.886 3.886 -1e-005 0 0 59.69001 11
2004 rcc 3.886 3.886 -29.07 0 0 19.54 11
2005 rcc 3.886 3.886 -1e-005 0 0 -9.52999 11
2006 rcc 3.886 3.886 59.69 0 0 15.07001 11
c
3001 rpp 0.43795 7.33405 0.43795 7.33405 -1e-005 59.69
3002 rpp 0.28555 7.48645 0.28555 7.48645 -1e-005 59.69
3003 rcc 3.886 3.886 -1e-005 0 0 59.69001 11
3004 rcc 3.886 3.886 -29.07 0 0 19.54 11
3005 rcc 3.886 3.886 -1e-005 0 0 -9.52999 11
3006 rcc 3.886 3.886 59.69 0 0 15.07001 11
c
c 4001 rcc 3.886 3.886 59.69 0 0 15.07001 0.7145
4001 rcc 3.886 3.886 REG_ROD_BASE 0 0 REG_ROD_LENGTH 0.7145
4002 rpp 1.28885 1.72065 1.28885 5.84815 59.69 74.76001
4003 rpp 1.18725 1.82225 1.18725 5.94975 59.69 74.76001
4004 rpp 6.05135 6.48315 1.92385 6.48315 59.69 74.76001
4005 rpp 5.94975 6.58475 1.82225 6.58475 59.69 74.76001
4006 rpp 1.92385 6.48315 1.28885 1.72065 59.69 74.76001
4007 rpp 1.82225 6.58475 1.18725 1.82225 59.69 74.76001
4008 rpp 1.18725 5.94975 5.94975 6.58475 59.69 74.76001
4009 rpp 0.75545 7.01655 0.75545 7.01655 -1e-005 74.76001
4010 rpp 0.12045 0.75545 0.12045 7.65155 -1e-005 59.69
4011 rpp 7.01655 7.65155 0.12045 7.65155 -1e-005 59.69
4012 rpp 0.75545 7.01655 0.12045 0.75545 -1e-005 59.69
4013 rpp 0.75545 7.01655 7.01655 7.65155 -1e-005 59.69
4014 rcc 3.886 3.886 -1e-005 0 0 59.69001 11
4015 rcc 3.886 3.886 -29.07 0 0 19.54 11
4016 rcc 3.886 3.886 -1e-005 0 0 -9.52999 11
4017 rcc 3.886 3.886 59.69 0 0 15.07001 11
c
c 5001 15 rpp 0.9462 1.5939 2.0231 28.7691 67.564 74.76001
5001 15 rpp 0.9462 1.5939 2.0231 28.7691 BLADE1_HEIGHT 74.76001
c [z_min of rpp for 5001 is] cr height from active fuel bottom -Dr. Mo
c 5002 15 rpp 0.79405 1.74605 1.8709 28.9212 67.564 74.76001
5002 15 rpp 0.79405 1.74605 1.8709 28.9212 BLADE1_HEIGHT 74.76001
5003 15 rpp 0.31755 2.22255 1.3944 29.3977 -1e-005 74.76001
5004 15 rpp 0.01905 2.52105 5e-005 34.974 -1e-005 74.76001

```

```

5005 15 rcc 1.27 17.484 -1e-005 0 0 74.76002 36
5006 15 rcc 1.27 17.484 -29.07 0 0 19.54 36
5007 15 rcc 1.27 17.484 -1e-005 0 0 -9.52999 36
c
c 6001 5 rpp 0.9462 1.5939 6.2051 32.9511 67.564 74.76001
6001 5 rpp 0.9462 1.5939 6.2051 32.9511 BLADE2_HEIGHT 74.76001
c [z_min of rpp for 6001 is] cr height from active fuel bottom -Dr. Mo
c 6002 5 rpp 0.79405 1.74605 6.0554 33.1032 67.564 74.76001
6002 5 rpp 0.79405 1.74605 6.0554 33.1032 BLADE2_HEIGHT 74.76001
6003 5 rpp 0.31755 2.22255 5.5764 33.5797 -1e-005 74.76001
6004 5 rpp 0.01905 2.52105 5e-005 34.974 -1e-005 74.76001
6005 5 rcc 1.27 17.484 -1e-005 0 0 74.76002 36
6006 5 rcc 1.27 17.484 -29.07 0 0 19.54 36
6007 5 rcc 1.27 17.484 -1e-005 0 0 -9.52999 36
c
c 7001 4 rpp 0.9462 1.5939 6.2051 32.9511 67.564 74.76001
7001 4 rpp 0.9462 1.5939 6.2051 32.9511 BLADE3_HEIGHT 74.76001
c [z_min of rpp for 7001 is] cr height from active fuel bottom -Dr. Mo
c 7002 4 rpp 0.79405 1.74605 6.0554 33.1032 67.564 74.76001
7002 4 rpp 0.79405 1.74605 6.0554 33.1032 BLADE3_HEIGHT 74.76001
7003 4 rpp 0.31755 2.22255 5.5764 33.5797 -1e-005 74.76001
7004 4 rpp 0.01905 2.52105 5e-005 34.974 -1e-005 74.76001
7005 4 rcc 1.27 17.484 -1e-005 0 0 74.76002 36
7006 4 rcc 1.27 17.484 -29.07 0 0 19.54 36
7007 4 rcc 1.27 17.484 -1e-005 0 0 -9.52999 36 $-9.53 0 0 9.52999 36
c
c 8001 14 rpp 0.9462 1.5939 2.0231 28.7691 67.564 74.76001
8001 14 rpp 0.9462 1.5939 2.0231 28.7691 BLADE4_HEIGHT 74.76001
c [z_min of rpp for 801 is] cr height from active fuel bottom -Dr. Mo
c 8002 14 rpp 0.79405 1.74605 1.8709 28.9212 67.564 74.76001
8002 14 rpp 0.79405 1.74605 1.8709 28.9212 BLADE4_HEIGHT 74.76001
8003 14 rpp 0.31755 2.22255 1.3944 29.3977 0 74.76001
8004 14 rpp 0.01905 2.52105 5e-005 34.974 -1e-005 74.76001
8005 14 rcc 1.27 17.484 -1e-005 0 0 74.76002 36
8006 14 rcc 1.27 17.484 -29.07 0 0 19.54 36
8007 14 rcc 1.27 17.484 -1e-005 0 0 -9.52999 36
c
1001 rcc 3.886 3.886 -1e-005 0 0 59.69001 0.23876
1002 rcc 3.886 3.886 -1e-005 0 0 59.69001 1.98374
1003 rcc 3.886 3.886 -1e-005 0 0 59.69001 2.06375
1004 rpp 0.02333 7.69667 0.02333 7.69667 -1e-005 59.69
1005 rcc 3.886 3.886 -1e-005 0 0 59.69001 11
1006 rcc 3.886 3.886 -29.07 0 0 19.54 11
1007 rcc 3.886 3.886 -1e-005 0 0 -9.52999 11
1008 rcc 3.886 3.886 59.69 0 0 15.07001 11
c
1101 rcc 3.886 3.886 -1e-005 0 0 59.69001 2.3749
1102 rcc 3.886 3.886 -1e-005 0 0 59.69001 2.54
1103 rpp 0.45446 7.31754 0.45446 7.31754 -1e-005 59.69
1104 rpp 0.13696 7.63504 0.13696 7.63504 -1e-005 59.69
1105 rcc 3.886 3.886 -1e-005 0 0 59.69001 11
1106 rcc 3.886 3.886 -29.07 0 0 19.54 11
1107 rcc 3.886 3.886 -1e-005 0 0 -9.52999 11
1108 rcc 3.886 3.886 59.69 0 0 15.07001 11
c
1201 rpp -1e-005 7.77201 -1e-005 7.77201 -1e-005 59.69
1202 rcc 3.886 3.886 -1e-005 0 0 59.69001 11
1203 rcc 3.886 3.886 -29.07 0 0 19.54 11
1204 rcc 3.886 3.886 -1e-005 0 0 -9.52999 11
1205 rcc 3.886 3.886 59.69 0 0 15.07001 11
c

c
c
c
c
mode n
kcode N_PER_CYCLE K_GUESS DISCARD_CYC TOTAL_CYC
ksrc 5.6705E+01 9.5805E+01 6.5595E+01
      5.7576E+01 9.6152E+01 6.5595E+01
      5.7555E+01 9.6504E+01 6.5595E+01
      5.7582E+01 9.6856E+01 6.5595E+01

```

```

5.7514E+01  9.7208E+01  6.5595E+01
5.7611E+01  9.7556E+01  6.5595E+01
5.7497E+01  9.7904E+01  6.5595E+01
5.7711E+01  9.8255E+01  6.5595E+01
5.7995E+01  9.8607E+01  6.5595E+01
5.7670E+01  9.8959E+01  6.5595E+01
5.7555E+01  9.9311E+01  6.5595E+01
5.7488E+01  9.9659E+01  6.5595E+01
5.7678E+01  1.0001E+02  6.5595E+01
5.7611E+01  1.0036E+02  6.5595E+01
5.4285E+01  1.0071E+02  6.5595E+01
5.5249E+01  1.0106E+02  6.5595E+01
5.5158E+01  1.0141E+02  6.5595E+01
5.4974E+01  1.0177E+02  6.5595E+01
5.5047E+01  1.0211E+02  6.5595E+01
5.5120E+01  1.0247E+02  6.5595E+01
5.4912E+01  1.0282E+02  6.5595E+01
5.5384E+01  1.0316E+02  6.5595E+01
c
ksen1 xs
c
ksen2 xs erg=0 0.000000625 0.1 1.00E+36
c
c 1/meat 2/clad 3/h2o 4/grid plate 5/Bot ref 6/Top ref
c 7/Shim Rod 8/Reg Rod 9/Pb 10/Graphite 11/Be -Dr. Mo
c
m1 92234. 5.6795e-009
92235. 0.00175523 92236. 7.1358e-009 92238. 0.00704193
13027. 0.0388984 14000. 0.00594365
c
m2 13027. 0.0602669
5010. 2.98636e-007 5011. 1.21115e-006
c
m3 1001. 0.066861
8016. 0.0334305
mt3 lwtr.01t
c
m4 1001. 0.040117
13027. 0.024107 8016. 0.020058 5010. 1.1945e-007
5011. 4.8446e-007
mt4 lwtr.01t
c
m5 1001. 0.05155
13027. 0.013064 14000. 0.00071537 12000. 3.5418e-005
5010. 1.5873e-008 5011. 6.4373e-008 8016. 0.025775
mt5 lwtr.01t
c
m6 1001. 0.033431
13027. 0.030133 8016. 0.016715 5010. 1.4932e-007
5011. 6.0557e-007
mt6 lwtr.01t
c
m7 5010. 0.007566
5011. 0.030685 6012. 0.01158 13027. 0.03839
mt7 grph.01t
c
m8 14000. 0.0017147
24000. 0.017598 25055. 0.0017532 26000. 0.058505
28000. 0.0082029
c
m9 82000. 0.032962
c
m10 6012. 0.08023
mt10 grph.01t
c
m11 4009. 0.12364
mt11 be.01t
c
tr2 52.629 95.598 35.75
tr3 26.773 64.51 35.75
tr4 42.317 64.51 35.75
tr14 42.317 99.484 35.75

```

```

tr5 68.173 64.51 35.75
tr15 68.173 99.484 35.75
tr6 70.713 64.51 35.75
c
c Debugging
c
RAND GEN 4 seed=5520000000000000007
LOST 10
DBCN 4J 6000
c
c Tallies!
c
FC04 Spatial Profile of Neutron Flux
N_PER_CYCLE n/cycle,
RES Core voxels (X_RES x Y_RES x Z_RES),
each X_BIN_LEN cm square
with a height of Z_BIN_LEN cm
fmesh04:n geom=xyz origin X1 Y1 Z2
imesh NEAR_X FAR_X X3 iints X_01 X_RES X_23
jmesh NEAR_Y FAR_Y Y3 jints Y_01 Y_RES Y_23
kmesh NEAR_Z FAR_Z Z5 kints Z_23 Z_RES Z_45
emesh 0.000000625 0.1 1.00E+36
out cf
print

c
c
c
c
c
c @-@-@ X-_-B-I-N-_-L-E-N = ((F-A-R-_-X - N-E-A-R-_-X)/X-_-R-E-S)
c @-@-@ Y-_-B-I-N-_-L-E-N = ((F-A-R-_-Y - N-E-A-R-_-Y)/Y-_-R-E-S)
c N.B. *_BIN_LEN are floats, so the above are exactly right! When I invert
the
c formula for *_RES, I'm forced to play games with int and an offset of 0.5.

```

Running Simulations

Had it been necessary to do the final runs on a consumer computer, the procedure would have been¹⁵:

1. Invoke an “initiate” run:

```
mcnp6 i=inp
```

2. Invoke a “continue” run, with no limit on dumps (checkpoints):

```
mcnp6 c i=continuation.txt
```

3. Plot the relative errors and the convergence plots.
4. Was everything satisfactory in step 3?

- a. No:

- i. Edit the “continue” deck, raising the total number of KCODE cycles.

ii. Choose between the “c” and “cn” options for the next
continue run:

1. Have there been at least two “continue” runs already
using “c”?

a. If not, “c” is probably best, because having
multiple dumps allows the user to re-start a
run from the $(n-1)$ th dump if something is
wrong with the n th run.

b. If so, did the last run use “c” or “cn”?

i. “cn”: Stick with “cn”.

ii. “c”: See next question.

2. Is the user worried that the binary restart file
 (“runtpe”) is nearing a problematic size?

a. Yes: “cn”

b. No: “c”

iii. Invoke another “continue” run:

```
mcp6 [c or cn] i=continuation.txt
```

iv. Repeat steps 3 and 4 (*i.e.*, plotting relative error and
convergence and reacting accordingly).

b. Yes (satisfactory:) move on to step 5.

5. Plot the final results.

Fortunately, a more powerful platform was utilized for the production runs -in
this case, a Beowulf cluster with TORQUE (see the appendix on extremely slow
runtimes as to why this was fortunate). However, there was a tradeoff between power

and complexity; things the user would have done in an interactive session are to be done by a script on their behalf instead and some of those scripts may invoke other scripts. MCNP is platform-independent as advertised; the various scripts that were made over the course of this study, generally speaking, were platform-dependent. This is especially true for PBS (TORQUE) scripts that were employed in running the simulations. Any reader hoping to replicate or extend this study would do well to focus on the rationale behind each of the scripts shared, as different platforms may require different technical details to achieve the same result. All of the PBS scripts mentioned herein began from a template made available online by the University of Houston²³.

Consequently, the actual procedure used (the simulations generating Figure 7 through Figure 26) was:

0. Make the input deck from the latest version of the template:

```
mcnp_pstudy -i Core_Six.tmplt -setup
```

1. Invoke the “initiate” run:

```
auto-node.sh ; cd case001
```

2. Make the “continue” deck, with the first guess as to how many total KCODE cycles will be needed; then run it:

```
qsub -l nodes=n001:ppn=6 keep_going.sh
```

3. Edit the script view_plots.sh (“[name]_[n].ps” -> “[name]_[n+1].ps”, where “name” is “ebin1”, “ebin4”, “rel_err”, *etc.*). Plot everything:

```
qsub -l nodes=n002:ppn=1 view_plots.sh
```

4. Check the relative error and convergence plots; are all of them satisfactory?
 - a. No:

- i. Edit the “continue” deck, raising the total number of KCODE cycles.
 - ii. Choose between keep_going.sh (“c”) and go-limited.sh (“cn”) for the next continue run:
 1. Have there been at least two “continue” runs already using keep_going?
 - a. If not, keep_going is probably best, because having multiple dumps allows the user to restart a run from the $(n-1)$ th dump if something is wrong with the n th run.
 - b. If so, did the last run use keep_going or go-limited?
 - i. go_limited: Stick with go_limited.
 - ii. keep_going: See next question.
 2. Is the user worried that the binary restart file (“runtpe”) is nearing a problematic size?
 - a. Yes: go-limited
 - b. No: keep_going
 - iii. Invoke another “continue” run:


```
qsub -l nodes=n003:ppn=6 [keep_going.sh or go-limited.sh]
```
 - iv. Repeat steps 3 and 4 (*i.e.*, plotting relative error and convergence and reacting accordingly).
- b. Yes (satisfactory:) The user is done running simulations.

The scripts mentioned above are shared below.

auto-node.sh

```
#!/bin/sh
#ver 6.2

prereqs() {
echo $@ | cut -f 1-$# -d " " --output-delimiter=":"
}

next_node() {
last_node=$(qstat | tail -n 1 | cut -f 1 -d "." | { read NMBR ; qstat -f
$NMBR ; }|\
grep "Resource_List.nodes" |tail -n 1| cut -f 2 -d "=" | cut -f 1 -d ":" |
cut -f 3 -d "0")
next_node=$((last_node+1))
if test $next_node -eq 7
then
next_node=$((1))
fi
if test $next_node -eq 4
then
next_node=$((5))
fi
echo n00$next_node
}

wait_for() {
if test $# -gt 0
then
echo '-W depend=afterany:'$(prereqs $@)
fi
}

last_job_on() {
PRIOR_JOBS=$(qstat | tail -n $(( $(qstat | wc -l | { read NMBR NAME ; echo
$NMBR ; }-2)) |cut -f 1 -d "."))
for j in ${PRIOR_JOBS[@]}
do
#echo $j
#echo $(mock_full_info $j | grep "Resource_List.nodes" | cut -f 2 -d "=")
if test $1 = $(qstat -f $j | grep "Resource_List.nodes" | cut -f 2 -d "=")
then
RELEVANT=(${RELEVANT[@]} $j)
fi
done
echo ${RELEVANT[@]}
}

FOOTHOLD=$PWD
if test ! -e to_do.txt
then
TO_DO=$(echo case*)
else
TO_DO=$(cat to_do.txt)
fi
echo ''
for f in ${TO_DO[@]}
do
echo "Moving to $f..."
cd $f
echo "Submitting job..."
echo "qsub -N $f -l nodes=$(next_node):ppn=6 $(wait_for $(last_job_on
$(next_node))) \${HOME}/reusable/auto-task.sh"
qsub -N $f -l nodes=$(next_node):ppn=6 $(wait_for $(last_job_on
$(next_node))) \${HOME}/reusable/auto-task.sh
echo ''
cd $FOOTHOLD
```

done

easy_parse.py

```
#!/python3

import sys

with open(sys.argv[1], 'r') as f:
    reading = False
    for line in f.readlines():
        if "#BEGIN DIRECTIVES" in line:
            reading = True
        elif "#END DIRECTIVES" in line:
            reading = False
        elif reading == True:
            print(line.strip())
```

auto-task.sh

```
#2018-04-26

#BEGIN DIRECTIVES
# to inherit all [my] environment
# variables[:]
#PBS -V

#PBS -S /bin/sh

### Switch to the working directory; by default TORQUE launches processes
### from your home directory.
cd $PBS_O_WORKDIR
#END DIRECTIVES

### Display the job context
echo Running on host `hostname`
echo Time is `date`
echo Directory is `pwd`
NPROCS=$(wc -l $PBS_NODEFILE | { read NMBR FILE; echo $NMBR; })
echo Using ${NPROCS} processors #across ${NNODES} nodes

### OpenMPI will automatically launch processes on all allocated nodes.
## MPIRUN=`which mpirun`
## ${MPIRUN} -machinefile $PBS_NODEFILE -np ${NPROCS} my-openmpi-program

#Onward to Ben's commands:
echo ''
echo "#   #   #   #   #   #   #   #   #"
echo ''

#printenv | grep "PBS"
#echo ''

THIS_SCRIPT=$HOME/reusable/auto-task.sh #"$0" is technically right, but
practically wrong

easy_parse.py $THIS_SCRIPT
echo ''

echo "PBS_NODEFILE:"
cat $PBS_NODEFILE

echo ''
echo "*   *   *   *   *   *   *   *   *"
echo ''

echo "Script invoked: "$THIS_SCRIPT
```

```

echo ''
echo "Gist" of this script:
tail -n $(( $(wc -l $THIS_SCRIPT | cut -f 1 -d " ")-$(grep -F "time" -m 2 -n
$THIS_SCRIPT | tail -n 1 | cut -f 1 -d ":")+1)) $THIS_SCRIPT
echo ''
echo "% % % % % % % % % % %"
echo '' #EVERYTHING AFTER (but excluding) THIS LINE SHOULD BE PRINTED BY THAT
LAST "TAIL" CMD!

```

```

time mcnp6 tasks $NPROCS
for T in {4,}
do
for e in {4,3,2,1}
do
time mcnp6 z notek plotm=fmesh$(echo $T)_ebin$(echo $e) com=<<FLUX
fmesh $T
ebin $e
zlev lin
file all
basis 1 0 0 0 1 0
basis 1 0 0 0 0 1
basis 0 1 0 0 0 1
origin 4.3492E+01 9.9484E+01 6.8365E+01 extent 4.2799E+01 4.2799E+01
origin 56.515 99.484 68.365
origin 6.9412E+01 9.9484E+01 6.8365E+01 extent 4.2799E+01 4.2799E+01
origin 38.406 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
origin 48.746 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
origin 56.515 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
origin 64.288 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
origin 74.624 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
end
end
FLUX
time mcnp6 z plotm=fmesh$(echo $T)_relerr_ebin$e notek com=<<FLUX_ERR
fmesh $T
ebin $e
fmrelerr
file all
basis 1 0 0 0 1 0
basis 1 0 0 0 0 1
basis 0 1 0 0 0 1
origin 4.3492E+01 9.9484E+01 6.8365E+01 extent 4.2799E+01 4.2799E+01
origin 56.515 99.484 68.365
origin 6.9412E+01 9.9484E+01 6.8365E+01 extent 4.2799E+01 4.2799E+01
origin 38.406 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
origin 48.746 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
origin 56.515 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
origin 64.288 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
origin 74.624 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
end
end
FLUX_ERR

```

```

done
done
time mcnp6 z notek plotm=Shannon com=<<SHANNON
kcode 6 &
title 1 "$(echo $PWD | cut -f 6 -d "/")" &
title 2 "$(grep -F 'Running for' inp|cut -f 7- -d ' ')"
file
end
end
SHANNON
time mcnp6 z notek plotm=k_eff com=<<K_EFF
kcode 16 &
title 1 "$(echo $PWD | cut -f 6 -d "/")" &
title 2 "$(grep -F 'Running for' inp|cut -f 7- -d ' ')"
file
end
end
K_EFF

```

keep_going.sh

```

#PBS -S /bin/sh
#PBS -V
#PBS -N continuing
cd $PBS_O_WORKDIR
NPROCS=$(wc -l $PBS_NODEFILE|{ read NMBR FILE; echo $NMBR; })
echo Using ${NPROCS} processors

mcnp6 c i=continuation.txt tasks $NPROCS

```

go-limited.sh

```
#PBS -S /bin/sh
#PBS -V
#PBS -N go-cn
cd $PBS_O_WORKDIR
NPROCS=$(wc -l $PBS_NODEFILE|{ read NMBR FILE; echo $NMBR; })
echo Using ${NPROCS} processors

mcnp6 cn i=continuation.txt tasks $NPROCS
```

view_plots.sh

```
#2018-05-02
#(Consult prior versions for more information as to how this script got this
way.)
#(Most recent previous version was 2018-04-26.)

# Note: group all PBS directives at the beginning of your script.
# Any directives placed after the first shell command will be ignored.

#BEGIN DIRECTIVES
# to inherit all [my] environment
# variables[:]
#PBS -V

#PBS -S /bin/sh

### Switch to the working directory; by default TORQUE launches processes
### from your home directory.
cd $PBS_O_WORKDIR
#END DIRECTIVES

### Display the job context
echo Running on host `hostname`
echo Time is `date`
echo Directory is `pwd`
NPROCS=$(wc -l $PBS_NODEFILE|{ read NMBR FILE; echo $NMBR; })
echo Using ${NPROCS} processors #across ${NNODES} nodes

### OpenMPI will automatically launch processes on all allocated nodes.
## MPIRUN=`which mpirun`
## ${MPIRUN} -machinefile $PBS_NODEFILE -np ${NPROCS} my-openmpi-program

### Or, just run your serial program
## $HOME/my-program

#Onward to Ben's commands:
echo ''
echo "#   #   #   #   #   #   #   #   #"
echo ''

#printenv|grep "PBS"
#echo ''

echo "PBS_NODEFILE:"
cat $PBS_NODEFILE

echo ''
echo "*   *   *   *   *   *   *   *   *"
echo ''

for T in {4,}
do
for e in {4,3,2,1}
do
time mcnp6 z notek plotm=fmesh$(echo $T)_ebin$(echo $e)_7 com=<<FLUX
fmesh $T
ebin $e
```

```

zlev lin
file all
basis 1 0 0 0 1 0
basis 1 0 0 0 0 1
basis 0 1 0 0 0 1
origin 4.3492E+01 9.9484E+01 6.8365E+01 extent 4.2799E+01 4.2799E+01
origin 56.515 99.484 68.365
origin 6.9412E+01 9.9484E+01 6.8365E+01 extent 4.2799E+01 4.2799E+01
origin 38.406 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
origin 48.746 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
origin 56.515 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
origin 64.288 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
origin 74.624 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
end
end
FLUX
time mcnp6 z plotm=fmesh$(echo $T)_relerr_ebin$(echo $e)_7 notek
com=<<FLUX_ERR
fmesh $T
ebin $e
fmrelerr
file all
basis 1 0 0 0 1 0
basis 1 0 0 0 0 1
basis 0 1 0 0 0 1
origin 4.3492E+01 9.9484E+01 6.8365E+01 extent 4.2799E+01 4.2799E+01
origin 56.515 99.484 68.365
origin 6.9412E+01 9.9484E+01 6.8365E+01 extent 4.2799E+01 4.2799E+01
origin 38.406 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
origin 48.746 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
origin 56.515 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
origin 64.288 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
origin 74.624 130.57 68.365 basis 1 0 0 0 1 0 extent 3.886
basis 1 0 0 0 0 1 extent 50
basis 0 1 0 0 0 1
end
end
FLUX_ERR
done
done
time mcnp6 z notek plotm=Shannon_7 com=<<SHANNON
kcode 6 &
title 1 "$(echo $PWD | cut -f 6 -d "/")" &
title 2 "$(grep -F 'Running for' inp|cut -f 7- -d ' ')"
file
end
end
SHANNON
time mcnp6 z notek plotm=k_eff_7 com=<<K_EFF
kcode 16 &
title 1 "$(echo $PWD | cut -f 6 -d "/")" &
title 2 "$(grep -F 'Running for' inp|cut -f 7- -d ' ')"
file
end

```

end
K_EFF

More plots for total fluence

Figure 41: MCNP neutron flux type “B” mesh tally for all energies (total fluence per source particle history) for the RINSC reactor, in the form of a heat map. This plot shows row 9.

More plots for relative error for total fluence.

Figure 42: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for all energies (relative error for total fluence per source particle history) for the RINSC reactor. This plot shows column F.

Figure 43: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for all energies (relative error for total fluence per source particle history) for the RINSC reactor. This plot shows row 9.

Figure 44: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for all energies (relative error for total fluence per source particle history) for the RINSC reactor. This plot shows column D.

More plots for thermal fluence

Figure 45: MCNP neutron flux type “B” mesh tally for thermal energies (thermal fluence per source particle history) for the RINSC reactor, in the form of a heat map. This plot shows row 9.

Figure 46: MCNP neutron flux type “B” mesh tally for thermal energies (thermal fluence per source particle history) for the RINSC reactor, in the form of a heat map. This plot shows column D.

Figure 47: MCNP neutron flux type “B” mesh tally for thermal energies (thermal fluence per source particle history) for the RINSC reactor, in the form of a heat map. This plot shows column B.

More plots for relative error for thermal fluence.

Figure 48: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for thermal energies (relative error for thermal fluence per source particle history) for the RINSC reactor.

Figure 49: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for thermal energies (relative error for thermal fluence per source particle history) for the RINSC reactor.

Figure 50: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for thermal energies (relative error for thermal fluence per source particle history) for the RINSC reactor.

Figure 51: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for thermal energies (relative error for thermal fluence per source particle history) for the RINSC reactor. This plot shows column D.

More plots for relative error for epithermal fluence.

Figure 52: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for epithermal energies (relative error for epithermal fluence per source particle history) for the RINSC reactor.

Figure 53: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for epithermal energies (relative error for epithermal fluence per source particle history) for the RINSC reactor.

Figure 54: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for epithermal energies (relative error for epithermal fluence per source particle history) for the RINSC reactor. This plot shows column B.

More plots for relative error for fast fluence.

Figure 56: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for fast energies (relative error for fast fluence per source particle history) for the RINSC reactor.

Figure 57: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for fast energies (relative error for fast fluence per source particle history) for the RINSC reactor. This plot shows column F.

Figure 58: Relative error as a decimal fraction for the MCNP neutron flux type “B” mesh tally for fast energies (relative error for fast fluence per source particle history) for the RINSC reactor. This plot shows row 9.

BIBLIOGRAPHY

1. RHODE ISLAND NUCLEAR SCIENCE CENTER, “Core Change Summary for Conversion from RINSC LEU Core #5 to LEU Core #6.”
2. J. R. LAMARSH, *Introduction to nuclear engineering*, Addison-Wesley Pub. Co, Reading, Mass (1975).
3. Z. A. AKCASU, G. S. LELLOUCHE, and L. M. SHOTKIN, *Mathematical methods in nuclear reactor dynamics*, Academic Press, New York (1971).
4. J. J. DUDERSTADT and L. J. HAMILTON, *Nuclear reactor analysis*, Wiley, New York (1976).
5. S. C. MO, *mcnp2*.
6. N. METROPOLIS, “The Beginning of the Monte Carlo Method,” Los Alamos Sci.(Special Issue), 125 (1987).
7. “Nuclear Engineering Review & Monte Carlo Basics (LA-UR-16-29043),” Los Alamos National Security, LLC.
8. N. METROPOLIS and S. ULAM, “The Monte Carlo Method,” J. Am. Stat. Assoc. **44** 247, 335 (1949); <https://doi.org/10.2307/2280232>.
9. S. DEAN et al., “Reactor Dosimetry Study of the Rhode Island Nuclear Science Center,” J. ASTM Int. **3** 9, 100341 (2006); <https://doi.org/10.1520/JAI100341>.
10. S. C. MO et al., “Modification of the RINSC LEU core to increase fluxes for BNCT study,” in 2000 International Reduced Enrichment for Research and Test Reactors Meeting Program (RERTR, <http://www.rertr.anl.gov>), Las Vegas, Nevada (2000).
11. T. GOORLEY et al., “Initial MCNP6 Release Overview - MCNP6 version 1.0,” Los Alamos National Laboratory (2012).
12. M. L. CROW et al., “Thermal neutron measurements of the Rhode Island Nuclear Science Center reactor after conversion to a compact low enriched uranium core,” Nucl. Instrum. Methods Phys. Res. A **365**, 433 (1995).
13. HATHAWAY, C., “RINSC Dry Irradiation Facility Mapping Project,” Senior Project, University of Rhode Island (2011).

14. R. MARTZ, "Introduction (LA-UR-16-29071)," Los Alamos National Security, LLC (2017).
15. D. B. PELOWITZ, Ed., "MCNP6 User's Manual, Version 1.0, Manual revision 0," Los Alamos National Security, LLC (2013).
16. "How to get MCNP;"
https://laws.lanl.gov/vhosts/mcnp.lanl.gov/mcnp_how_to_get_to_mcnp.shtml.
17. "Tallies (LA-UR-16-29071)," Los Alamos National Security, LLC.
18. "Criticality Calculations (LA-UR-16-29071)," Los Alamos National Security, LLC.
19. R. MARTZ, "Tallies: An Introduction (LA-UR-07-6503, LA-UR-08-0849, LA-UR-16-29071)," Los Alamos National Security, LLC (2017).
20. F. BROWN, (2017).
21. F. X. GALLMEIER, J. S. TANG, and R. T. PRIMM, "MCNP-Model for the OAEP Thai Research Reactor," Oak Ridge National Laboratory (1998).
22. R. MARTZ, "Advanced Geometry (LA-UR-07-6503, LA-UR-08-0849, LA-UR-16-29071)," Los Alamos National Security, LLC (2017).
23. RESEARCH COMPUTING CENTER, UNIVERSITY OF HOUSTON, "Example PBS Job Script;" <http://baragon.hpc.uh.edu/pbs-template.sh>; (current as of Mar. 14, 2016).