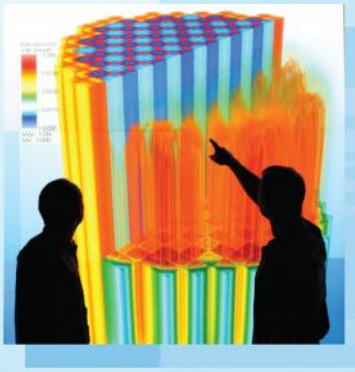
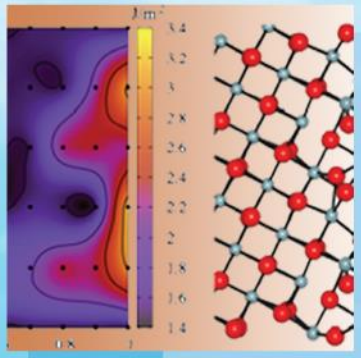
Power uprates and plant life extension



Engineering design and analysis

Science-enabling high performance computing



Fundamental science

Plant operational data

Consortium for Advanced Simulation of LWRs

Modeling an iPWR Startup Core Cycle with VERA

Progress Report 2

Milestone L4:AMA.APP.P10.04

Kelly Kenner
University of Tennessee - Knoxville

Advisors:
Ivan Maldonado, UTK
Rose Montgomery, TVA
Dudley Raine, B&W

June 26, 2014

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Executive Summary

The purpose of this report is to provide an update on the research work performed by Kelly Kenner, a Master's Candidate at the University of Tennessee's Department of Nuclear Engineering, as funded by Tennessee Valley Authority (TVA) and the Consortium for the Advanced Simulation of Light Water Reactors (CASL).

The research being performed is intended to investigate a small modular reactor (SMR) integral pressurized water reactor (iPWR) core cycle design and associated economics. The primary evaluation was completed using the CASL suite of codes, called VERA, the Virtual Environment for Reactor Applications. Comparisons of results were made and the deterministic solutions were verified against Shift, a new continuous energy Monte Carlo neutron transport code. The initial cases run for this research utilized the Oak Ridge National Laboratory's (ORNL) Fissile-4 multi-core cluster, and did not exceed 49 cores. For the larger problems, including 3D models and depletion studies, it is necessary to use OLCF's (Oak Ridge Leadership Computing Facility) supercomputers, Titan and Eos. This report will cover all work performed for this study, including 2D neutronics work performed using Insilico to determine core design, single 3D assembly and full 3D core modeling, Shift analyses, and 2D depletion using MPACT.

Single assembly and quarter-symmetric full core cases were run in 2D using CASL's VERA. These single assembly cases included lattices of varying BPR pins and gadolinia fuel rods. Using a given set of lattices, variances were made to the 2D core layout, and changes were made to the enrichments of the fuel within each assembly for comparison. After multiple cases were analyzed, one core was chosen to move on to the 3D work and 2D depletion. A 3D core was modeled using Insilico, and this image can be found further in this report.

Upon gaining the ability to deplete the 2D core using MPACT in VERA, the results for the core chosen after modeling the initial 2D cases in Insilico showed that this original core did not have the capability to remain critical at 1400 EFPD (the goal cycle length for the SMR being modeled). Therefore, it was necessary to perform several cases using MPACT to try to determine a core design that would produce the desired results. Many cases were analyzed, and it was determined that continuing to study the original core and changing the goal cycle length to 1300 EFPD would be the best plan of action.

In addition to advancing into 3D and depletion, this report will reflect on the work done with Shift. Shift, which can also be used with VERA, is a neutron transport code that uses Monte Carlo. The results from Shift were compared to the MPACT results obtained with VERA. It was found through these analyses that MPACT compared well to Shift, with a 0.767% maximum difference in relative pin powers between the two cases and a -327 +/- 4 pcm difference in k-effective.

An economic study was performed to compare and contrast three different core designs chosen with the Insilico and MPACT studies for this project. These three economic options can be found in the Economic Study section further in this report. Additionally, the fuel cost for an axially

uniform SMR core was compared to the fuel cost for a 4-loop pressurized water reactor (PWR). It was seen that the fuel cost per GWy for the SMR is much higher than the fuel cost per GWye for the 4-loop PWR. However, this study was only concerned with the fuel costs for a Small Modular Reactor. As described in the Economic Study section, many other costs of a nuclear power plant must be taken into account to perform a true and fair comparison in economics between the two plants. A number of these factors are discussed in this report.

This report is to be considered the final report for this study. Additional follow-up work is expected to be performed as additional VERA capabilities become available.

Table of Contents

Executive Summary i
Listing of Tables v
Introduction 1
Small Modular Reactor Design 2
Computer Software 3
VERA 3
Insilico 4
MPACT 4
Shift 5
Visualization of Results 5
Computing Requirements 6
Model Description 7
2D Lattice Modeling 7
2D Core Loading and Modeling 10
3D Modeling with Insilico 12
2D and 3D Modeling with MPACT 12
MPACT Depletion 14
Benchmarking with Shift 19
Comparison of Shift to Insilico 19
Comparison of Shift to MPACT 19
Economic Study 20
Option 1 – Core Design from Figure 26, Axially Uniform 22
Option 2 – 10% Radial Increase, Axially Uniform 22
Option 3 – Axial Blankets Included 23
Economic Comparison to a 4-loop PWR Core 24
Remarks on VERA Usage 25
Results 26
Conclusions and Future Work 27
References 28
Appendix A – Sample VERA Common Input with Insilico 29
Appendix B – VERA Input with Shift 33
Appendix C – VERA Input with MPACT 38
Appendix D – Input Parameters 44

Listing of Figures

Figure 1: Illustration of the mPower SMR [2] 2
Figure 2: Diagram of VERA components as available in late 2013 [5] 3
Figure 3: Layout of Assembly A, 12-BPR 8
Figure 4: Layout of Assembly B, 16-BPR 8
Figure 5: Layout of Assembly C, 20-BPR 8
Figure 6: Layout of Assembly D, 24-BPR 8
Figure 7: Layout of Assembly E, 28-BPR 8
Figure 8: Relative pin power distribution of the 12-BPR lattice 9
Figure 9: Relative pin power distribution of the 16-BPR lattice 9
Figure 10: Relative pin power distribution of the 20-BPR lattice 9
Figure 11: Relative pin power distribution of the 24-BPR lattice 9
Figure 12: Relative pin power distribution of the 28-BPR lattice 9
Figure 13: Core design determined from the first study using Insilico 10
Figure 14: Average and maximum relative powers for each assembly in the core design chosen 11
Figure 15: Relative pin power distribution of a 2D core using the core design shown in Figure 13 . 11
Figure 16: 3D model of the SMR core design as shown in Figure 13 using Insilico 12
Figure 17: 3D SMR modeled using MPACT 13
Figure 18: Axial layout of the 3D core modeled using MPACT 14
Figure 19: Graph describing the change in k-effective over time 16
Figure 20: Image of the 2D SMR core from Figure 13 at the 3 EFPD time step, where k-effective is 1.100708 17
Figure 21: Image of the 2D SMR core from Figure 13 at the 500 EFPD time step, where k-effective is 1.123723 17
Figure 22: Image of the 2D SMR core from Figure 13 at the 900 EFPD time step, where k-effective is 1.073917 18
Figure 23: Image of the 2D SMR core from Figure 13 at the 1350 EFPD time step, where k-effective is 0.99374 18
Figure 24: Graph of results comparing the use of substepping to no substepping 19
Figure 25: Visualization of the differences in relative pin power values between the two cases 20
Figure 26: Core design for Options1, 2, and 3 21
Figure 27: Axial loading of the core in Option 3 23
Figure 28: Pie chart describing the economics of nuclear plant costs [15] 25

Listing of Tables

Table 1: Core design parameters used to model the iPWR 2
Table 2: Table showing runtimes and number of cores used for the problems described in this report 6
Table 3: Fuel assembly lattice specifications 7
Table 4: Table of assembly specifications for Figure 13 10
Table 5: Value of k-effective for each EFPD for varying radial dimensions and poisons 15
Table 6: Eigenvalue per EFPD for the SMR core from Figure 13 16
Table 7: Ore, conversion, SWU, and fabrication prices used for this study, using the economics tools from the Ux Consulting Company and ORNL's Reactor Physics Team [13] 20
Table 8: Specifications for the core design in Figure 26 for Options 1, 2, and 3 21
Table 9: Volume and masses of the core of option 1 22
Table 10 Volume and masses of the core of option 2 22
Table 11: Volume and masses of the core of option 3 23
Table 12: Specifications for the 4-loop PWR [14] 24
Table 13: Table of Fuel Cost for Life of Plant 24
Table 14 Dimensions used to model the iPWR 44
Table 15 Material inputs for the iPWR 45
Table 16 Additional inputs used to model the iPWR 45

Introduction

The purpose of this report is to provide an update on the research work performed by Kelly Kenner, a Master's Candidate at the University of Tennessee's Department of Nuclear Engineering, as funded by Tennessee Valley Authority (TVA) and the Consortium for Advanced Simulation of Light Water Reactors (CASL), a DOE NE consortium led by Oak Ridge National Laboratory (ORNL).

The research being performed is intended to investigate a small modular reactor (SMR) integral pressurized water reactor (iPWR) core cycle design and associated economics. The scope of the research work includes:

1. Establish a general geometric and material description of the core of an iPWR.
2. Using the VERA (Virtual Environment for Reactor Applications) tools under development at CASL, create models:
    a. 2D single assembly lattices
    b. 2D quarter core
    c. 3D single assembly
    d. 3D quarter core
    e. 2D depletion studies
3. Run the same problems using multiple methods for comparison.
4. As possible and as applicable, compare the findings of this work with models and analyses performed by iPWR vendors.
5. Establish an economic analysis of a fuel cycle based on the findings of this research work. The analysis will be based upon variations in core loading (tons of uranium and necessary enrichment) that can achieve the specified energy requirements (power output and duration) given cost estimates of uranium and enrichment.

This report provides an update on the work performed to date, which includes completion of Tasks 1, 2, 3, and 5. The report also provides detailed information where necessary to describe any assumptions used in this analysis. The models generated with VERA will be provided, and an example VERA input deck can be found in Appendix A.

Small Modular Reactor Design

Small modular reactors constitute a new generation of nuclear power reactors that are being studied and developed. SMRs are more compact than currently operating plants, thus producing less power, around 200 MWe compared to 1000 MWe or higher for currently operating plants. The smaller size of the SMR allows for these reactors to be fabricated in a factory and delivered to the plant site fully constructed. This provides a decrease in time and labor cost for on-site construction and assembly-line fabrication, as well as increased containment efficiency and nuclear materials security [1]. This will also allow each iPWR to be constructed and operated in the exact same manner, which will increase the safety of plant operation, as well as reduce the overall costs associated with "cookie cutter" fabrication, and standardized operational support, training, and maintenance.

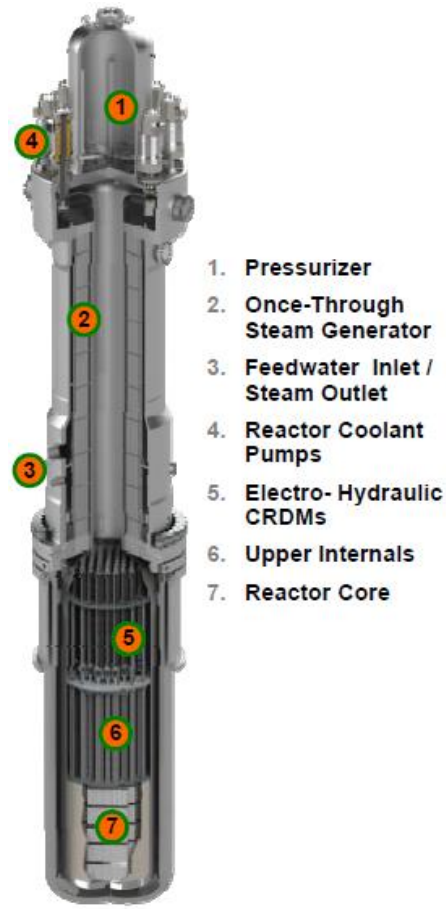


Figure 1: Illustration of the mPower SMR [2]

The iPWR refers to a pressurized water reactor design in which the primary coolant system and most of its subcomponents are contained within a single pressure vessel. This is illustrated in Figure 1, which is an image of the proposed B&W mPower iPWR [2].

The iPWR core modeled in this study includes 69 17x17 fuel assemblies with an active fuel height of ~241.3 cm [3]. A 4-year fuel cycle length is assumed, and this fuel cycle length will play a part in the economics calculations and analyses. All parameters, assumed and known, are found in Appendix B in this report.

Table 1 provides the core design parameters for the iPWR. These parameters were used in the VERA input deck to model the reactor.

Table 1: Core design parameters used to model the iPWR

Core Power (MWt)	530
System Pressure (psia)	2050
Core Inlet Temperature (degF)	566
Number of fuel assemblies	69
Average Linear Power Density (kW/ft)	4.82
Coolant boron concentration (ppm)	0

Computer Software

VERA

VERA, the Virtual Environment for Reactor Applications, is an environment of software and methods currently under development at CASL. The goal of VERA is to provide the capability for coupled nuclear reactor analysis with focus on neutronics, thermal hydraulics, and fuel mechanics, among others [4]. VERA is the main modeling tool that has been used in this research, and only the neutronics capability has been explored and utilized for this project. Figure 2 provides an illustration of the VERA capabilities as of recently. As shown in Figure 2, VERA utilizes MPACT, Insilico, and Shift to perform neutron transport problems. All three codes were used in this study. The VERA input is user-friendly, and copies of example inputs using the VERA generic input syntax for Insilico, MPACT, and Shift are provided in Appendices A, B, and C of this report.

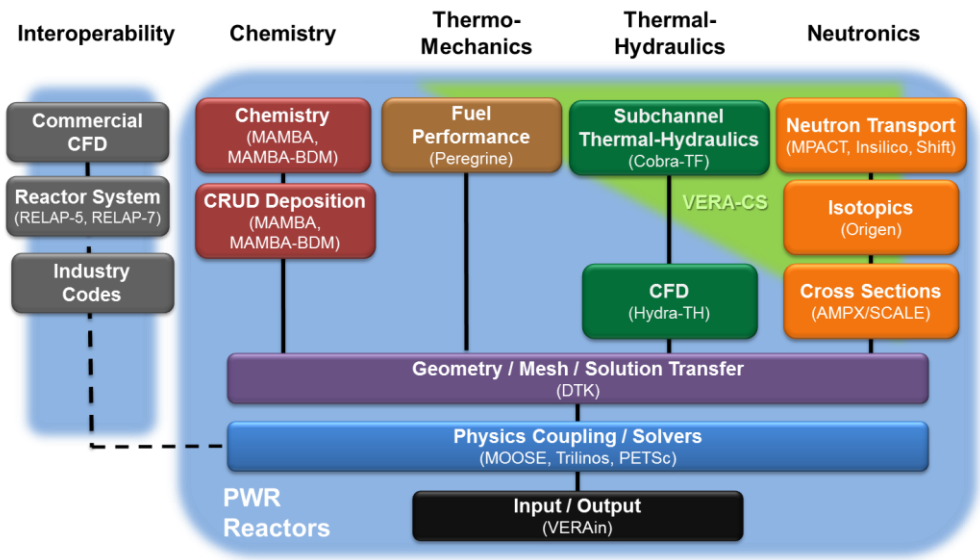


Figure 2: Diagram of VERA components as available in late 2013 [5]

The VERA input is separated into different "blocks" to define the assemblies, inserts, controls, instrumentation, core geometry, state data, and code specific input used for each case. For this project, there were no inserts (burnable poisons) as all BPR rods are modeled as already inserted in the core. Additionally, control rods were modeled as all out for each case in this project, since no depletion studies can be done at this time for 3-dimensional work. The block for code specific input provides the location for describing which code will be used. Having a separate block in the VERA input for code specification allows for the user to continuously use the same input for each code without having to make a number of models. This also allows for consistency among models, as the same input can be used each time with changes to only one block, keeping the geometry the same. The specific codes used for this project follow in the next three sections.

The standard output generated with VERA includes an HDF5 binary format file that contains the neutronics information in a binary format. This output can be visualized in a number of ways using available tools. To view the file in its original format, HDFView has been utilized [6].

This program displays the pin powers for each location in a table (similar to an Excel table) and the eigenvalue for the problem.

A parser that has been developed by VERA users, which allows the HDF5 file information to be converted into the format of a SILO file, has been used for this study. The SILO files were viewed using VisIt, which is described in a following section [7]. The ability to have the results in a SILO format was convenient, as this type of file can be opened directly with VisIt. This provided the ability for visualization of pin power distribution, which was a necessary component in completing this study. This allowed for pin power distributions to be easily viewed to see the amount of power peaking and the locations in which the power peaking occurred, which greatly helped with core design work.

Insilico

Insilico is one code utilized by VERA to perform neutronics calculations. Insilico uses SCALE's XSProc for cross section data and Denovo, the 3D neutron transport code developed at ORNL, for deterministic transport calculations. Denovo uses either discrete ordinant (S_N) or Simplified P_N (SP_N) solvers to calculate scalar fluxes. SP_N was used for this study. The SP_N method is a space-angle approximation of the Boltzmann transport equation, and is a low-order option used in VERA. With SP_N, the matrix that represents the transport operator is explicitly formed, which allows for parallel decomposition, preconditioning, and solvers. This makes the SP_N equations to be solved more easily than the S_N equations [4].

The Insilico conditions that have been utilized are as follows:

- Cross sections in 252 groups, collapsed into 23 groups
- SP_5 angular approximation
- P_N order of 3
- 2-by-2 pin mesh
- Pin cell homogenization

The 2D Insilico cases were all run on the Fissile 4 machine at ORNL. The Insilico build for these cases is the 01/23/2014 build. The 3D Insilico cases were all run on OLCF's Titan machine. The Insilico build used for these cases is the 05/14/2014 build.

MPACT

MPACT (Michigan Parallel Characteristics-based Transport) is a pin resolved transport code that is being developed to allow CASL the capability of MOC (Method of Characteristics) reactor analysis [8]. This code allows for the problem to be decomposed by space, angle, and characteristic rays, as specified in the inputs below [4]. MPACT is easily used with the existing common VERA input. Using MPACT, it is possible to run depletion cases in 2D. MPACT is used by inserting a new block of inputs into the VERA input (the block is titled [MPACT]). The following conditions have been used for the problems so far:

- 0.1 cm ray spacing
- 8 azimuthal angles per octant

- 2 polar angles per octant
- Chebyshev-Yamamoto quadrature set
- Flux tolerance of 1e-4
- Eigenvalue tolerance of 1e-5
- P2 scattering treatment
- CMFD (Coarse Mesh Finite Difference) solver
- NEM (Nodal Expansion) nodal method
- 56 group cross section library: declib56g_e7_09042013_p0mixed.fmt

All MPACT cases were run on the OLCF supercomputers, Eos and Titan. The MPACT builds used for this study on Eos were the 04/25/2014 build and the 06/17/2014 build. The MPACT build used for this study on Titan was the 06/12/2014 build.

Shift

Shift is another neutron transport code that can be used with the common VERA input. Shift is a CASL-developed tool that performs calculations using Monte Carlo. This allows for low-uncertainty power distribution comparisons to be obtained. To use Shift, additional cards are added to the [INSILICO] block in the VERA common input. The same input that was used for the Insilico case for the core design shown in Figure 13 was used for the Shift case, to maintain consistency for validation.

All Shift cases run so far have used ORNL's supercomputer, Titan. The Shift case used to compare to Insilico was modeled to use 100 inactive cycles at the beginning, 1100 active cycles, and 10,000,000 particles. The Shift build used for this study is the 03/27/2014 build.

Visualization of Results

Each code (Insilico, MPACT, and Shift) generates an HDF5 file as an output. This file contains the neutronics results for the problem. An output parser is used to convert the HDF5 file into a SILO file, so that the relative pin power distribution may be visualized. The SILO files are opened with VisIt, a visualization tool that was developed at Lawrence Livermore National Laboratory. VisIt reads the SILO file and generates a visualization of the results from the model, and these models can be seen further in this report [7].

An executable, "veradiff," has also been used to help visualize differences between results for different codes, mainly between MPACT and Shift. The executable takes the two HDF5 files from each case and compares the relative pin powers at each location and the k-effective values for each case. The reactivity difference is given by $(k_1 - k_2) \times 10^5$. The pin power differences and pin power performances were both given with the program, with the differences being a percentage based on $(P_1 - P_2) \times 100$, and the performances based on a root mean square difference and maximum absolute difference [9]. This program produces its own HDF5 file, which is converted into a SILO file to visualize the differences in VisIt.

Computing Requirements

All cases that have been run using VERA have utilized ORNL computing capabilities. ORNL's Fissile-4 multi-core cluster has been used to run the early cases (2D work from the first report and 3D single assemblies) with VERA, and 16 cores have been used for each case. So far, these runs have taken anywhere from 2 to 10 minutes. The smaller, 2D single-assembly cases take the least amount of time, while the 3D single assembly and 2D quarter core cases take the longest amount of time.

ORNL's supercomputers Eos and Titan have been used for the later work that is reported in this update. This work includes 3D core modeling using Insilico, verification of VERA results using Shift, and depletion studies in 2D using MPACT. Eos is a 744-node Cray XC30 cluster with 47.6 TB of memory and 11,904 traditional processor cores (23,808 logical cores with Hyper-Threading). Titan is a Cray X7 system with a theoretical peak performance that exceeds 27 petaflops. Titan has a total system memory of 710 TB, 18,688 compute nodes, and 299,008 CPU cores.

The Shift cases run using Titan have taken between 2.5 – 3 hours, and have used 64 cores. The MPACT cases run on Eos have taken between 1.5 – 3 hours, and have used up to 264 cores for 2D. The 3D Insilico case run using Titan took about 20 minutes and used 400 cores.

Table 2: Table showing runtimes and number of cores used for the problems described in this report

Code	Machine	Number of Cores	Runtime
Insilico 2D Quarter Core	Fissile 4 (Natasha)	16	~2.5 minutes
		36	~2.5 minutes
		49	~2.5 minutes
Insilico 3D Single Assembly (Type A)	Titan	16	~5.75 minutes
		64	~4.5 minutes
		100	~4.25 minutes
Insilico 3D Quarter Core	Titan	400	~20 minutes
		625	~16 minutes
		900	~14 minutes
Shift 2D	Titan	264	~2.5 hours
		3200	~2 hours
		8000	~45 minutes
MPACT 2D (depletion, coarse, 11 time steps)	Eos	264	~28 minutes
		396	~26 minutes
		528	~24 minutes
MPACT 2D (depletion, fine)	Eos	264	~1.67 hours
		396	~1.5 hours
		528	~1.25 hours
MPACT 2D (no depletion)	Eos	264	~9 minutes
		396	~8 minutes
		528	~6 minutes
MPACT 3D	Eos	858	~1.33 hours
		1155	~1 hour
		1683	~1.5 hours

Model Description

The complete details of proposed commercial SMR iPWR core designs are proprietary and not publicly known; however, five notional lattices were defined with varying numbers of burnable poison rods and gad fuel pins to be used as representative inputs. Additionally, some information is publically available that will allow for non-proprietary iPWR bundle and core designs to be modeled in order to generate a realistic representation of a commercial iPWR design.

2D Lattice Modeling

The lattices provided gave fuel rod, BPR, control rod, and gad fuel rod placements only, and no information was given regarding fuel enrichment. These lattices were modeled individually with a standard fuel enrichment of 4.95% and a 3.95% fuel enrichment for the rods with gadolinia. The specifications for each lattice are given in Table 2, and Figures 3-7 give a general design of each lattice, as well as the Insilico results for the maximum relative pin power and k-effective value for each lattice. The peaking factor limits used for this study was an $F\Delta H < 1.55$ and an $FQ < 2.4$ [10]. Additionally, the average assembly peaking factor limit was assumed to be less than 1.45 [11].

Figures 8 through 12 are images generated with VisIt, showing the relative pin power distribution for the top right quadrant of each lattice type. These cases were run with a standard fuel enrichment of 4.95% and the layouts as seen in Figures 3-7 below. The models in Figures 8-12 give the relative pin powers for each pin within the assembly, and these pin powers can be seen in the labels. The white spaces represent places with control rods and burnable poisons, and the green-colored square represents a fuel rod mixed with gad. The maximum relative pin power value in the five assembly types was ~1.1 for each type.

Table 3: Fuel assembly lattice specifications

Assembly ID	# Standard Fuel Pins	# BPR Pins	# Gd Fuel Pins	Maximum Relative Pin Power	k-effective
A	244	12	8	1.1078	1.2152
B	240	16	8	1.1120	1.1739
C	240	20	4	1.1010	1.1686
D	236	24	4	1.0823	1.1281
E	236	28	0	1.0717	1.1242

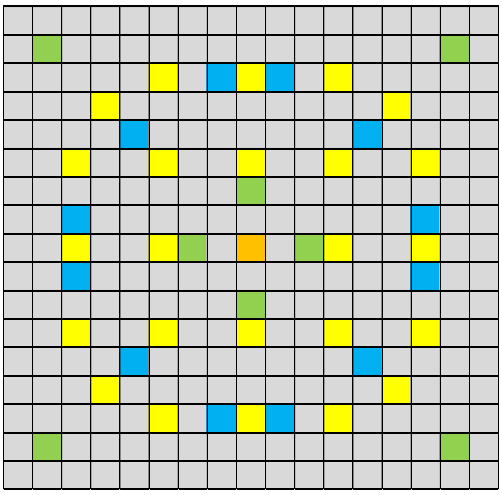


Figure 3: Layout of Assembly A, 12-BPR

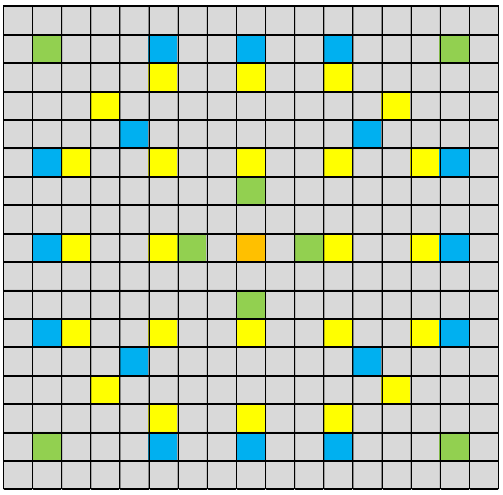


Figure 4: Layout of Assembly B, 16-BPR

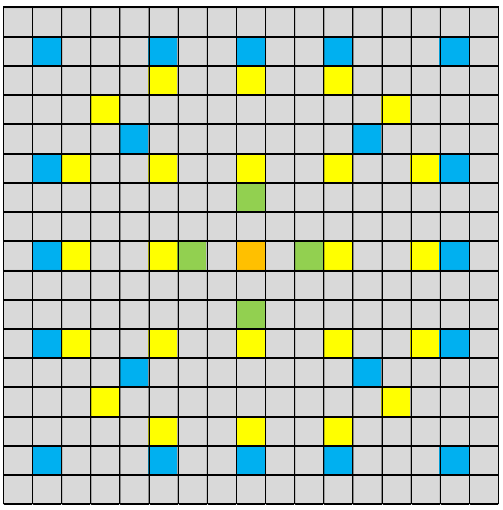


Figure 5: Layout of Assembly C, 20-BPR

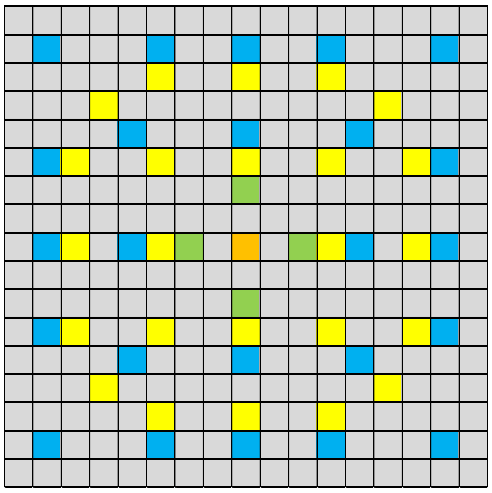


Figure 6: Layout of Assembly D, 24-BPR

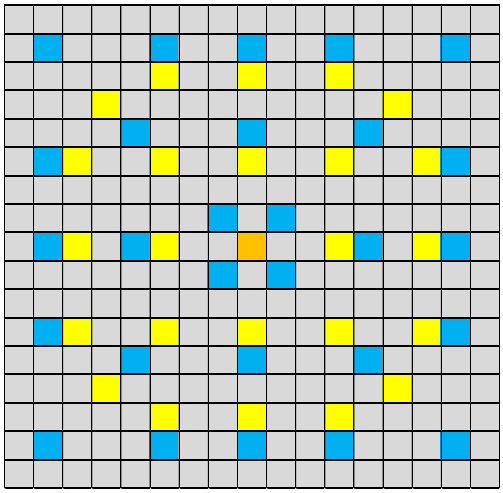


Figure 7: Layout of Assembly E, 28-BPR

	Standard Fuel Pin
	Control Rod
	Gd Fuel Pin
	BPR
	Instrument Tube

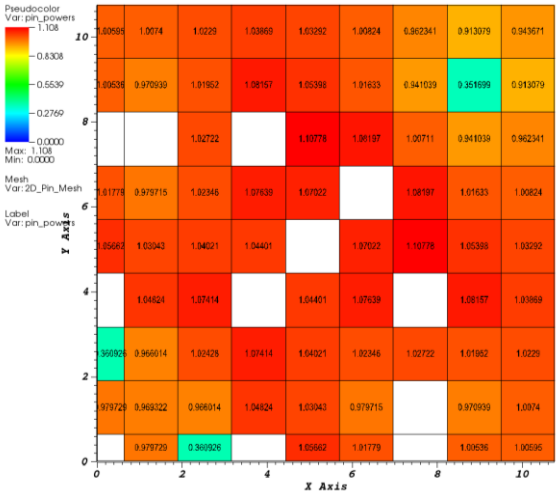


Figure 8: Relative pin power distribution of the 12-BPR lattice

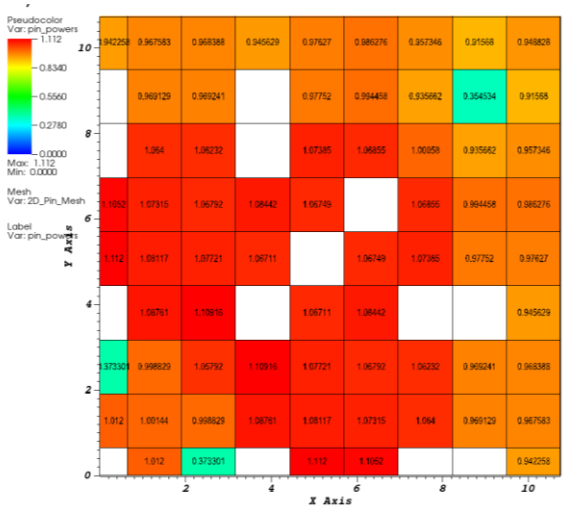


Figure 9: Relative pin power distribution of the 16-BPR lattice

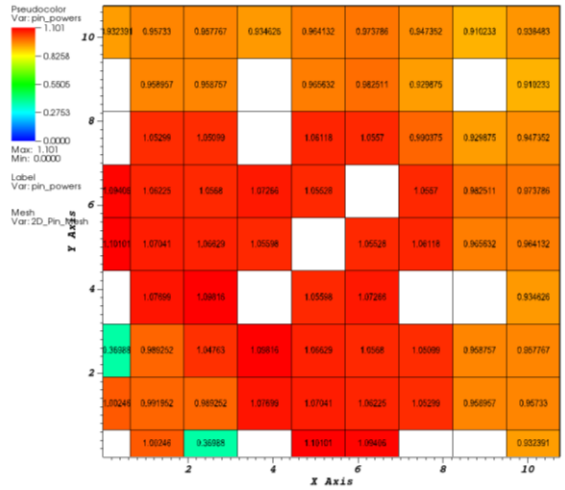


Figure 10: Relative pin power distribution of the 20-BPR lattice

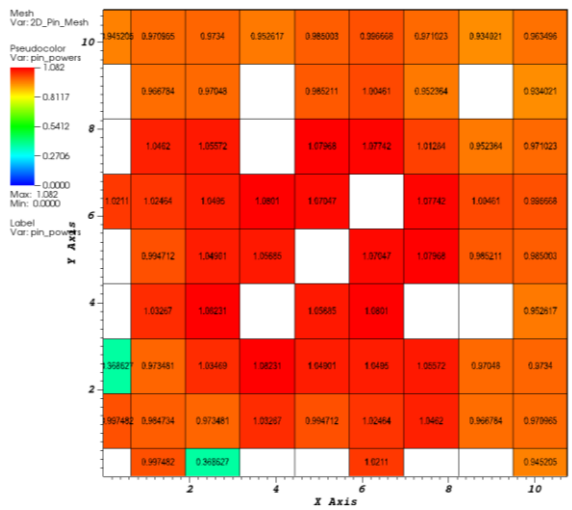


Figure 11: Relative pin power distribution of the 24-BPR lattice

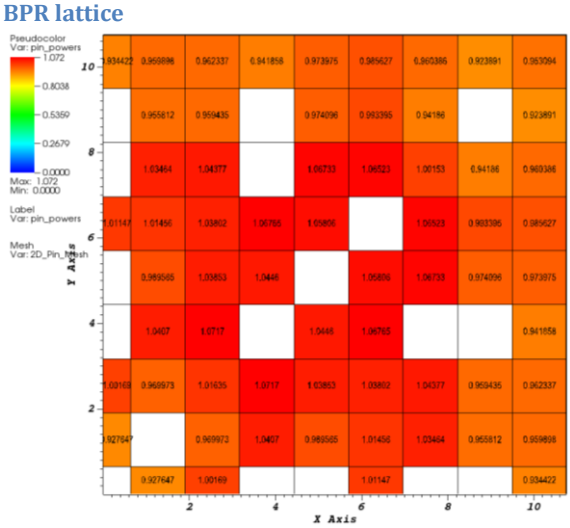


Figure 12: Relative pin power distribution of the 28-BPR lattice

2D Core Loading and Modeling

The single assemblies from the section above were loaded in various patterns into a quarter-symmetric core using VERA. Many cases were run to design an optimum core, beginning with a case where only the type C assemblies were loaded in the core and then adding one assembly type at a time into the core depending on power peaking locations. Finally, a design was chosen as the "best" of all the options, based on power peaking and eigenvalue. This design is shown in the figure below. The 2D models were all assumed to be a slice through the center of the SMR core.

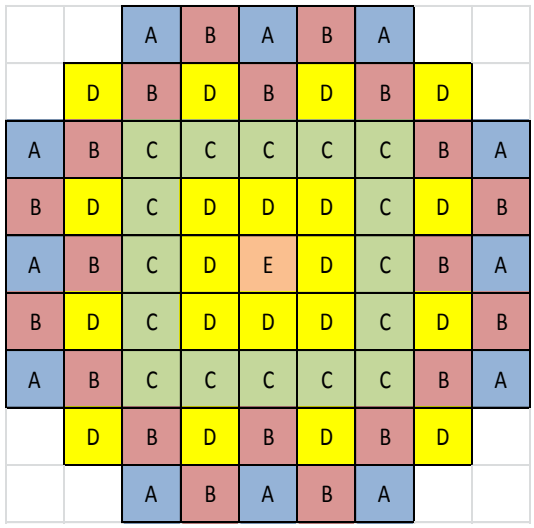


Figure 13: Core design determined from the first study using Insilico

Table 4: Table of assembly specifications for Figure 13

Assembly Type	# Standard Fuel Pins	Standard Fuel Pin Enrichment	# Gd Fuel Pins	Wt% Gd	Enrichment of Gd Pins	# BPR Pins
A	248	4.95	4	3	3.95	12
B	244	4.95	4	3	3.95	16
C	240	4.95	4	3	3.95	20
D	236	4.95	4	3	3.95	24
E	236	4.95	0	3	3.95	28

1.352 1.447	1.379 1.480	1.424 1.566	1.274 1.520	0.791 1.077
1.379 1.480	1.334 1.469	1.325 1.522	1.055 1.318	0.697 0.957
1.424 1.566	1.325 1.522	1.194 1.402	0.935 1.185	0.553 0.803
1.274 1.520	1.055 1.318	0.935 1.185	0.593 0.862	
0.791 1.077	0.697 0.957	0.553 0.803		

Avg Pwr
FΔH

Figure 14: Average and maximum relative powers for each assembly in the core design chosen

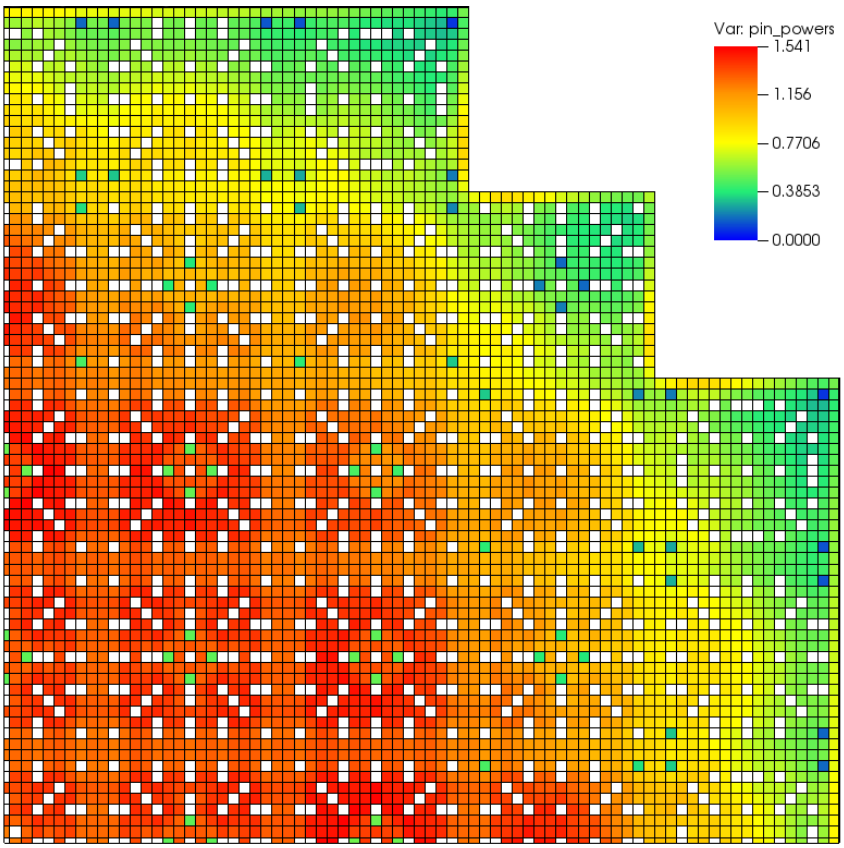


Figure 15: Relative pin power distribution of a 2D core using the core design shown in Figure 13

The baffle was modeled to be almost all steel (95% steel/5% water instead of 50% steel/50% water). The baffle was also made to be very thick – about 21 cm (almost the same width as the assembly pitch of 21.5 cm). Since the VERA default for the baffle region assumes that the steel-to-water ratio is 50/50, it was necessary to create a new material card for this application (see Appendix B or C). It was found that Insilico could not handle a baffle thickness greater than 10 cm (this was reported to the VERA development team, see the Remarks on VERA Usage section below). There was a 4% maximum difference in the relative pin power between the thin baffle (50% steel/50% water) and the thick baffle (95% steel/5% water), which is quite significant. Therefore, it was determined that increasing the baffle thickness and changing the baffle composition would be useful.

3D Modeling with Insilico

The core design from Figure 13 was taken and expanded into a 3D model by including axial dimensions in the VERA common input. Since no information was available as to the axial variations in the SMR, the fuel rods, BPRs, gad rods, etc., are uniform throughout their dimensions. The initial 3D model was created using the Titan supercomputer to run Insilico through VERA, since the Fissile-4 machines do not have enough cores to run a case of this size. An image of this model is shown below in Figure 16 (generated using VisIt). This image shows a full 3D SMR core, with the top piece cut away to demonstrate the relative pin power distribution at startup. The eigenvalue for this model is 1.1049, with a peaking factor of 2.252.

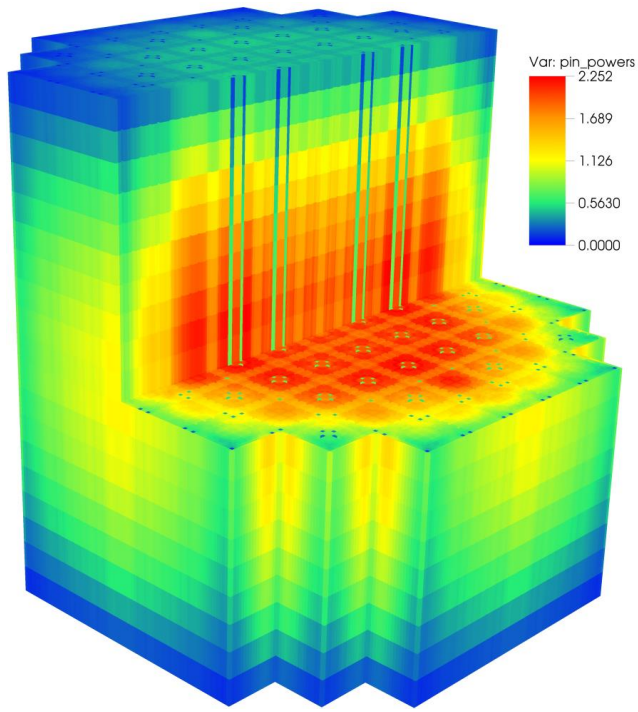


Figure 16: 3D model of the SMR core design as shown in Figure 13 using Insilico

2D and 3D Modeling with MPACT

MPACT was used to model both a 2D and 3D core (no depletion) in order to determine the target eigenvalue for the end of the cycle. This is done to account for axial leakage in the 2D core, since 3D depletion is not yet ready with VERA. The core design from Figure 13 was modeled for both case, and the 3D case was axially uniform. The target eigenvalue was assumed to be equal to the eigenvalue from the 2D case minus the eigenvalue from a 3D case plus 1 (k_{crit}). This value is equal to 1.1392 - 1.1184 = 0.028 +1 = 1.028. Therefore, 1.028 is the target eigenvalue for this core.

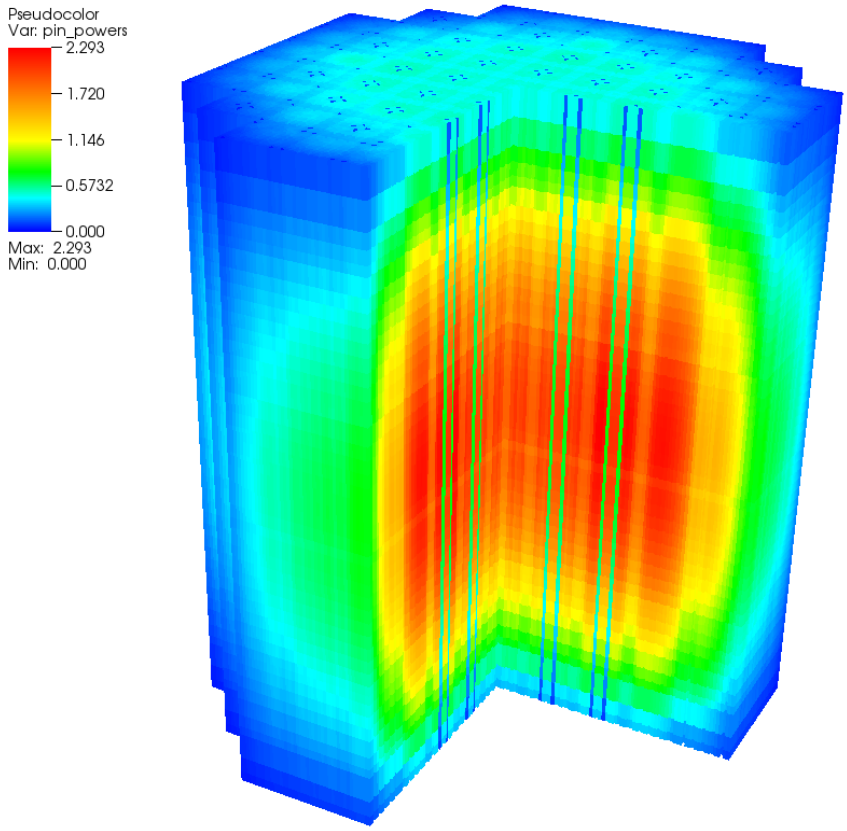


Figure 17: 3D SMR modeled using MPACT

In addition to modeling the axially uniform 3D core in MPACT, another core was created with axial blankets. These blankets are shown in Figure 18 below.

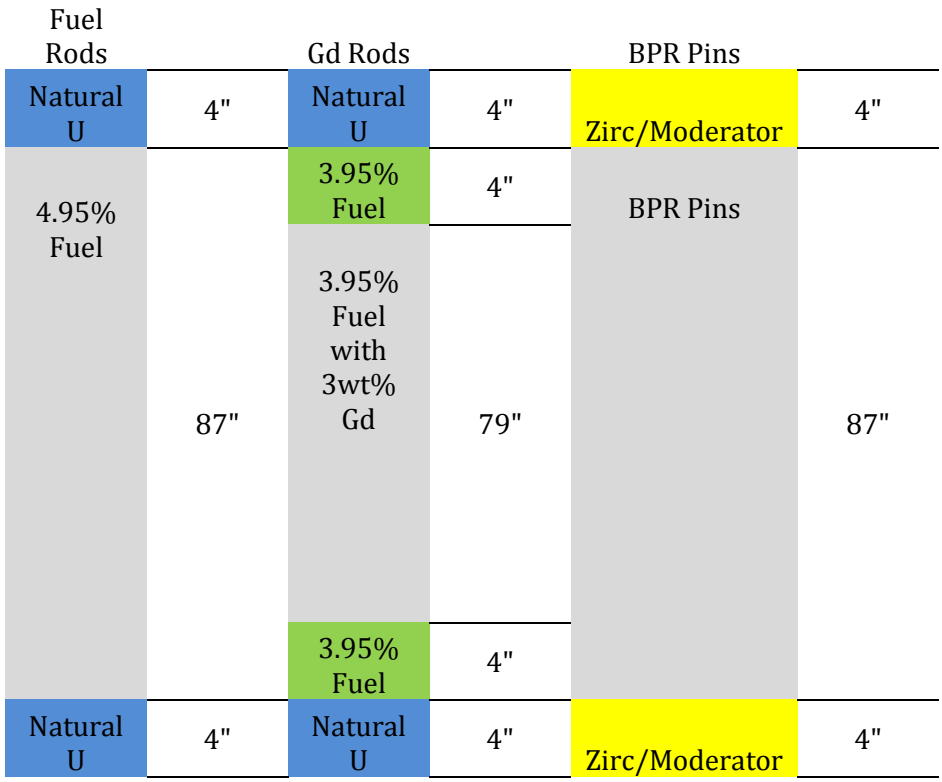


Figure 18: Axial layout of the 3D core modeled using MPACT

The 3D core from Figure 18, with the same core design as shown in Figure 13, gave a k-effective of 1.1280. Compared to the k-effective from the axially uniform 3D core, the k-effective for the core with axial blankets is about 957 pcm greater. This could be due to the fact that less poison is present in the core with axial blankets. It is also possible that this design allows the fuel to burn more efficiently throughout the core.

MPACT Depletion

The core design from Figure 13 was modeled using MPACT for depletion. The depletion steps used for this study were measured in EFPD (Effective Full Power Days). Depletion steps were taken up to 1400 EFPD, which was the goal length of time for the SMR core to stay critical. The same input was used as in the Insilico case from the 2D Lattice Modeling section above. It was found that the reactor went subcritical after the 1300 EFPD time step. Additionally, it was seen that some severe power peaking occurred throughout the depletion, and there was not a good, flat distribution. Therefore, it was necessary to begin making modifications to the core design using MPACT for depletion as a guideline, and the process for this is similar to the process that was used to design the core for the Insilico model. Locations with power peaking were observed, and the core was modified based on these locations. With each modification, it was necessary to look at how the core behaved over time, and each change made was based on this behavior. Some changes made included higher concentration of burnable poisons in certain locations, removal of certain poisons to make room for more fuel, replacing of BPRs with gad rods, etc. Unfortunately, the results with each change still showed a subcritical reactor between 1300 EFPD and 1400 EFPD.

In order to determine if it would be possible to reach 1400 EFPD at all, all poisons were removed to allow for as much fuel as possible in the core. When all poisons (BPRs and gad rods) were replaced with 4.95% fuel (so that only fuel and control rod locations existed in the core) the reactor remained critical at

1400 EFPD, with an eigenvalue of 1.002473. When all poisons and all fuel locations were replaced with 4.99% fuel, the reactor remained critical at 1.004621. Therefore, it is possible to reach 1400 EFPD, but it would have been more desirable to have achieved a slightly larger eigenvalue, given that no poisons or control rods were present in these models, and the target eigenvalue determined from the section above is 1.02.

Final modifications were made after removing all poisons to determine the possibility of achieving a larger eigenvalue at 1400 EFPD. The only way to achieve an increased eigenvalue is to add more fuel in the reactor. This is possible, at this point, only by increasing the size of the fuel rods, either radially or axially. In order to keep the height constant, only the radial dimensions were modified. First, a model was created with a 10% increase in the fuel assembly and pin pitches. This produced an eigenvalue of 1.060090 at 1400 EFPD. Second, a model was created with a 10% increase in the fuel rod radius, while holding the clad thickness constant, which lowered the eigenvalue back down to a value of 1.002655. This decrease in eigenvalue is expected, as a smaller amount of moderator is present to allow for the slowing down of neutrons. Table 4 shows the k-effective value over time for three different scenarios where the radial dimensions were altered.

Table 5: Value of k-effective for each EFPD for varying radial dimensions and poisons

	k-effective			
EFPD	Original Core Design	10% Radial Increase No Poisons	Lower Moderator-to-Fuel Ratio	10% Radial Increase with Gad
3	1.101	1.356	1.283	1.333
50	1.101	1.335	1.262	1.316
100	1.107	1.321	1.247	1.306
300	1.126	1.267	1.191	1.262
500	1.126	1.221	1.146	1.221
700	1.105	1.181	1.108	1.181
900	1.073	1.144	1.074	1.144
1100	1.038	1.109	1.043	1.109
1300	1.002	1.076	1.016	1.076
1400	0.993	1.060	1.003	1.060

After studying the effect on cycle length for different core designs with time, it was decided to stay with a modification of the original design from the first report and to aim for a cycle length of 1300 EFPD. This was chosen because the assembly pitch and pin pitch dimensions are one of the only aspects of the SMR known [12], and changing the radial dimensions could have a negative effect on thermal hydraulics. The core modeled has an eigenvalue of almost 1.0069 at 1300 EFPD, which is much lower than the determined target of 1.028. Below is a series of images of pin power distribution taken at different time steps throughout the life of the 2D core (the core shown in Figure 13).

Table 6: Eigenvalue per EFPD for the SMR core from Figure 13

MWD/kgHM	EFPD	k-effective
0.080	3	1.110
1.329	50	1.110
2.657	100	1.115
3.986	150	1.121
5.315	200	1.127
6.644	250	1.132
7.972	300	1.135
9.301	350	1.137
10.630	400	1.138
11.958	450	1.137
13.287	500	1.135
15.944	600	1.126
18.602	700	1.114
21.259	800	1.098
23.917	900	1.081
26.574	1000	1.064
29.231	1100	1.045
31.889	1200	1.026
34.546	1300	1.007
35.875	1350	0.998

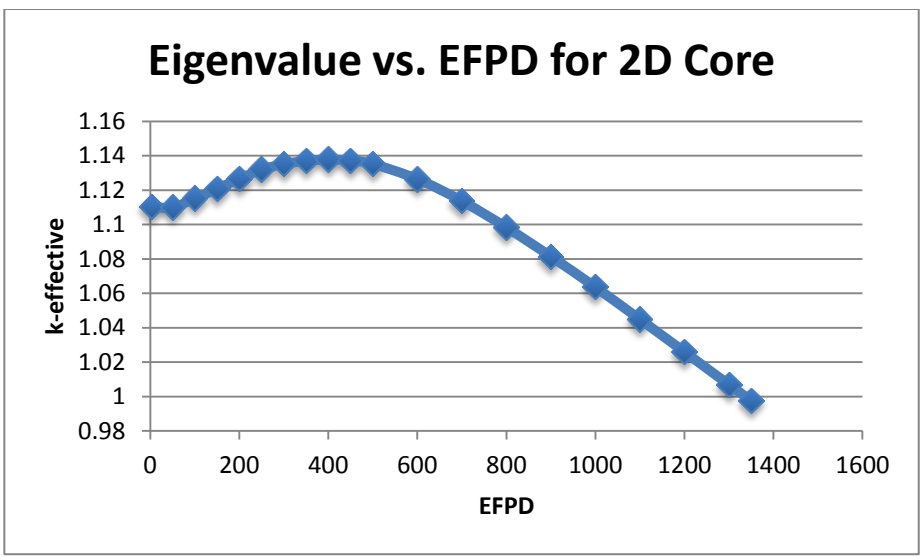


Figure 19: Graph describing the change in k-effective over time

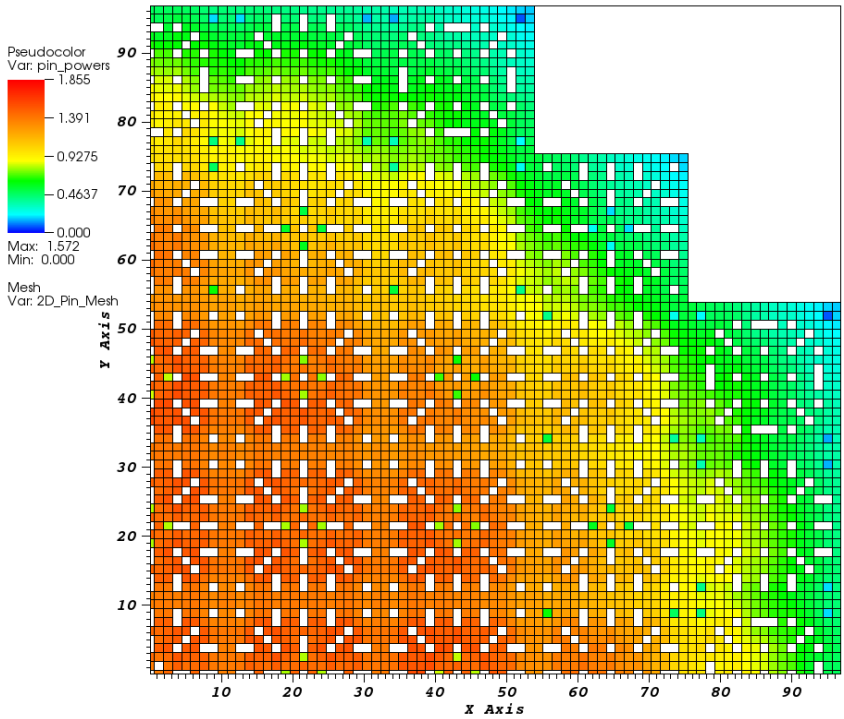


Figure 20: Image of the 2D SMR core from Figure 13 at the 3 EFPD time step, where k-effective is 1.100708

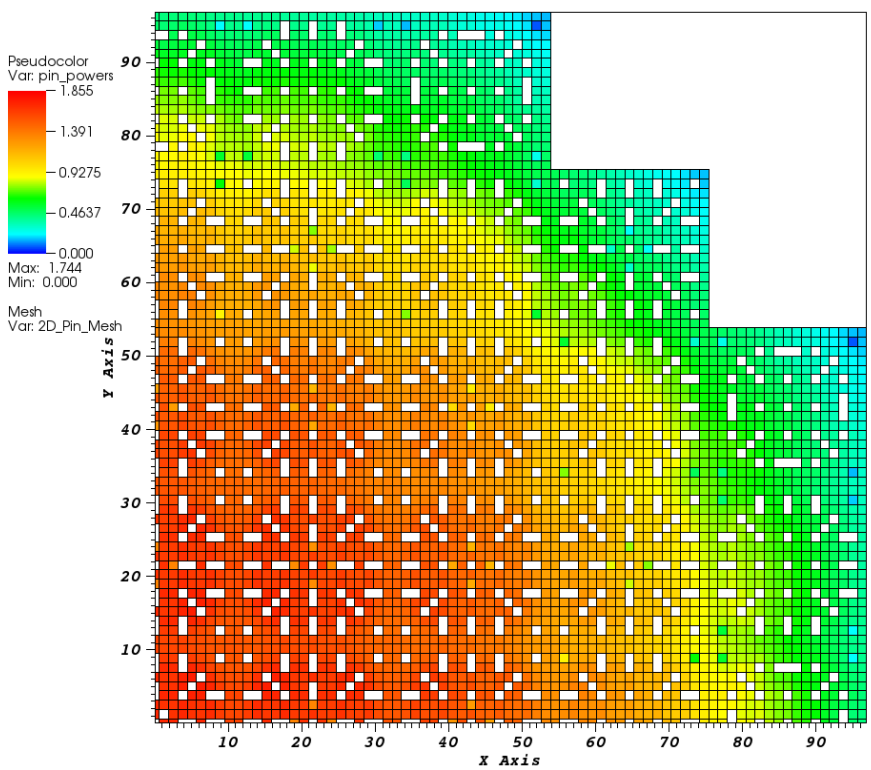


Figure 21: Image of the 2D SMR core from Figure 13 at the 500 EFPD time step, where k-effective is 1.123723

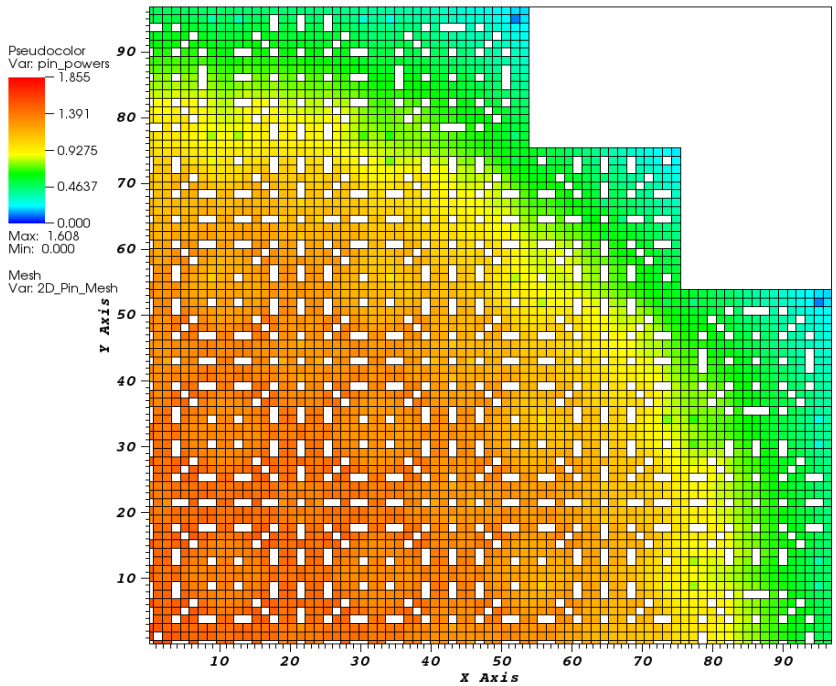


Figure 22: Image of the 2D SMR core from Figure 13 at the 900 EFPD time step, where k-effective is 1.073917

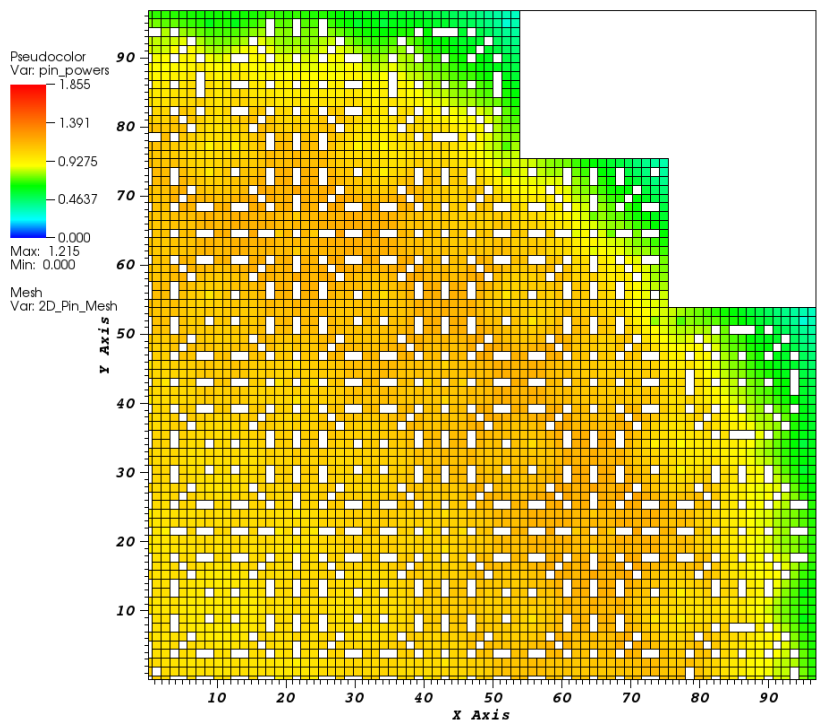


Figure 23: Image of the 2D SMR core from Figure 13 at the 1350 EFPD time step, where k-effective is 0.99374

An additional MPACT model was made to incorporate a recent update to the code, substepping. This was done to determine the significance in using the substeps compared to the original MPACT model, as the addition of substepping could improve the accuracy of depletion. As seen in Figure 24, the k-effective values for the two did not differ much (the delta k stayed between -40 and 100 pcm and stayed relatively

consistent. The dips in delta k occur at the very beginning and very end of the cycle. The best assumption for the reasoning behind this is that the time steps at the start and end of the cycle are shorter than the 100 EFPD time steps that occur in the middle of the cycle.

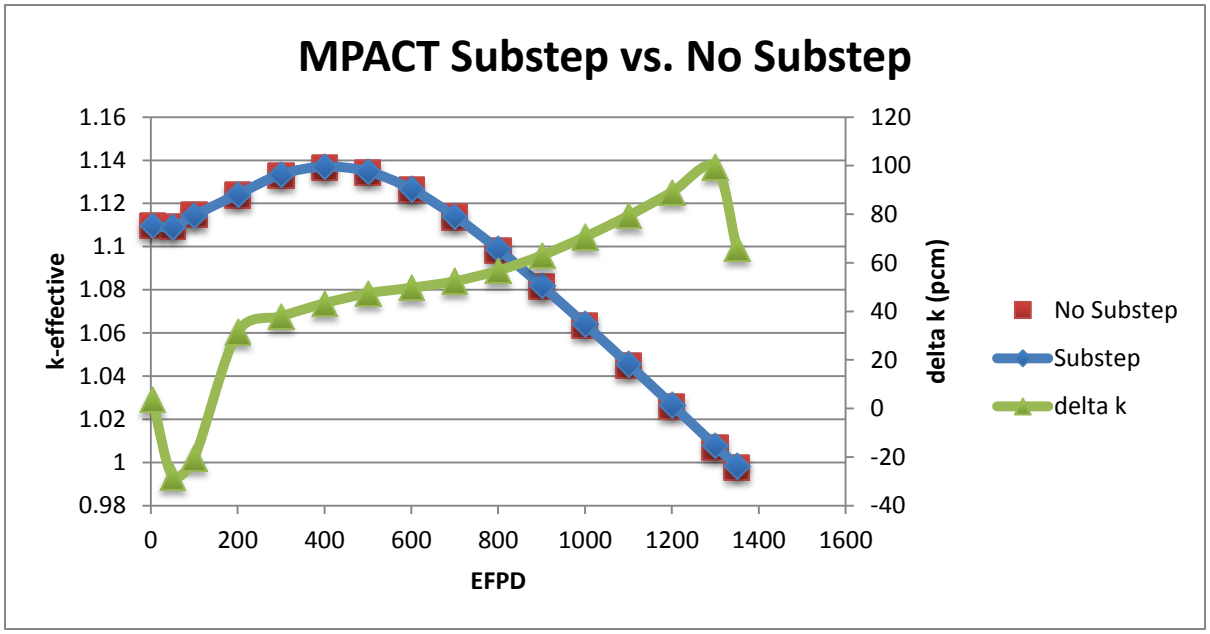


Figure 24: Graph of results comparing the use of substepping to no substepping

Benchmarking with Shift

Shift performs neutron transport calculations using Monte Carlo, and was used as a benchmark for Insilico and MPACT for this study. Shift can be easily used with the VERA input, so the same models were used for Insilico and Shift and MPACT and Shift to maintain consistency for comparison.

Comparison of Shift to Insilico

A 2D case was run in Shift with a 10-cm baffle of 95% steel and 5% water to compare with a 2D case in Insilico with a 10-cm baffle of 95% steel and 5% water. The Shift case gave a k-effective of 1.142343, and the Insilico case gave a k-effective of 1.1407003. This resulted in a 164.267 pcm difference when comparing Shift to Insilico.

Comparison of Shift to MPACT

A 2D case was run using Shift with the same input that was used for the 2D MPACT case (no depletion). The HDF5 files that contain the neutronics information for each case were compared using a program that determines the differences between the two files, called veradiff. After the comparison of the two, with Shift being the reference case, the following differences were noted:

- k-effective Difference = -327 +/- 4 pcm
- RMS Difference = 0.236%
- Maximum Difference = 0.767%
- Average Difference = 0.000%

Figure 25 shows a visualization of the differences in relative pin powers between the two codes.

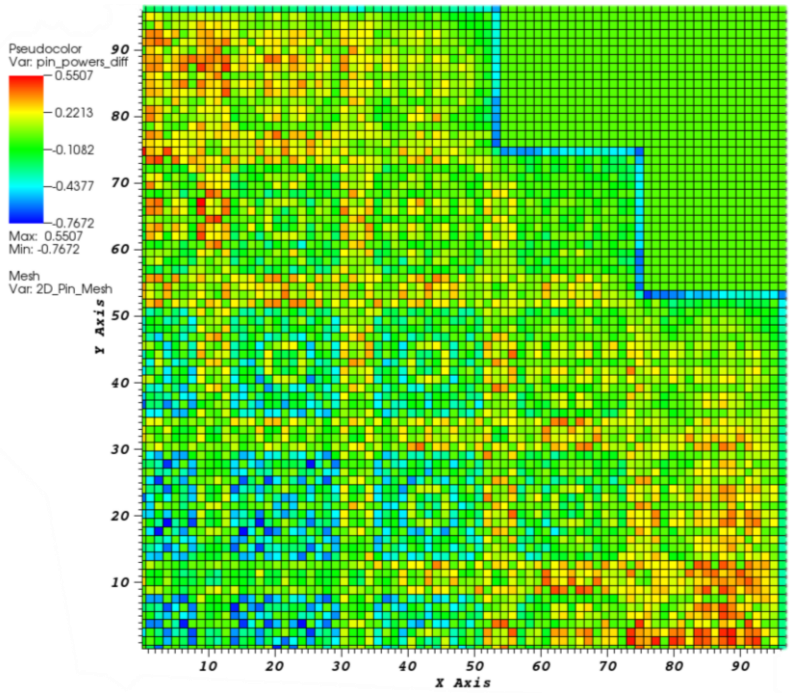


Figure 25: Visualization of the differences in relative pin power values between the two cases

Economic Study

The economics of the proposed SMR have been studied using an economics tool from ORNL's Reactor Physics Team and the available spot market prices and past market fuel prices of ore, conversion and SWU from The Ux Consulting Company [13]. Three different core designs were examined for comparison of fuel costs – the main core design from this study, shown in Figure 26, considered to be axially uniform; the core design from Figure 26 with a 10% radial increase in fuel and core, also considered to be axially uniform; and the core design from Figure 26 with axial blankets of 3.95% enriched fuel and natural uranium. The fuel costs for each option are given in the following sections. The table below gives the nominal, minimum, and maximum fuel costs (based on fuel cost history) that were used for this study. The core design and specifications for the core are also given below.

Table 7: Ore, conversion, SWU, and fabrication prices used for this study, using the economics tools from the Ux Consulting Company and ORNL's Reactor Physics Team [13]

	Nominal (Today's Prices)	Minimum (Prices of ~yr 2000)	Maximum (Prices of ~yr 2007)
Ore Price ($/lb)	28	10	130
Conv Price ($/kg)	8	5	12
SWU Price ($)	95	90	140
Fab Price ($/kg)	300	300	300
TOTAL COST ($/kg) - 4.95 wt% U235	2018	1408	5469
TOTAL COST ($/kg) - 3.95 wt% U235	1611	1133	4308

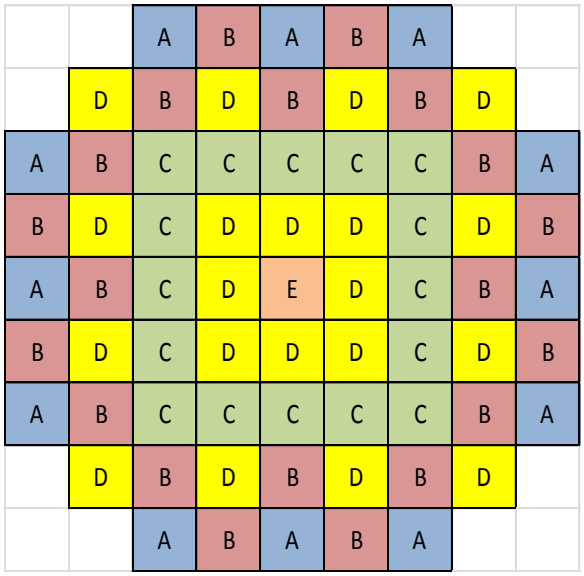


Figure 26: Core design for Options1, 2, and 3

Table 8: Specifications for the core design in Figure 26 for Options 1, 2, and 3

Assembly Type	# Standard Fuel Pins	Standard Fuel Pin Enrichment	# Gd Fuel Pins	Wt% Gd	Enrichment of Gd Pins	# BPR Pins
A	248	4.95	4	3	3.95	12
B	244	4.95	4	3	3.95	16
C	240	4.95	4	3	3.95	20
D	236	4.95	4	3	3.95	24
E	236	4.95	0	3	3.95	28

Option 1 – Core Design from Figure 26, Axially Uniform

The first option studies the core design from Figure 26 as axially uniform throughout, with standard radial dimensions (0.4095 cm fuel rod radius and 21.5 cm assembly pitch). The core height is 241.3 centimeters, and the density of UO_2 used is 10.52 g/cm^3. Additionally, it was determined that 88.15% of the UO_2 is made up of the heavy metal.

- Volume = (active fuel height) * π * (fuel rod radius)^2
  - Total Volume = ((241.3 cm)(π)(0.4095)^2)(# of rods)
- Mass $_{\text{standard fuel}}$ = 0.8815(Total Volume(10.52 g/cm^3))
- Mass $_{\text{fuel in gad rod}}$ = 0.8815(Total Volume(10.52 g/cm^3)) – 0.3(Total Volume(10.52 g/cm^3))

Table 9: Volume and masses of the core of option 1

Volume of 4.95% Fuel (m^3)	2.117
Volume of 3.95% Fuel (m^3)	0.035
Mass of 4.95% Fuel (kg)	19631.745
Mass of 3.95% Fuel (kg)	323.518

The mass of 4.95% fuel and 3.95% fuel were multiplied by the nominal values for total cost ($/kg) of fuel from Table 6 to give a total fuel cost for the startup cycle of about $40.14 million per core.

Option 2 – 10% Radial Increase, Axially Uniform

The core design from Figure 26, with the specifications from Table 7, was expanded radially by 10% (10% increase in fuel rod radius, clad radius, and assembly pitch, and the fuel to moderator ratio remained constant) to create a larger core and allow for more fuel. The values for volume and mass increased and are given in Table 9, and the cycle length increased to be longer than the goal length of 1400 EFPD.

Table 10 Volume and masses of the core of option 2

Volume of 4.95% Fuel (m^3)	2.561
Volume of 3.95% Fuel (m^3)	0.042
Mass of 4.95% Fuel (kg)	23749.13
Mass of 3.95% Fuel (kg)	376.23

The total cost of fuel for the startup cycle using this option, using the nominal values from Table 6, is $80.89 million per core.

Option 3 – Axial Blankets Included

The core design from Figure 26, with the specifications from Table 7, is also used for this option. However, this option includes axial blankets, as seen in Figure 27.

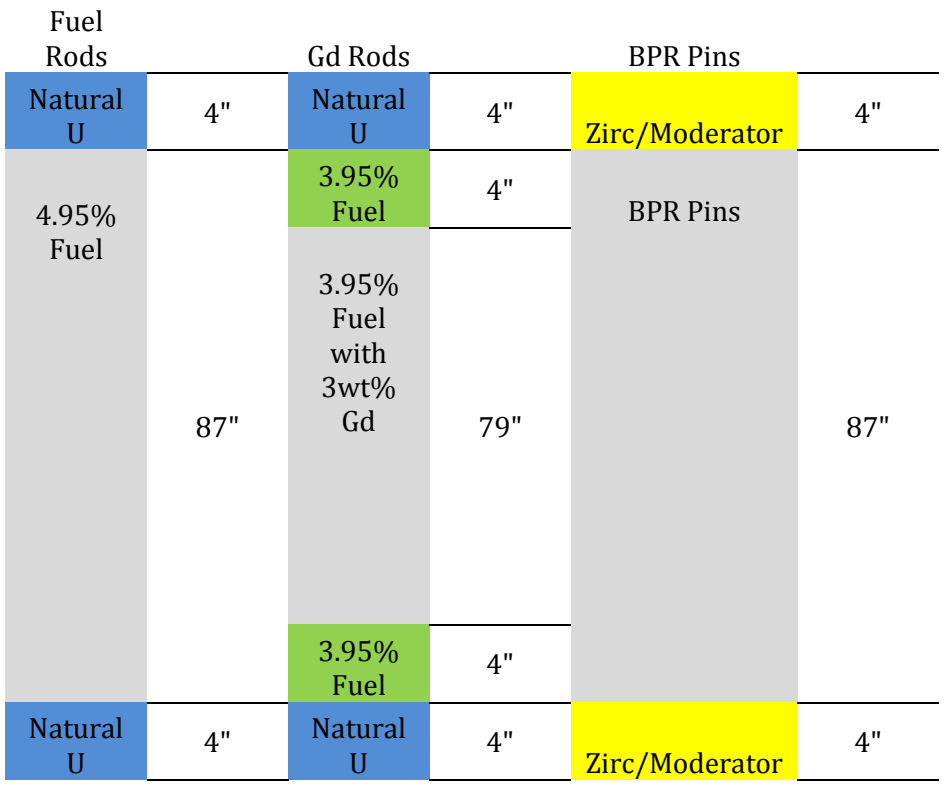


Figure 27: Axial loading of the core in Option 3

The price of natural uranium was assumed to not have much of an effect on the total cost, as it does not make up much of the fuel rods. Therefore, this study again only takes into account the cost of the enriched fuel.

Table 11: Volume and masses of the core of option 3

Volume of 4.95% Fuel (m^3)	18.819
Volume of 3.95% Fuel (m^3)	0.003
Mass of 4.95% Fuel (kg)	17976.913
Mass of 3.95% Fuel (kg)	268.730

The total cost of enriched fuel for this core is $36.71 million per core.

Economic Comparison to a 4-loop PWR Core

An axially uniform SMR core, like the one seen in Figure 26, was compared to an axially uniform PWR core. This was done under the assumption that the SMR will output 180 MW_e per year and will have the same core design and cycle length as the core used in this study (1210 EFPD). This cycle length of 1210 EFPD is based on the answer from the MPACT case and a target end of cycle eigenvalue of 1.028. Additionally, it was assumed that the SMR core would be completely removed and a totally fresh core will be reloaded (no twice-burning of the fuel).

It was assumed that the 4-loop PWR will operate for 18 months before an outage and output 1150 MW_e per year. It was also assumed that the PWR core would remove one-third of the assemblies per outage and load the missing spaces with fresh fuel. The 4-loop PWR was assumed to have the specifications given in Table 12.

Table 12: Specifications for the 4-loop PWR [14]

Active Core Height (cm)	365.8
Fuel Rod Radius (cm)	0.4095
Number of Assemblies	193
Number of Fuel Rods	264
Electrical Output (MWe)	1150
Volume of a Fuel Rod (cm^3)	192.709
Mass of HM in a Fuel Rod (kg)	2.114

To be conservative in the comparison, all fuel in this 4-loop PWR would be enriched to 4.95%. Using these specifications and the prices from Table 7, the total cost for 76 feed assemblies for this 4-loop PWR would be about $72.3 million per reload.

The table below describes the analysis and provides the total cost at the end of the operation in $million/GWye.

Table 13: Table of Fuel Cost for Life of Plant

	Number of Years Between Reload	Number of Reloads for 60 years of Operation	Cost per Reload ($M)	Total Cost for 60 Years ($M)	Electrical Output (GWy)	Fuel Cost ($M)/GWy
SMR	3.32	18	40.1	721.8	10.8	66.83
PWR	1.5	40	72.3	2892	69	41.9

As seen in Table 11, the cost of fuel per GWy for the SMR is much higher than the cost for a currently operating PWR. However, it is important to note that the fuel cost is only one piece of the economics behind a nuclear reactor. The following pie chart shows that only 12% of the cost of a nuclear plant goes into the fuel prices [15].

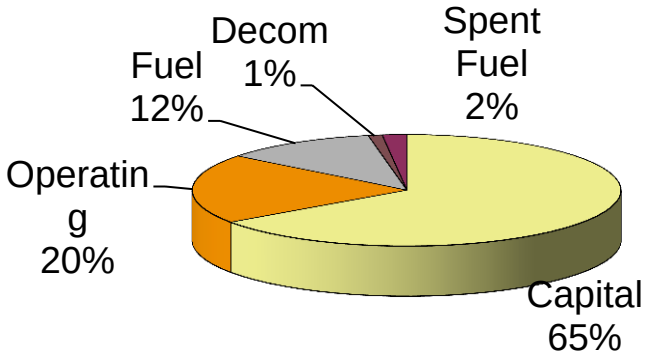


Figure 28: Pie chart describing the economics of nuclear plant costs [15]

It is also important to recognize that the advanced reactors under development are striving to reduce capital costs, which is the majority of the total cost of a nuclear reactor (65%). In the case of a Small Modular Reactor, this can be achieved by assembly-line fabrication, as each reactor is to be made alike, and each core is fully removed and replaced with each outage. Since each SMR will be made alike, the cost for repairs and maintenance should decrease, as parts should be more readily available and problems should be easier to fix due to the consistency between reactors. Additionally, the Operations and Maintenance costs for the SMR should be significantly lower. This is due to a much lower number of outages for a 60-year life (15 compared to 40), requiring fewer workers during the outage time.

After performing this analysis, it was seen that, although the costs for the fuel were much higher for an SMR compared to a 4-loop PWR, many other costs factor into the total cost of a nuclear power plant. Therefore, a much larger, more detailed study will be necessary to develop a fair comparison between the two types of nuclear reactors.

Remarks on VERA Usage

VERA-CS proved to be very capable in handling the advancements in nuclear power that come with small modular reactors. The VERA common input is user-friendly and easily understood. By separating the input into blocks, the input stays organized and consistent from code to code. A sample input deck was provided before beginning this study, and in using this example the input requirements were easy to follow. It was found that, unless the user has a true understanding of the code and methods used within the code, it is difficult to determine what inputs should be used for the code block. This was not a huge problem, only requiring some research on the codes and help form more experienced users.

The main issues found while using VERA to model a small modular reactor mostly had to do with adjusting the baffle. Insilico could not model a baffle greater than 10 cm, while the goal was to model the

baffle to be the same thickness as the assembly pitch (21.5 cm). MPACT and Shift could model a much thicker baffle, but the baffle thickness for these two codes could not equal the assembly pitch. Therefore, a 21-cm baffle was used. The code developers have been notified of this. Additionally, the baffle was modeled as almost all steel, with a 95/5 steel to water ratio. A special material had to be defined for this material mixture, but once the material and baffle were correctly specified to agree with the code requirements, the case ran without issues.

One other issue occurred during this study was with the VERA input when using Shift. The inlet temperature input had to be 565 Kelvin for Shift, and the fuel temperature could only increase or decrease by certain increments. When using Shift to validate the other two results, the inputs had to be modified for MPACT and Insilico to reflect this temperature change and keep consistency for comparison.

An interesting note about the small modular reactor modeled for this study is that the burnable poison rods (modeled as AL_2O_3-B_4C) were not "inserts" and were modeled as already inserted in the core with the fuel and gad rods. This meant that the insert block in the VERA input was not needed, and the burnable poison rods were modeled in the assembly block with the fuel rods and guide tubes. VERA seemed to handle this well.

The output for all 3 codes used included an HDF5 binary format file. It was possible to view the contents of this file, which included the eigenvalue and relative pin powers. It was often beneficial to convert this file to a SILO file for easier viewing of the results. The programs used to convert the HDF5 files into SILO files, and to compare the differences between two HDF5 files, were found to be useful tools, and it is recommended that this become available to all VERA users, as they certainly made the results easy to visualize.

While the overall experience of the usage of VERA-CS was positive, it would be helpful and worthwhile to develop a user manual for the input. The sample input deck provided for this study was often easier to follow than the CASL Wiki page for the VERA input, as the Wiki was not updated enough for all input requirements while performing this research. Including a sample input in a user manual, along with a description of each input block and its components, would increase the usability of VERA. It would also be advantageous to include average runtimes for coarser/finer specifications in the code input blocks, as the runtime has to be included in the run script.

Results

Due to the sensitivity of the information around the Babcock & Wilcox mPower SMR, very little information was known going into this study. Due to this, a great amount of core design work was necessary to come up with a small modular reactor core that would produce reasonable results, mainly in eigenvalue, cycle length, and power peaking. The initial core design work was performed with VERA using Insilico. The control of power peaking was the main concern for this piece of the study, and the core design in Figure 13 was chosen as the "best" design. The core design used for this study met the peaking factor requirements of $F\Delta H < 1.55$, $FQ < 2.4$, and average assembly power < 1.45.

MPACT was the next code used in VERA, in order to study cycle length. More core design work occurred here, as the core from Figure 13 chosen with Insilico did not meet the goal cycle length of 1400 EFPD. However, only by extreme measures using the lattices provided could the small modular reactor

modeled for this project meet the goal cycle length. Therefore, it was determined to keep the core design in Figure 13 and to meet a new cycle length of 1300 EFPD.

An economic study was performed with three different core designs. Many assumptions were made to complete this study, so it should be noted that these economic studies are just for comparison in cost among the differences in the three designs. A comparison was also made between fuel costs for the SMR and fuel costs for a 4-loop PWR. This comparison showed that the fuel cost for the SMR is much higher than the fuel cost for the 4-loop reactor. However, as noted in the Economic Study section above, a number of factors go into the cost of a nuclear plant, and the cost of fuel only makes up about 12% of the total cost. Therefore, a much more in depth analysis of the economics should be performed in order to determine a true comparison in costs between the two reactors.

Conclusions and Future Work

At this point, the SMR designs modeled with VERA, reported here, have not been compared with designs and studies from actual SMR vendors. Therefore, this work should be seen as modeling an assumed core design for a typical iPWR SMR, and not as an actual solution to possible future SMR core cycle designs and cycle behavior. Additionally, Task 4 may not be a completed task for this project, which is acceptable because Task 4 is an "as possible and as applicable" task. However, this work is set to be compared to the Babcock & Wilcox mPower SMR this fall (2014).

Future work should be done to study the thermal-hydraulics effects for this core, and for variations to the core shown in Figure 13. This should allow for a more accurate economic conclusion. Furthermore, once the capability becomes available, future work should be done to use MPACT to deplete a 3D core, and control rod studies and axial blanket studies should become more relevant at this point. As seen from the result of modeling the core with the axial layout shown in Figure 18, varying the rods axially can have a significant effect on the k-effective for the core. This study was only concerned with the fuel costs for the SMR, so three core design options were studied and fuel costs for each design were evaluated. Additionally, the fuel cost for the SMR core design from the Insilico tests, using the cycle length from the MPACT tests, was compared to the fuel cost for an axially uniform 4-loop PWR. There was a significant difference in the fuel cost between the two for a 60-year lifetime. As more knowledge of the SMRs under development becomes available, a more in-depth economic study should be performed that will take into account all factors that go into the cost of a nuclear reactor, from construction to decommissioning. This will allow for a truer analysis and comparison between already operating plants and the Small Modular Reactor.

References

[1]. "Small Modular Nuclear Reactors." *Energy.Gov.* Office of Nuclear Energy. Web 8 Dec 2013. <http://energy.gov/ne/nuclear-reactor-technologies/small-modular-nuclear-reactors>

[2]. Stout, Dan. (2013). *TVA's Clinch River Small Modular Reactor Project*. [PowerPoint slides]. Retrieved from website: http://eec.ky.gov/Documents/TVA%20Clinch%20River.pdf

[3]. *Generation mPower: Snapshot.* Charlotte: Generation mPower, LLC. 2012. Print.

[4]. Godfrey, Andrew T., et al. "Operational Reactor Model Demonstration with VERA: Watts Bar Unit 1 Cycle 1", Revision 1 August 1 2013 CASL-U-2013-0105-001.

[5]. "Consortium for Advanced Simulation of Light Water Reactors: Second Five-Year Term Proposal." Revision 2.0, Consortium for Advanced Simulation of LWRs. June 6, 2014.

[6]. HDFView, February 12, 2013. http://www.hdfgroup.org/hdf-java-html/hdfview/

[7]. VisIt Visualization Tool, LLNL, March 25, 2013. https://wci.llnl.gov/codes/visit/

[8]. Collins, B., et. al., "Application of MPACT 2D/1D to AMA Benchmark Problem 5", Revision 0, CASL-U-2013-0273-000, CASL, November 30, 2013.

[9]. Godfrey, Andrew T. "MPACT Testing and Benchmarking Results." Revision 0, CASL-U-2014-0045-000, CASL, March 31, 2014.

[10]. *Watts Bar Nuclear Reactor FSAR.* Tennessee Valley Authority. Print.

[11]. *Sequoyah HTP Fuel Transition*. Attachment 8, Rev 2. AREVA NP Inc. June 2011. Print.

[12]. Erighin, Madalina Aimee. "A 48-Month Extended Fuel Cycle for the B&W mPower Small Modular Nuclear Reactor." April 15-20 2012. Paper presented at the PHYSOR Conference, Knoxville, TN.

[13]. *The Ux Consulting Company.* Website. June 20, 2014. http://www.uxc.com.

[14]. *The Westinghouse Pressurized Water Reactor Nuclear Power Plant*. Pittsburgh, PA: Westinghouse Electric, Water Reactor Division, 1984. Web. 19 June 2014.

[15]. Worral, Andy. "Seminar 8: Economics of Nuclear Energy." Oak Ridge National Laboratory. Seminar Lecture.

[16]. Duderstadt, James J., & Hamilton, Louis J. *Nuclear Reactor Analysis.* New York: Wiley, 1976. Print.

Appendix A – Sample VERA Common Input with Insilico

```
[CASEID]
 title  'SMR Surrogate Model – 2D'

[STATE]
  power  0.0            ! %
  tinlet 566.33         ! F
  tfuel  840            ! K
  boron  0              ! ppmB  (No Boron)
  modden 0.7065         ! g/cc
  feedback off
  sym qtr

  rodbank A 1           ! All rods out?

[CORE]
 size 9                 ! assemblies across core
 rated 530 30           ! MWt, Mlbs/hr
 apitch 21.5            ! cm
 height 1.0

  core_shape
0 0 1 1 1 1 1 0 0
0 1 1 1 1 1 1 1 0
1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1
0 1 1 1 1 1 1 1 0
0 0 1 1 1 1 1 0 0

  assm_map
5 4 3 2 1
4 4 3 4 2
3 3 3 2 1
2 4 2 4
1 2 1

 crd_map
    - - - - -
  - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
  - - - - - - -
    - - - - -
 crd_bank
    - - - - -
  - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
  - - - - - - -
    - - - - -

! the detector map is upside down for denovo
  det_map
    - - - - -
  - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
  - - - - - - -
    - - - - -

  bc_top reflecting
  bc_bot reflecting

! baffle mat, thickness,gap to fuel?
  baffle ss 2.8575 0.19

!  lower_plate ss  5.08 0.5   ! mat, thickness, vol frac
!  upper_plate ss  7.6 0.5    ! mat, thickness, vol frac

!  lower_ref  mod 20.0 1.0    ! additional moderator reflector depth
!  upper_ref  mod 20.0 1.0    ! additional moderator reflector depth

!  xlabel  R P N M L K J H G  F  E  D  C  B  A
!  ylabel  1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

  mat zirc 6.55 zirc4
  mat ss   7.94
  mat he 0.0001786
```

```
  mat pyrex 2.25
  mat b4c 2.9441
  mat inc 8.19
  mat b4c-al2o3  2.9441 b4c 0.04 al2o3 0.96

[ASSEMBLY]
  title "mPower 17x17"
  npin 17
  ppitch 1.26                 ! pin half pitch = .63 cm, so double is pin pitch? (Task1.doc)

  fuel U395 10.5216 96 / 3.95
  fuel U495 10.5216 96 / 4.95
  fuel g300 10.5216 94.5 / 3.95 / gad=3.0

  cell 1   0.4095 0.42 0.475 / U395 he zirc
  cell 2   0.4095 0.42 0.475 / U495 he zirc
  cell 3   0.5715 0.6121 / mod zirc                 ! guide/instrument tube
  cell 4   0.42 0.475 / he zirc                     ! plenum
  cell 5   0.475 / zirc                             ! end plug
  cell 6   0.4095 0.42 0.475 / g300 he zirc         ! Gad fuel
  cell 7   0.4095 0.42 0.475 / b4c-al2o3 he zirc    ! BPR

  lattice LAT1
       3
       2 2
       2 2 2
       3 2 2 3
       2 2 2 2 7
       2 2 2 2 2 3
       3 7 2 3 2 2 2
       2 2 2 2 2 2 2 6
       2 2 2 2 2 2 2 2 2

  lattice LAT2
       3
       2 2
       2 2 2
       3 2 2 3
       2 2 2 2 7
       2 2 2 2 2 3
       3 2 2 3 2 2 2
       7 2 2 7 2 2 2 6
       2 2 2 2 2 2 2 2 2

 lattice LAT3
       3
       2 2
       6 2 2
       3 2 2 3
       2 2 2 2 7
       2 2 2 2 2 3
       3 2 2 3 2 2 2
       7 2 2 7 2 2 2 7
       2 2 2 2 2 2 2 2 2


  lattice LAT4
       3
       2 2
       6 2 2
       3 2 2 3
       7 2 2 2 7
       2 2 2 2 2 3
       3 2 2 3 2 2 2
       7 2 2 7 2 2 2 7
       2 2 2 2 2 2 2 2 2

  lattice LAT5
       3
       2 7
       2 2 2
       3 2 2 3
       7 2 2 2 7
       2 2 2 2 2 3
       3 2 2 3 2 2 2
       7 2 2 7 2 2 2 7
       2 2 2 2 2 2 2 2 2

  lattice PLEN
       3
       4 4
       4 4 4
       3 4 4 3
       4 4 4 4 4
       4 4 4 4 4 3
       3 4 4 3 4 4 4
       4 4 4 4 4 4 4 4 4
       4 4 4 4 4 4 4 4 4

  lattice ENDPL
       3
```

```
        5 5
        5 5 5
        3 5 5 3
        5 5 5 5 5
        5 5 5 5 5 3
        3 5 5 3 5 5 5
        5 5 5 5 5 5 5 5
        5 5 5 5 5 5 5 5 5

   axial  1  0.0   LAT1  1.0
   axial  2  0.0   LAT2  1.0
   axial  3  0.0   LAT3  1.0
   axial  4  0.0   LAT4  1.0
   axial  5  0.0   LAT5  1.0

!  grid END inc  610 1.859 ! grid id, material, mass, height
!  grid MID inc  610 1.859 ! assume mid grids are same design

!  lower_nozzle  ss 5.061 6250.0  ! mat, height, mass (g)
!  upper_nozzle  ss 5.061 6250.0  ! mat, height, mass (g)


[CONTROL]
  title "B4C with AIC tips"
  npin 17
  stroke  1.0 1    ! 1 step for in/out?

  mat aic 10.17
  mat b4c 2.9441

  cell 9  0.432 0.438 0.489 / aic he ss
  cell 10  0.432 0.438 0.489 / b4c he ss

rodmap AIC
-
- -
- - -
9 - - 9
- - - - -
- - - - - 9
9 - - 9 - - -
- - - - - - - -
- - - - - - - - -

rodmap B4C
-
- -
- - -
10 - - 10
- - - - -
- - - - - 10
10 - - 10 - - -
- - - - - - - -
- - - - - - - - -

   axial  A 0.0 AIC 1.0
   axial  B 0.0 B4C 1.0

[DETECTOR]
  title "Incore instrument thimble"
  npin 17

  cell 11  0.5715 0.6121 / he ss

  rodmap  LAT
     11
     - -
     - - -
     - - - -
     - - - - -
     - - - - - -
     - - - - - - -
     - - - - - - - -
     - - - - - - - - -

!  axial 1  0.0 LAT 227.811
   axial 1  0.0 LAT 1.0



[INSILICO]
    dimension 3
    cell_homogenize true
    eq_set        spn_fv
    SPN_order     5
    Pn_order      3
    tolerance     1e-6

    mat_library casl_comp_r2.sh5
    xs_library  lib252_hetbondoneabs-noabssigp
```

```
    mesh 2

!    pin_partitioning true
    Pn_correction true
    num_blocks_i  4
    num_blocks_j  4
!    num_z_blocks  1
    num_groups    23
    num_sets      1
    max_delta_z   1.0

    azimuthals_octant  4
    polars_octant      4
    quad_type          qr

    SILO_output  'SMR_rev10'

    new_grp_bounds
       8.2085e+05
       1.1109e+05
       5.5308e+03
       1.8644e+02
       3.7612e+01
       3.5379e+01
       2.7697e+01
       2.1684e+01
       2.0397e+01
       1.5968e+01
       7.1500e+00
       6.7000e+00
       6.3000e+00
       1.0970e+00
       1.0450e+00
       9.5000e-01
       3.5000e-01
       2.0600e-01
       1.0700e-01
       5.8000e-02
       2.5000e-02
       1.0000e-02
       1.0000e-05
```

Appendix B – VERA Input with Shift

```
[CASEID]
 title  'SMR 2D Model – Shift'

[STATE]
  power  0.0            ! %
  tinlet 566.33         ! F
  tfuel  840            ! K
  boron  0              ! ppmB
  modden 0.7065         ! g/cc
  feedback off
  sym qtr

  rodbank A 1           ! All rods out

[CORE]
 size 9                 ! assemblies across core
 rated 530 30           ! MWt, Mlbs/hr)
 apitch 21.5            ! cm
height 1.0

  core_shape
0 0 1 1 1 1 1 0 0
0 1 1 1 1 1 1 1 0
1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1
0 1 1 1 1 1 1 1 0
0 0 1 1 1 1 1 0 0

  assm_map
5 4 3 2 1
4 4 3 4 2
3 3 3 2 1
2 4 2 4
1 2 1

 crd_map
    - - - - -
  - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
  - - - - - - -
    - - - - -
 crd_bank
    - - - - -
  - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
  - - - - - - -
    - - - - -

  det_map
    - - - - -
  - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
  - - - - - - -
    - - - - -
```

```
  bc_top reflecting
  bc_bot reflecting

  mat ss  8.0
  mat ref 7.0 ss 0.95 water 0.05

  baffle ref 0.19 21

  mat zirc 6.55 zirc4
  mat ss   7.94
  mat he 0.0001786
  mat pyrex 2.25
  mat b4c 2.9441
  mat inc 8.19
  mat b4c-al2o3  2.9441 b4c 0.04 al2o3 0.96

[ASSEMBLY]
  title "mPower 17x17"
  npin 17
  ppitch 1.26

  fuel U395 10.5216 96 / 3.95
  fuel U495 10.5216 96 / 4.95
  fuel g300 10.5216 94.5 / 3.95 / gad=3.0

  cell 1   0.4095 0.42 0.475 / U395 he zirc
  cell 2   0.4095 0.42 0.475 / U495 he zirc
  cell 3   0.5715 0.6121 / mod zirc                 ! guide/instrument tube
  cell 4   0.42 0.475 / he zirc                     ! plenum
  cell 5   0.475 / zirc                             ! end plug
  cell 6   0.4095 0.42 0.475 / g300 he zirc         ! Gad fuel
  cell 7   0.4095 0.42 0.475 / b4c-al2o3 he zirc    ! BPR

  lattice LAT1
       3
       2 2
       2 2 2
       3 2 2 3
       2 2 2 2 7
       2 2 2 2 2 3
       3 7 2 3 2 2 2
       2 2 2 2 2 2 2 6
       2 2 2 2 2 2 2 2 2

  lattice LAT2
       3
       2 2
       2 2 2
       3 2 2 3
       2 2 2 2 7
       2 2 2 2 2 3
       3 2 2 3 2 2 2
       7 2 2 7 2 2 2 6
       2 2 2 2 2 2 2 2 2

 lattice LAT3
       3
       2 2
       6 2 2
       3 2 2 3
       2 2 2 2 7
       2 2 2 2 2 3
       3 2 2 3 2 2 2
       7 2 2 7 2 2 2 7
       2 2 2 2 2 2 2 2 2


  lattice LAT4
       3
       2 2
       6 2 2
       3 2 2 3
```

```
      7 2 2 2 7
      2 2 2 2 2 3
      3 2 2 3 2 2 2
      7 2 2 7 2 2 2 7
      2 2 2 2 2 2 2 2 2

  lattice LAT5
      3
      2 7
      2 2 2
      3 2 2 3
      7 2 2 2 7
      2 2 2 2 2 3
      3 2 2 3 2 2 2
      7 2 2 7 2 2 2 7
      2 2 2 2 2 2 2 2 2

  lattice PLEN
      3
      4 4
      4 4 4
      3 4 4 3
      4 4 4 4 4
      4 4 4 4 4 3
      3 4 4 3 4 4 4
      4 4 4 4 4 4 4 4
      4 4 4 4 4 4 4 4 4

  lattice ENDPL
      3
      5 5
      5 5 5
      3 5 5 3
      5 5 5 5 5
      5 5 5 5 5 3
      3 5 5 3 5 5 5
      5 5 5 5 5 5 5 5
      5 5 5 5 5 5 5 5 5

   axial  1  0.0   LAT1  1.0
   axial  2  0.0   LAT2  1.0
   axial  3  0.0   LAT3  1.0
   axial  4  0.0   LAT4  1.0
   axial  5  0.0   LAT5  1.0




[CONTROL]
  title "B4C with AIC tips"
  npin 17
  stroke  1.0 1

  mat aic 10.17
  mat b4c 2.51

  cell 9  0.432 0.438 0.489 / aic ss he
  cell 10  0.432 0.438 0.489 / b4c ss he

rodmap AIC
-
- -
- - -
9 - - 9
- - - - -
- - - - - 9
9 - - 9 - - -
- - - - - - - -
- - - - - - - - -
```

```
rodmap B4C
-
- -
- - -
10 - - 10
- - - - -
- - - - - 10
10 - - 10 - - -
- - - - - - - -
- - - - - - - - -

   axial  A 0.0 AIC 1.0
   axial  B 0.0 B4C 1.0

[DETECTOR]
  title "Incore instrument thimble"
  npin 17

  cell 11  0.5715 0.6121 / he ss

  rodmap  LAT
     11
     - -
     - - -
     - - - -
     - - - - -
     - - - - - -
     - - - - - - -
     - - - - - - - -
     - - - - - - - - -
   axial 1  0.0 LAT 1.0

[EDITS]
   axial_edit_bounds
    0.0 1.0

[INSILICO]
    transport     ce_mc
    do_transport  true
    output_geometry  true
    use_symmetry  true
    celib_file    ce_v7np_endf_565.xml
    mesh          1
    thermal_energy_cutoff  10.0

    num_cycles    1100
    num_inactive_cycles  100
    Np            10000000

    dimension 3
    cell_homogenize true
    eq_set        spn_fv
    SPN_order     5
    Pn_order      3
    tolerance     1e-6

    mat_library casl_comp_r2.sh5
    xs_library  v7-252

!    mesh 2

!    pin_partitioning true
    Pn_correction true
    num_blocks_i  4
    num_blocks_j  4
!    num_z_blocks  1
    num_groups    23
    num_sets      1
    max_delta_z   1.0

    azimuthals_octant  4
    polars_octant      4
```

```
quad_type          qr

SILO_output  '2DSMR_SHIFT'

new_grp_bounds
   8.2085e+05
   1.1109e+05
   5.5308e+03
   1.8644e+02
   3.7612e+01
   3.5379e+01
   2.7697e+01
   2.1684e+01
   2.0397e+01
   1.5968e+01
   7.1500e+00
   6.7000e+00
   6.3000e+00
   1.0970e+00
   1.0450e+00
   9.5000e-01
   3.5000e-01
   2.0600e-01
   1.0700e-01
   5.8000e-02
   2.5000e-02
   1.0000e-02
   1.0000e-05
```

Appendix C – VERA Input with MPACT

```
[CASEID]
 title  'SMR 3D Model - MPACT'

[STATE]
  power  0.0            ! %
  tinlet 566.33         ! F
  tfuel  840            ! K
  boron  0              ! ppmB
  modden 0.7065         ! g/cc
  feedback off
  sym qtr

  rodbank A 1           ! All rods out

[CORE]
 size 9                 ! assemblies across core
 rated 530 30           ! MWt, Mlbs/hr
 apitch 21.5            ! cm
 height 264.825

  core_shape
0 0 1 1 1 1 1 0 0
0 1 1 1 1 1 1 1 0
1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1
0 1 1 1 1 1 1 1 0
0 0 1 1 1 1 1 0 0

  assm_map
5 4 3 2 1
4 4 3 4 2
3 3 3 2 1
2 4 2 4
1 2 1

 crd_map
    - - - - -
  - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
  - - - - - - -
    - - - - -
 crd_bank
    - - - - -
  - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
  - - - - - - -
    - - - - -
! the detector map is upside down for denovo
  det_map
    - - - - -
  - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
- - - - - - - - -
  - - - - - - -
    - - - - -
mat ref 7.0 ss 0.95 water 0.05
```

```
baffle ref 0.19 21.5

  lower_plate ss  5.08 0.5    ! mat, thickness, vol frac
  upper_plate ss  7.62 0.5    ! mat, thickness, vol frac

  xlabel  R P N M L K J H G  F  E  D  C  B  A
  ylabel  1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

  mat zirc 6.55 zirc4
  mat ss   7.94
  mat he 0.0001786
  mat pyrex 2.25
  mat b4c 2.9441
  mat inc 8.19
  mat b4c-al2o3  2.9441 b4c 0.04 al2o3 0.96

[ASSEMBLY]
  title "mPower 17x17"
  npin 17
  ppitch 1.26

  fuel U395 10.5216 96 / 3.95
  fuel U495 10.5216 96 / 4.95
  fuel g300 10.5216 94.5 / 3.95 / gad=3.0

  cell 1   0.4095 0.42 0.475 / U395 he zirc
  cell 2   0.4095 0.42 0.475 / U495 he zirc
  cell 3   0.5715 0.6121 / mod zirc                 ! guide/instrument tube
  cell 4   0.42 0.475 / he zirc                     ! plenum
  cell 5   0.475 / zirc                             ! end plug
  cell 6   0.4095 0.42 0.475 / g300 he zirc         ! Gad fuel
  cell 7   0.4095 0.42 0.475 / b4c-al2o3 he zirc    ! BPR

  lattice LAT1
       3
       2 2
       2 2 2
       3 2 2 3
       2 2 2 2 7
       2 2 2 2 2 3
       3 7 2 3 2 2 2
       2 2 2 2 2 2 2 6
       2 2 2 2 2 2 2 2 2

  lattice LAT2
       3
       2 2
       2 2 2
       3 2 2 3
       2 2 2 2 7
       2 2 2 2 2 3
       3 2 2 3 2 2 2
       7 2 2 7 2 2 2 6
       2 2 2 2 2 2 2 2 2

 lattice LAT3
       3
       2 2
       6 2 2
       3 2 2 3
       2 2 2 2 7
       2 2 2 2 2 3
       3 2 2 3 2 2 2
       7 2 2 7 2 2 2 7
       2 2 2 2 2 2 2 2 2


  lattice LAT4
       3
       2 2
       6 2 2
       3 2 2 3
```

```
      7 2 2 2 7
      2 2 2 2 2 3
      3 2 2 3 2 2 2
      7 2 2 7 2 2 2 7
      2 2 2 2 2 2 2 2 2

  lattice LAT5
      3
      2 7
      2 2 2
      3 2 2 3
      7 2 2 2 7
      2 2 2 2 2 3
      3 2 2 3 2 2 2
      7 2 2 7 2 2 2 7
      2 2 2 2 2 2 2 2 2

  lattice PLEN
      3
      4 4
      4 4 4
      3 4 4 3
      4 4 4 4 4
      4 4 4 4 4 3
      3 4 4 3 4 4 4
      4 4 4 4 4 4 4 4
      4 4 4 4 4 4 4 4 4

  lattice ENDPL
      3
      5 5
      5 5 5
      3 5 5 3
      5 5 5 5 5
      5 5 5 5 5 3
      3 5 5 3 5 5 5
      5 5 5 5 5 5 5 5
      5 5 5 5 5 5 5 5 5

! Dimensions (other than active fuel height) assumed to be equivalent to typical dimensions
   axial  1  7.62 ENDPL 8.89 LAT1 250.19 PLEN 264.19 ENDPL 264.825
   axial  2  7.62 ENDPL 8.89 LAT2 250.19 PLEN 264.19 ENDPL 264.825
   axial  3  7.62 ENDPL 8.89 LAT3 250.19 PLEN 264.19 ENDPL 264.825
   axial  4  7.62 ENDPL 8.89 LAT4 250.19 PLEN 264.19 ENDPL 264.825
   axial  5  7.62 ENDPL 8.89 LAT5 250.19 PLEN 264.19 ENDPL 264.825

  grid END inc  610 3.81 ! grid id, material, mass, height
  grid MID inc  610 3.81 ! assume mid grids are same design

  grid_axial
      END 10.795     ! to center of grid
      MID 65.284
      MID 115.963
      MID 166.642
      MID 217.321
      END 264

  lower_nozzle  ss 7.62 6250.0  ! mat, height, mass (g)
  upper_nozzle  ss 12.7 6250.0  ! mat, height, mass (g)

[CONTROL]
  title "B4C with AIC tips"
  npin 17
  stroke  1.0 1

  mat aic 10.17
  mat b4c 2.51

  cell 9  0.432 0.438 0.489 / aic ss he
  cell 10  0.432 0.438 0.489 / b4c ss he

rodmap AIC
```

```
-
- -
- - -
9 - - 9
- - - - -
- - - - - 9
9 - - 9 - - -
- - - - - - - -
- - - - - - - - -

rodmap B4C
-
- -
- - -
10 - - 10
- - - - -
- - - - - 10
10 - - 10 - - -
- - - - - - - -
- - - - - - - - -

  axial  1 9.429 AIC 65.679 B4C  264.825

[DETECTOR]
  title "Incore instrument thimble"
  npin 17

  cell 11  0.5715 0.6121 / he ss

  rodmap  LAT
     11
     - -
     - - -
     - - - -
     - - - - -
     - - - - - -
     - - - - - - -
     - - - - - - - -
     - - - - - - - - -

  axial 1  0.0 LAT 227.811



[EDITS]
  axial_edit_bounds
    8.89
    12.7
    17.7
    22.7
    27.7
    32.7
    37.7
    44.7
    49.7
    54.7
    59.7
    63.379
    67.189
    72.189
    77.189
    82.189
    87.189
    92.189
    97.189
    102.189
    107.189
    114.058
    117.868
    122.868
    127.868
    132.868
```

```
    137.868
    142.868
    147.868
    152.868
    157.868
    164.737
    168.547
    173.547
    178.547
    183.547
    188.547
    193.547
    198.547
    203.547
    208.547
    215.416
    219.226
    224.226
    229.226
    234.226
    239.226
    244.226
    249.226
    254.226


[INSILICO]
    dimension 3
    cell_homogenize true
    eq_set        spn_fv
    SPN_order     5
    Pn_order      3
    tolerance     1e-6

    mat_library casl_comp_r2.sh5
    xs_library  lib252_hetbondoneabs-noabssigp

    mesh 2

!    pin_partitioning true
    Pn_correction true
    num_blocks_i  20
    num_blocks_j  20
!    num_z_blocks  1
    num_groups    23
    num_sets      1
    max_delta_z   1.0

    azimuthals_octant  4
    polars_octant      4
    quad_type          qr

    SILO_output  '3DSMR'

    new_grp_bounds
       8.2085e+05
       1.1109e+05
       5.5308e+03
       1.8644e+02
       3.7612e+01
       3.5379e+01
       2.7697e+01
       2.1684e+01
       2.0397e+01
       1.5968e+01
       7.1500e+00
       6.7000e+00
       6.3000e+00
       1.0970e+00
       1.0450e+00
       9.5000e-01
       3.5000e-01
```

```
       2.0600e-01
       1.0700e-01
       5.8000e-02
       2.5000e-02
       1.0000e-02
       1.0000e-05


[MPACT]
  vis_edits         core
  ray_spacing       0.1
!quad_set
  quad_type         CHEBYSHEV-YAMAMOTO
  polars_octant     2
  azimuthals_octant 8
!iteration_control
  flux_tolerance    1e-4
  num_inners        2
  k_tolerance       1e-5
  up_scatter        2
  num_outers        500
  scattering        P2
!cmfd
  cmfd              cmfd
  cmfd_solver       mgnode
  k_shift           1.5
  cmfd_num_outers   20
!2D1D
  split_TL          true
  TL_treatment      lflat
  nodal_method      nem
! under_relax       1.0
!parallel
  num_space         1155
  num_angle         1
  num_energy        1
  num_threads       1
!  export OMP_NUM_THREADS=2
  par_method EXPLICITFILE
  par_file part_smr_asy.txt
!xs_library
  xs_filename       declib56g_e7_09042013_p0mixed.fmt
  xs_type           ORNL
  subgroup_set      4
!mesh
  mesh fuel         3 1 1 / 4 4 4 4 4 4
  mesh gtube        3 1   / 4 4 4 4 4
  mesh cell_6         5 1 / 5*4 4 4
  mesh cell_7         2 1 / 2*4 4 4
 automesh_bounds   2 20 ! min, max
 meshing_method    nonfuel
```

Appendix D – Input Parameters

Table 14 Dimensions used to model the iPWR

Dimension Inputs	Value	Units	Source
Fuel Pellet Radius	0.4095	cm	Reference 16
Fuel Gap Radius	0.42	cm	Reference 16
Fuel Clad Radius	0.475	cm	Reference 16
Guide Tube Inner Radius	0.5715	cm	Reference 16
Guide Tube Outer Radius	0.6120	cm	Reference 16
BPR Absorber Radius	0.4095	cm	Assumed
BPR Gap Radius	0.42	cm	Assumed
BPR Clad Radius	0.475	cm	Assumed
Control Rod Absorber Radius	0.432	cm	Assumed
Control Rod Gap Radius	0.438	cm	Assumed
Control Rod Clad Radius	0.489	cm	Assumed
Assembly Pitch	21.5	cm	Reference 5
Baffle Thickness	21.5	cm	Assumed
Baffle Gap to Fuel	0.19	cm	*
Upper Plate Thickness	7.6	cm	*
Lower Plate Thickness	5.08	cm	*
Upper Reflector Depth	20	cm	Estimated
Lower Reflector Depth	20	cm	Estimated
Pin Pitch	1.26	cm	Reference 16
End Grid Height	1.859	cm	*
Mid Grid Height	1.859	cm	*
Upper Nozzle Height	5.061	cm	*
Lower Nozzle Height	5.061	cm	*

* Assumed based on ratio between SMR active core height and Westinghouse 4-loop PWR active core height.

Table 15 Material inputs for the iPWR

Material Inputs	Value	Units	Source
Moderator Density	0.7065	g/cc	Assumed
Zirc 4 Density	6.55	g/cc	Assumed
Stainless Steel Density	7.94	g/cc	Assumed
Helium Density	0.000178	g/cc	Reference 16
Pyrex Density	2.25	g/cc	Assumed
B_4C Density	2.51	g/cc	Assumed
Inconel Density	8.19	g/cc	Assumed
Standard UO_2 Fuel Pin Enrichment	4.95	%	Assumed
Standard UO_2 Denisty	10.96	g/cc	Assumed
Lower Enriched UO_2 Density	10.96	g/cc	Assumed
Mixed Gd_2O_3 and UO_2 Fuel Pin Enrichment	3.95	%	Assumed
Gd_2O_3 Density	7.41	g/cc	Assumed
Baffle Material	Stainless Steel	N/A	Assumed
Upper and Lower Plate Material	Stainless Steel	N/A	Assumed
Upper and Lower Reflector Material	Moderator	N/A	Assumed
Mid/End Grid Material	Inconel	N/A	Assumed
Mid/End Grid Mass	610	G	Assumed
Upper Nozzle Material	Stainless Steel	N/A	Assumed
Upper Nozzle Mass	6250	g	Assumed

Table 16 Additional inputs used to model the iPWR

Other Necessary Inputs	Value	Units	Source
Inlet Temperature	566.33	F	Assumed
Fuel Temperature	840	K	Assumed
Rated Power	530	MWt	Assumed
Coolant Flow Rate	30	Mlbs/hr	Assumed
Upper Plate Volume Fraction	0.5	N/A	Assumed
Lower Plate Volume Fraction	0.5	N/A	Assumed
Upper Reflector Volume Fraction	1	N/A	Assumed
Lower Reflector Volume Fraction	1	N/A	Assumed