NE 412/512 NUCLEAR FUEL CYCLE COURSE PROJECT

DUE DATE: NOVEMBER 16, 2018

NAME: CAMERON MARAS

INSTRUCTOR: Dr. J. Hou

TEACHING ASSISTANT: Mr. Yuchao Xu

ABSTRACT

The initial cycle of a 3-loop Westinghouse Pressurized Water Reactor was designed using Studsvik's SIMULATE-3 two group nodal diffusion code on the RDFMG NCSU cluster. An optimized designed was achieved that maximized cycle energy output (14.611 GWD/MTU or 378.9 Effective Full Power Days) while meeting specific design constraints: Max $F_{\Delta H}$ = 1.453 < Limit 1.48, Max F_Q = 2.097 < Limit 2.1, and Max Boron = 1285.0 ppm < Limit Boron 1300 ppm. The final design was based upon a provided initial zone scatter out-in model with pre-designed fuel types. This project and resulting analysis successfully built upon theory on reactor cores and fuel design to produce an experience that directly shadows engineering designs frequently made in industry.

TABLE OF CONTENTS

INTRODUCTION AND METHODOLOGY

In order to take a step into practical nuclear engineering, specifically loading pattern and core design, we must understand the fundamentals of why a fuel loading pattern is important. Nuclear reactors during their time of operation must operate on 3 main bases: Safety, Reliability, and Economics. One of the very first requirements for achieving these is designing a solid loading pattern (LP).

The fuel LP determines important information regarding the reactor core and its operation. Some of these characteristics include:

- Core Power/neutron flux/temperature distributions
- Fuel Stress (Burnup or Power vs. time)
- Energy Output for the cycle (Cycle Length)
- Fuel efficiency
- Safety parameters (pin power peaking, etc.)

When analyzing the core power distribution, it is important to note the different factors that affect radial and axial power distributions. Some of the factors that impact the radial distribution include geometry/leakage, enrichment, burnup/exposure, and burnable absorbers/poisons. The factors that affect the axial power distribution include control rod insertion, moderator density, power level, xenon, burnup/exposure, and burnable absorber/poisons. The LP design process has much more of an effect on the radial power distribution, therefore those relevant factors will be of concern. For our project, the LP assumptions and constraints include the following:

- Initial Core Loading of **157** feed fuel assemblies (FA)
  - **53 FA at 2.0% w/o U-235**
  - **52 FA at 2.5% w/o U-235**
  - **52 FA at 3.2% w/o U-235**
- Maximum axially integrated pin-power peaking factor (**$F_{\Delta H}$) < 1.48**
- Maximum pin-power peaking factor (including axial intranodal peaking) **F_Q < 2.1**
- Maximum Hot Full Power (HFP) Boron Concentration **< 1300 ppm**
- EOC Target Boron Concentration **= 10 ppm**
- Maximize cycle energy (Burnup/EFPD) at EOC **≥ 14.608 GWD/MTU**

In order to accomplish these design goals for our design, multiple pre-made fuel assembly designs have been generated for our project. Table 1 shows the fuel inventory including the U-235 enrichment % and information regarding integral burnable poison rods per assembly. Figure 1 shows the initial quarter core LP (with reflective symmetry) provided to us for the project with assembly names corresponding to the fuel types in Table 1. This model LP can be seen to be of the type Out-In, which will help minimize power peaking with the most reactive fuel placed on the periphery and a lower reactivity checkerboard interior. Additional information regarding the fuel types is provided in Appendix A.

Table 1. Fuel assembly inventory for the initial PWR core

Fuel type	w/o	BPs
2	2.0	None
3	2.5	None
4	2.5	16 Gad rods
5	3.2	None
6	3.2	16 Gad rods

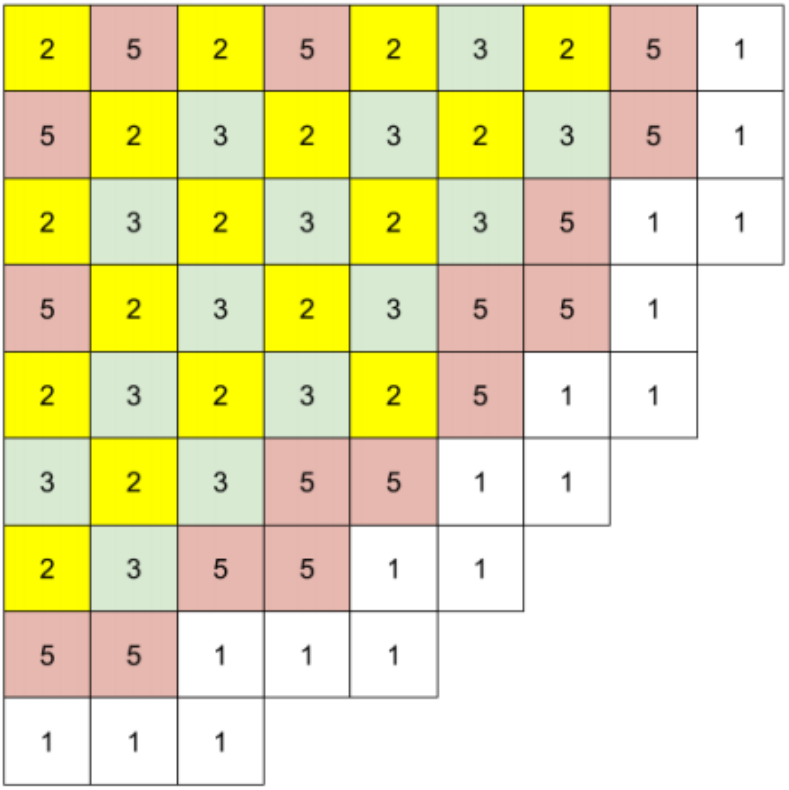

Figure 1: Initial Cycle Model Loading Pattern

From the RDFMG server cluster, SIMULATE-3 will be used to develop and run the core design. SIMULATE-3 is an advanced, two-group nodal code for solving 3-D coarse mesh diffusion problems. The provided input for the code will use a boron search method for eigenvalues while holding pressure, power, and flow constant. The provided input is set up for 11 case burnup steps from 0.00 GWD/MTU to approximately 14.6 GWD/MTU. The necessary files provided for the design include the following:

- Input file: s3_init.inp
- Output file: s3_init.out
- Restart file: cycle1.res
- Library file: cms.pwr-all.lib
- Run script: simulate.sh

Note: From the SIMULATE-3 manual, the $F_{\Delta H}$ and F_Q are determined respectively using the following equations:

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{l=1}^{N}\sum_{m=1}^{N} max\left[\frac{1}{K}\sum_{k=1}^{K} P_{i,j,k}^{l,m}\right] \tag{1}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{N}\sum_{m=1}^{N} max\left[P_{i,j,k}^{l,m}\frac{max\{P_{i,j,k}(z)\}}{P_{i,j,k}}\right] \tag{2}$$

OBJECTIVES

The objective of this project is to design an initial loading pattern (Cycle 1) for a 3-loop Westinghouse Pressurized Water Reactor. This design will be created and tested using the Studsvik's SIMULATE-3 code and several design constraints will be applied. These parameters include meeting specific thermal margins and reactivity limits, while also maximizing cycle energy with the design we create. Overall, the objective of this course project is to apply many of the topics studied in lecture to a hands-on, real world example of nuclear engineering.

RESULTS AND ANALYSIS

OVERALL FINDINGS

An optimum design was created for the 3-loop Westinghouse core using a similar Out-In LP compared to the initial LP but with more BP in various assemblies and higher enriched assemblies near the periphery. The limiting max $F_{\Delta H}$ for the cycle was found to be 1.453 at BOC (0.00 GWD/MTU). The limiting max F_Q was found to be 2.097 at 1.00 GWD/MTU. The EOC burnup was determined to be 14.611 GWD/MTU, which equates to 378.9 Effective Full Power Days. The maximum boron concentration (at BOC) was found to be 1285.0 ppm.

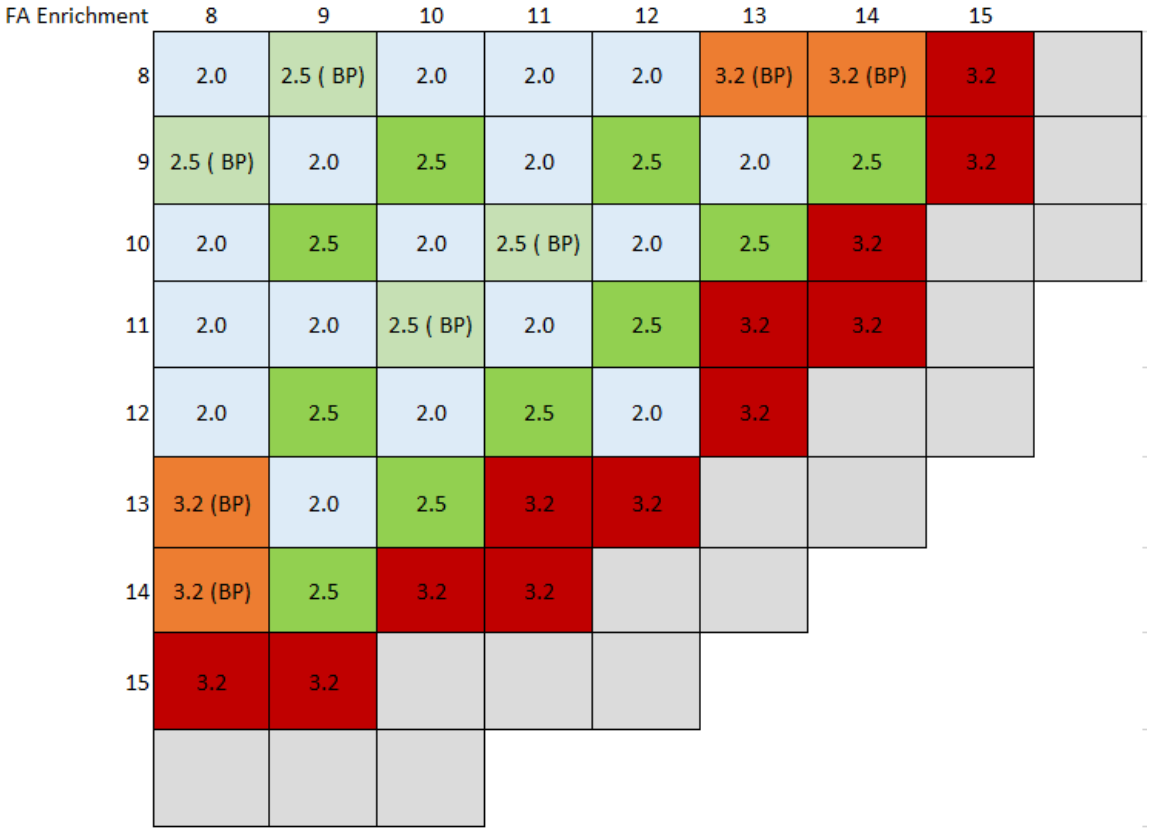

Figure 2 | Final LP Map
This figure shows the final loading pattern design for one quarter of the core by enrichment percent for our 3-loop PWR. Similar to the initial LP (Figure 1), the cycling scheme utilized for this core will be a zone scatter out-in approach with reflective symmetry. The fuel assemblies with integral Gd_2O_3 burnable poison rods are indicated as well. This design was found to not only meet the requirements for the design constraints, but also match or slightly extend the cycle energy compared to the initial design.

MULTIPLICATION FACTOR RESULTS

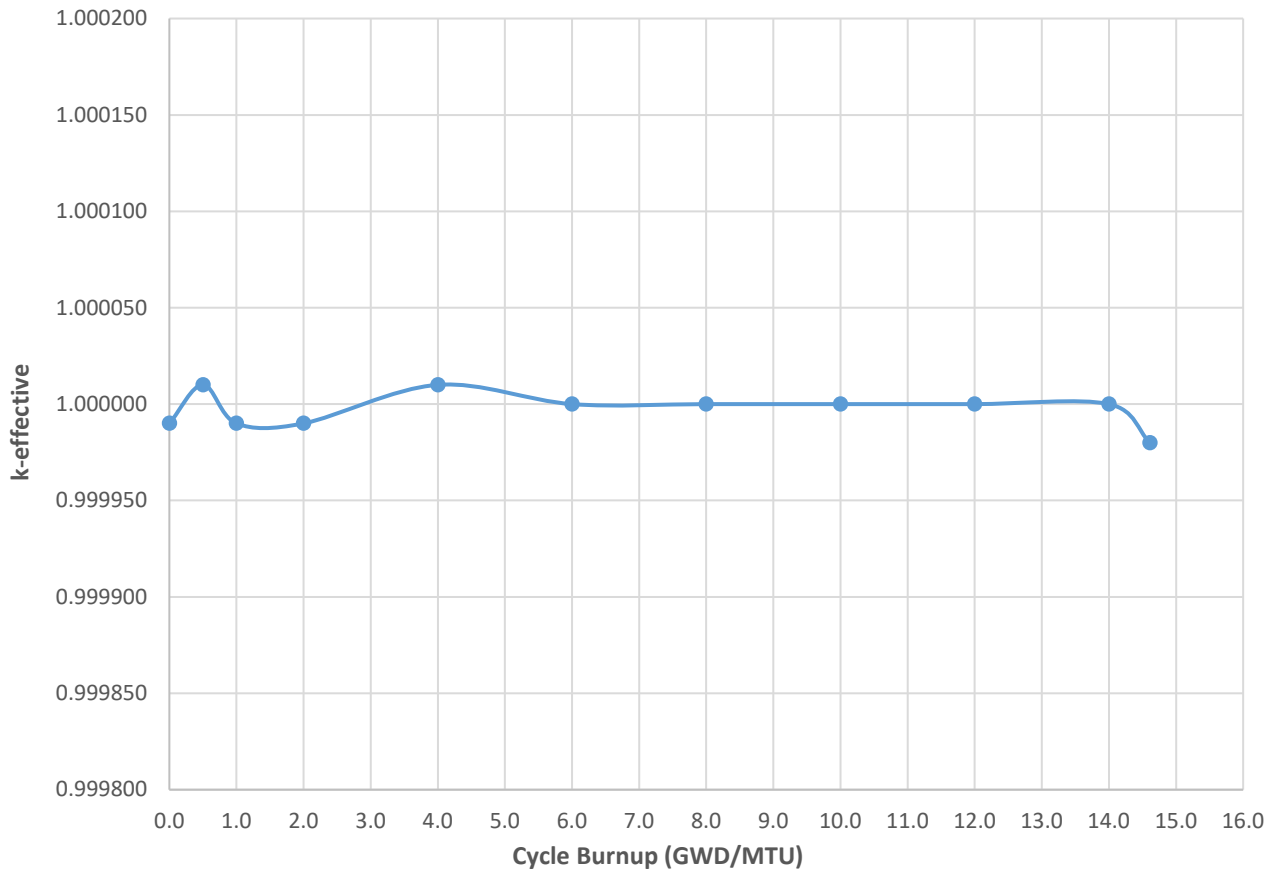

Figure 3 | Core K-Effective vs. Cycle Burnup
This figure shows cycle k-effective vs. cycle burnup determined from the SIMULATE output. As seen from the plot, the multiplication factor for the core changes very little over the cycle with just small changes due to the burnable poisons near BOC and the born letdown curve near EOC.

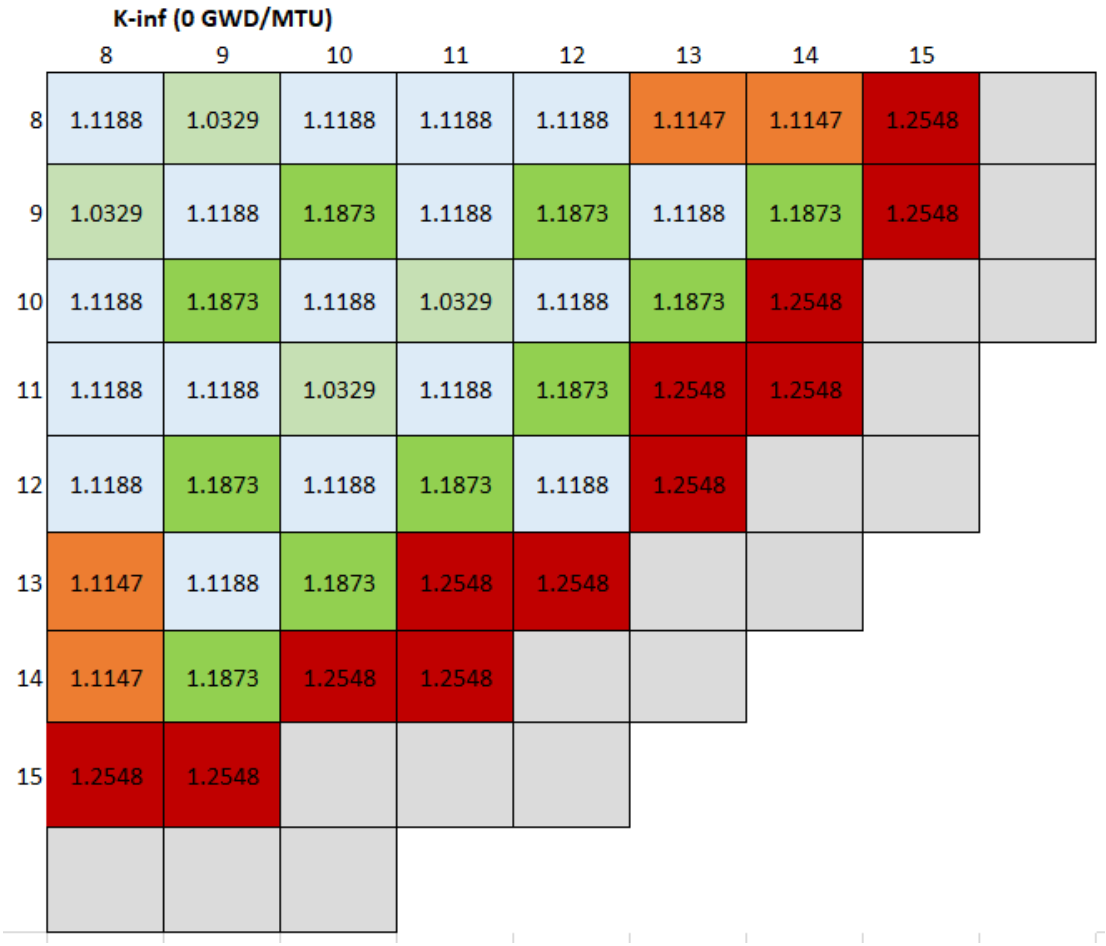

Figure 4 | Core K-Infinity Map at 0.00 GWD/MTU
This figure shows the interpolated k-infinity map for one quarter of our core design at BOC. These k-infinities were found using the burnup output map from SIMULATE and interpolating by assembly type using Tables A1 through A3 in Appendix A. The figure shows the reactivity differences between the higher and lower enriched assemblies, as well as the reactivity suppression via BP within the fuel (Note cell 14,8 vs. 15,8).

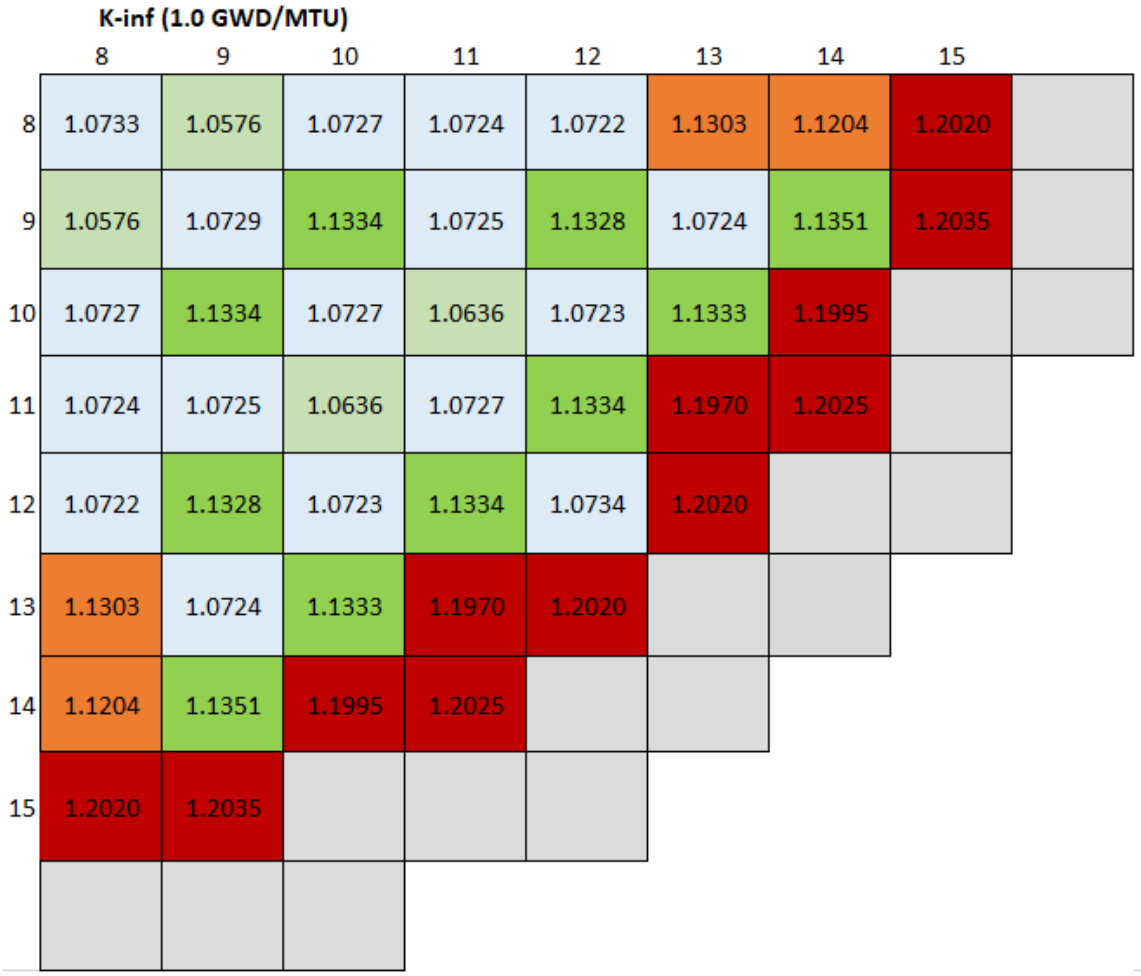

Figure 5 | Core K-Infinity Map at 1.00 GWD/MTU
This figure shows the interpolated k-infinity map for one quarter of our core design at burnup step of 1.00 GWD/MTU. These k-infinities were found using the burnup output map from SIMULATE and interpolating by assembly type using Tables A1 through A3 in Appendix A. Additionally, some of the reactivates in this figure are a bit higher than Figure 4 as the burnable poisons are beginning to wear off within the fuel. (Note FA 14,8)

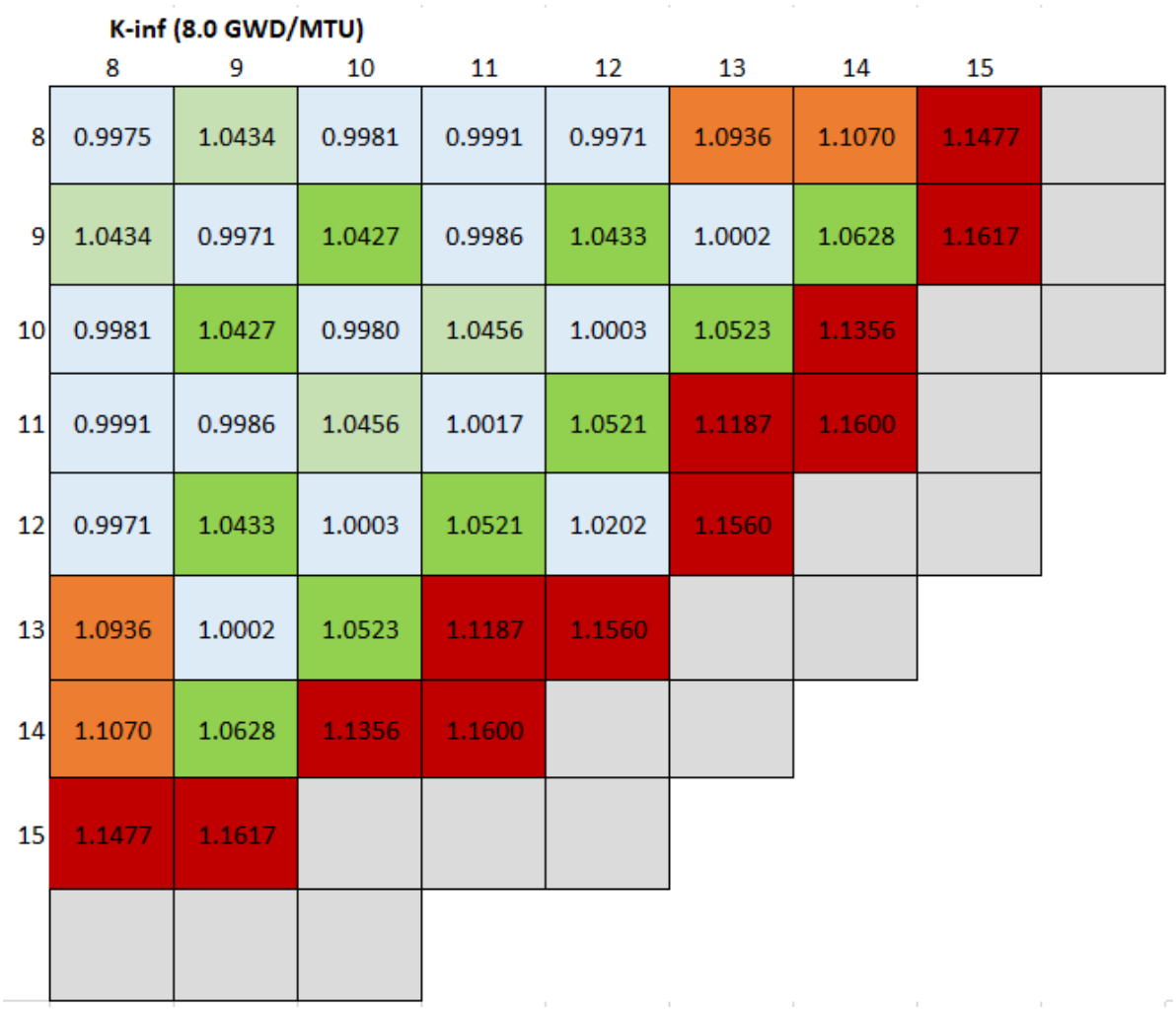

Figure 6 | Core K-Infinity Map at 8.00 GWD/MTU
This figure shows the interpolated k-infinity map for one quarter of our core design at burnup step of 8.00 GWD/MTU. These k-infinities were found using the burnup output map from SIMULATE and interpolating by assembly type using Tables A1 through A3 in Appendix A. Compared to Figures 4 and 5, we can see the decreases in reactivity through the cycle as fresh fuel is burned.

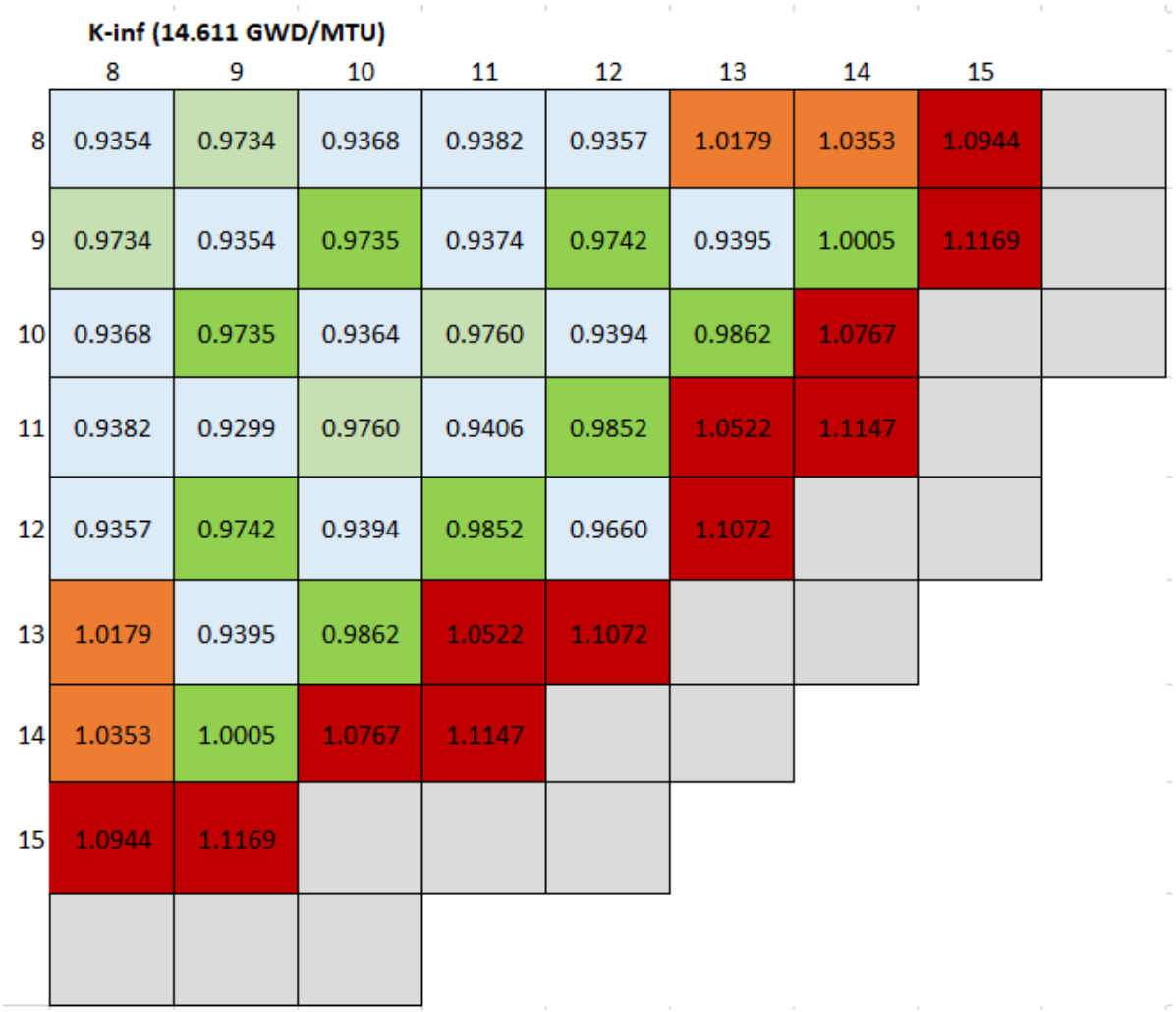

Figure 7 | Core K-Infinity Map at 14.611 GWD/MTU
This figure shows the interpolated k-infinity map for one quarter of our core design at EOC of 14.611 GWD/MTU. These k-infinities were found using the burnup output map from SIMULATE and interpolating by assembly type using Tables A1 through A3 in Appendix A. Some of the multiplication factors can be seen to drop below 1.0, which corresponds to the reactor having used up all excess reactivity and no longer being able to support criticality.

Core $F_{\Delta H}$ Results

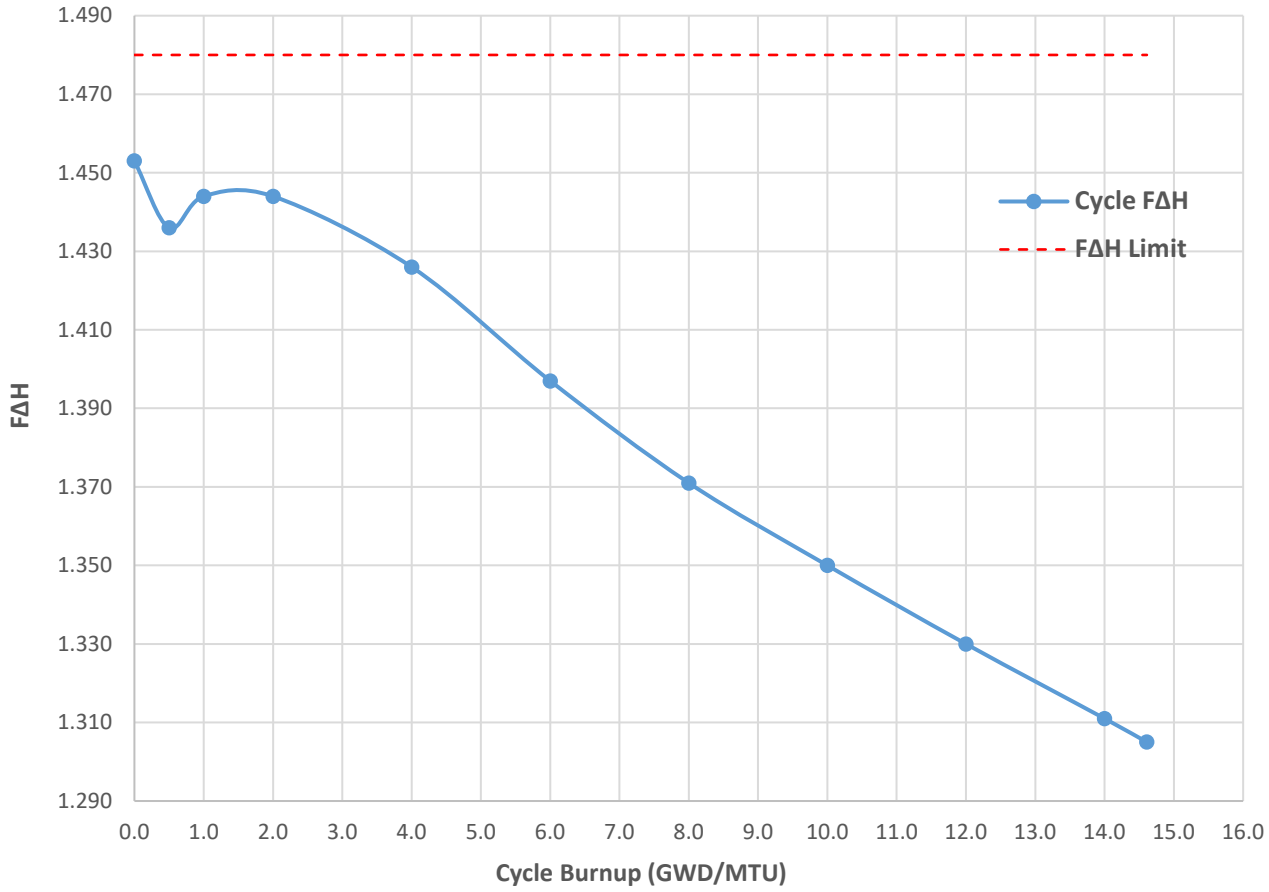

Figure 8 | Core Maximum $F_{\Delta H}$ vs. Cycle Burnup
This graph shows the maximum axially integrated pin-power peaking factor $F_{\Delta H}$ for the cycle as a function of burnup. These values were determined in SIMULATE using Eq. 1. The maximum value is shown at 1.453 at 0.00 GWD/MTU. Near 1.0 GWD/MTU, the effect of the burnable poisons wearing off can be seen as the peaking factor begins to increases before decreasing relatively monotonically until EOC.

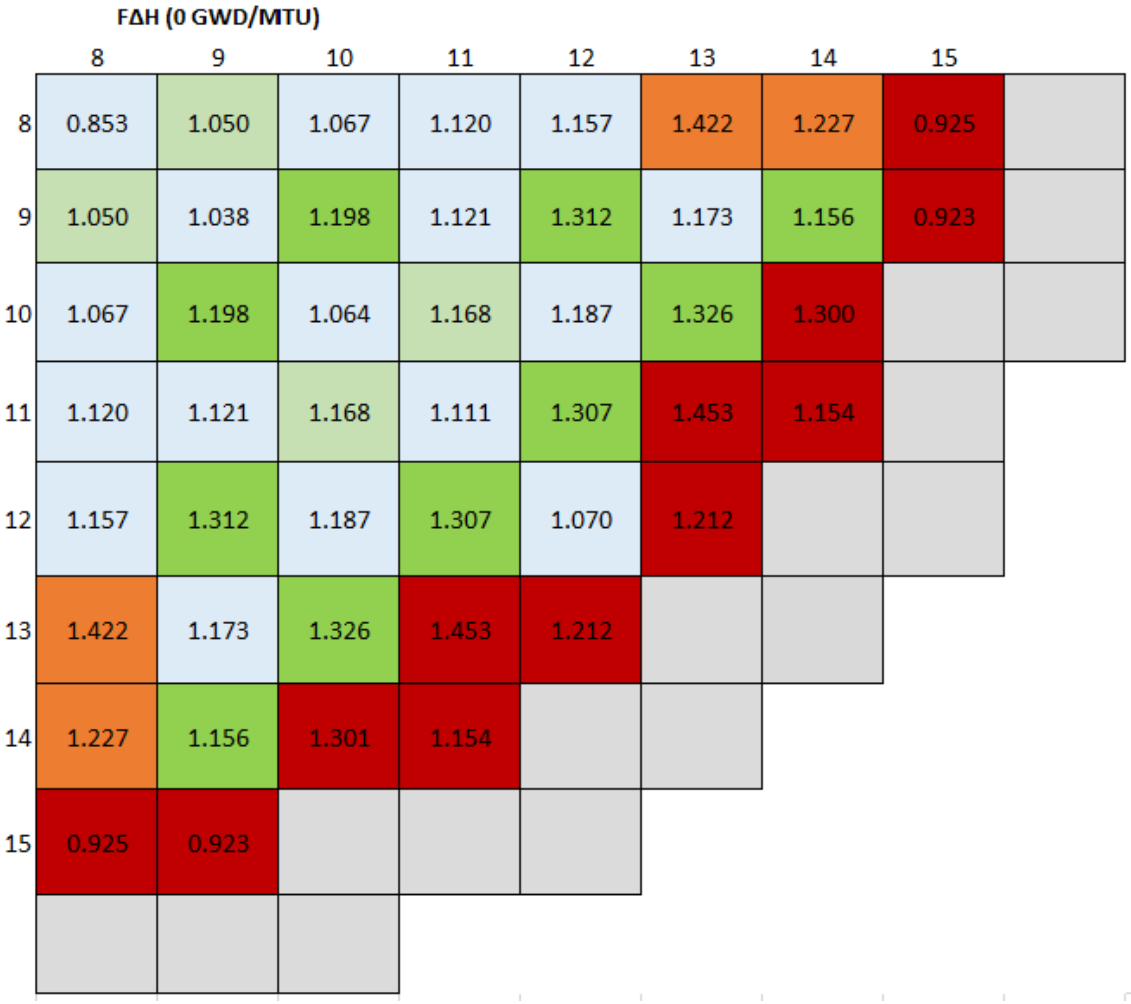

Figure 9 | Core $F_{\Delta H}$ Map at 0.00 GWD/MTU
This figure shows core $F_{\Delta H}$ map for a quarter of the core design at BOC. These peaking factors were found from SIMULATE's 2PIN output edit. Similar to Figure 8, the max $F_{\Delta H}$ value can be seen here at 0.00 GWD/MTU for assembly 11,13 and 13,11.

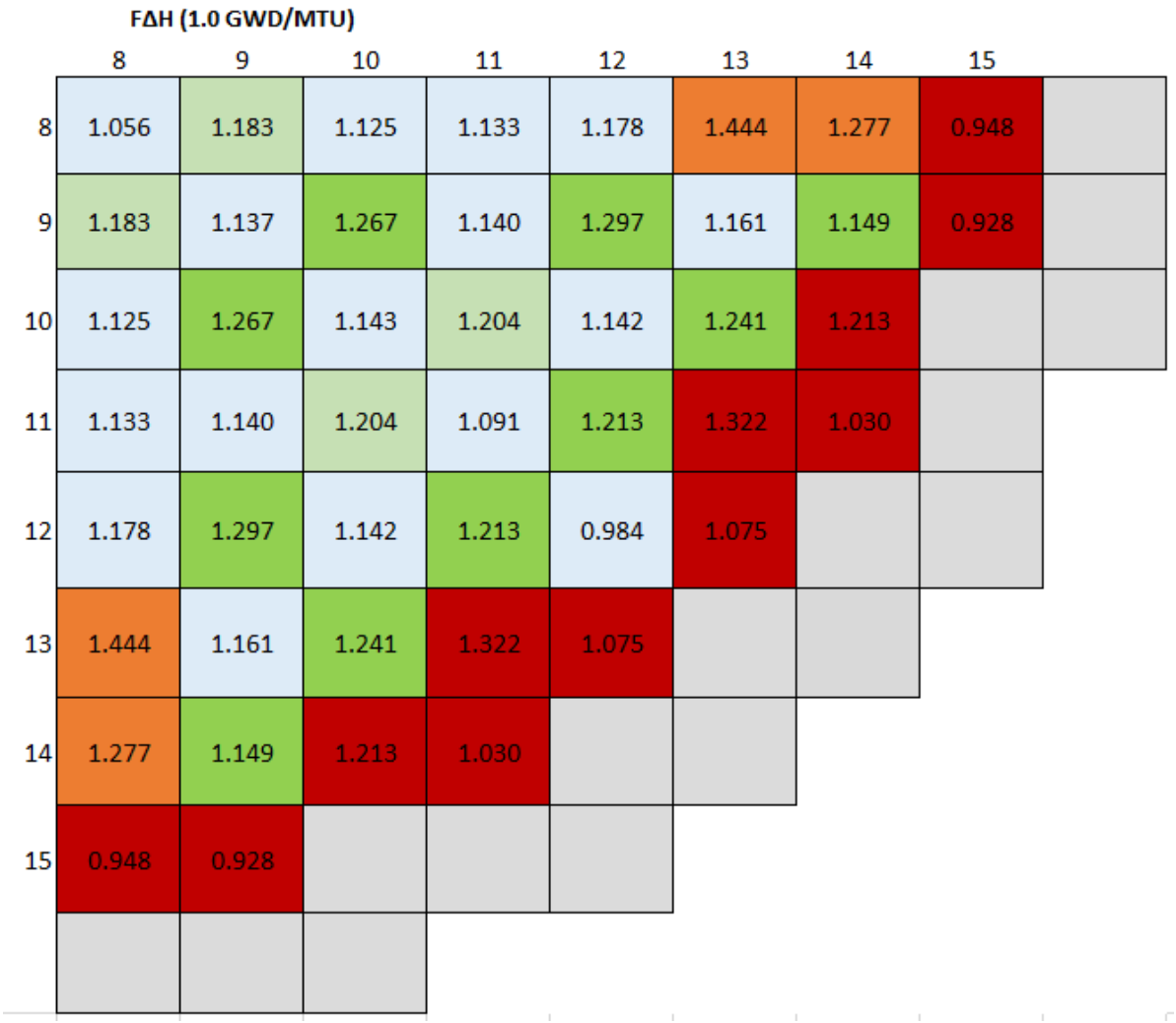

Figure 10 | Core $F_{\Delta H}$ Map at 1.00 GWD/MTU
This figure shows core $F_{\Delta H}$ map for a quarter of the core design burnup step 1.00 GWD/MTU. These peaking factors were found from SIMULATE's 2PIN output edit. Similar to Figure 5, some of the peaking factors for the BP assemblies can be seen to rise compared to Figure 9 as the burnable poisons burn out.

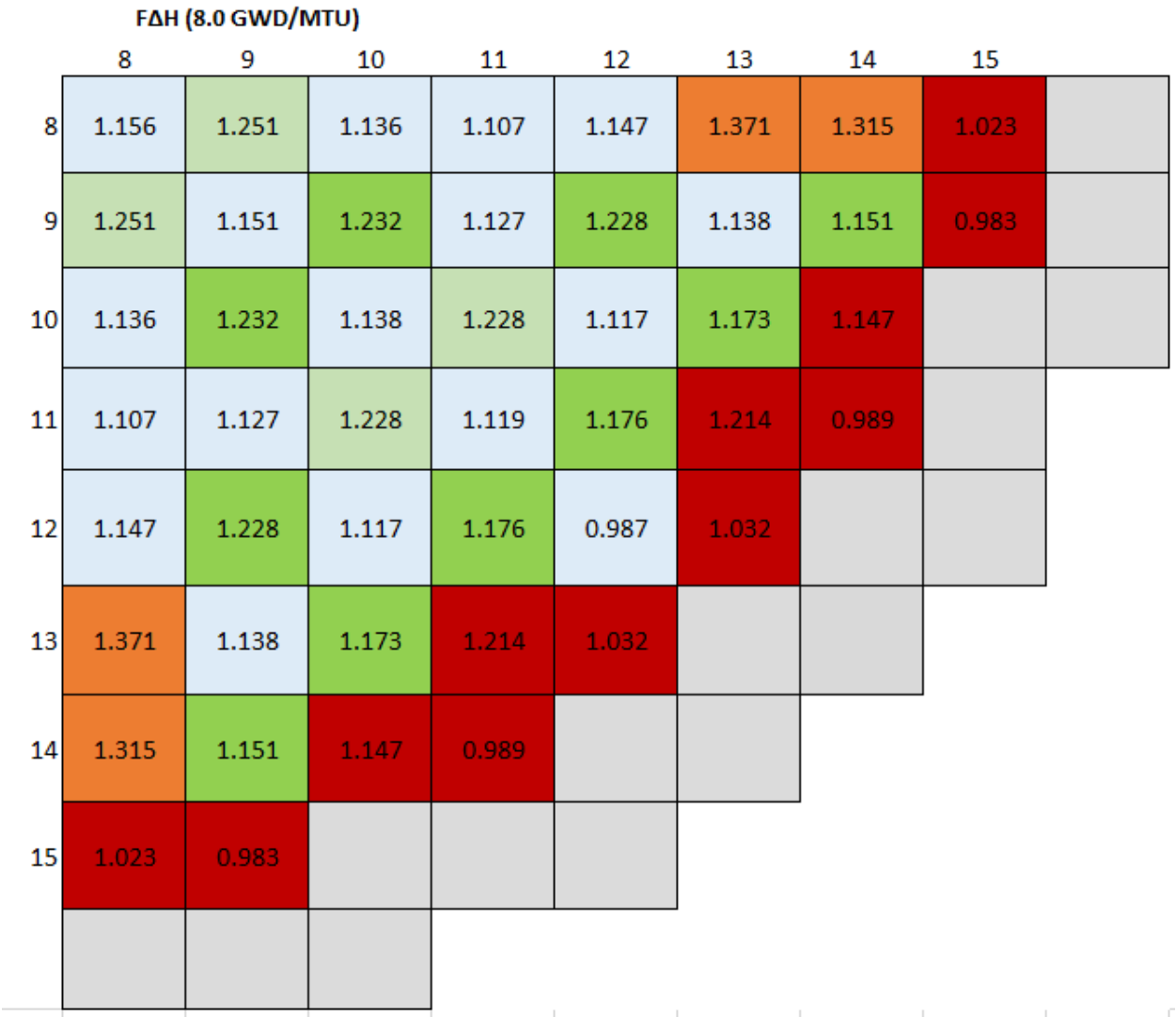

Figure 11 | Core $F_{\Delta H}$ Map at 8.00 GWD/MTU
This figure shows core $F_{\Delta H}$ map for a quarter of the core design burnup step 8.00 GWD/MTU. These peaking factors were found from SIMULATE's 2PIN output edit. The peaking factors continue to drop farther below the limit of 1.48 as more and more fresh fuel burns up.

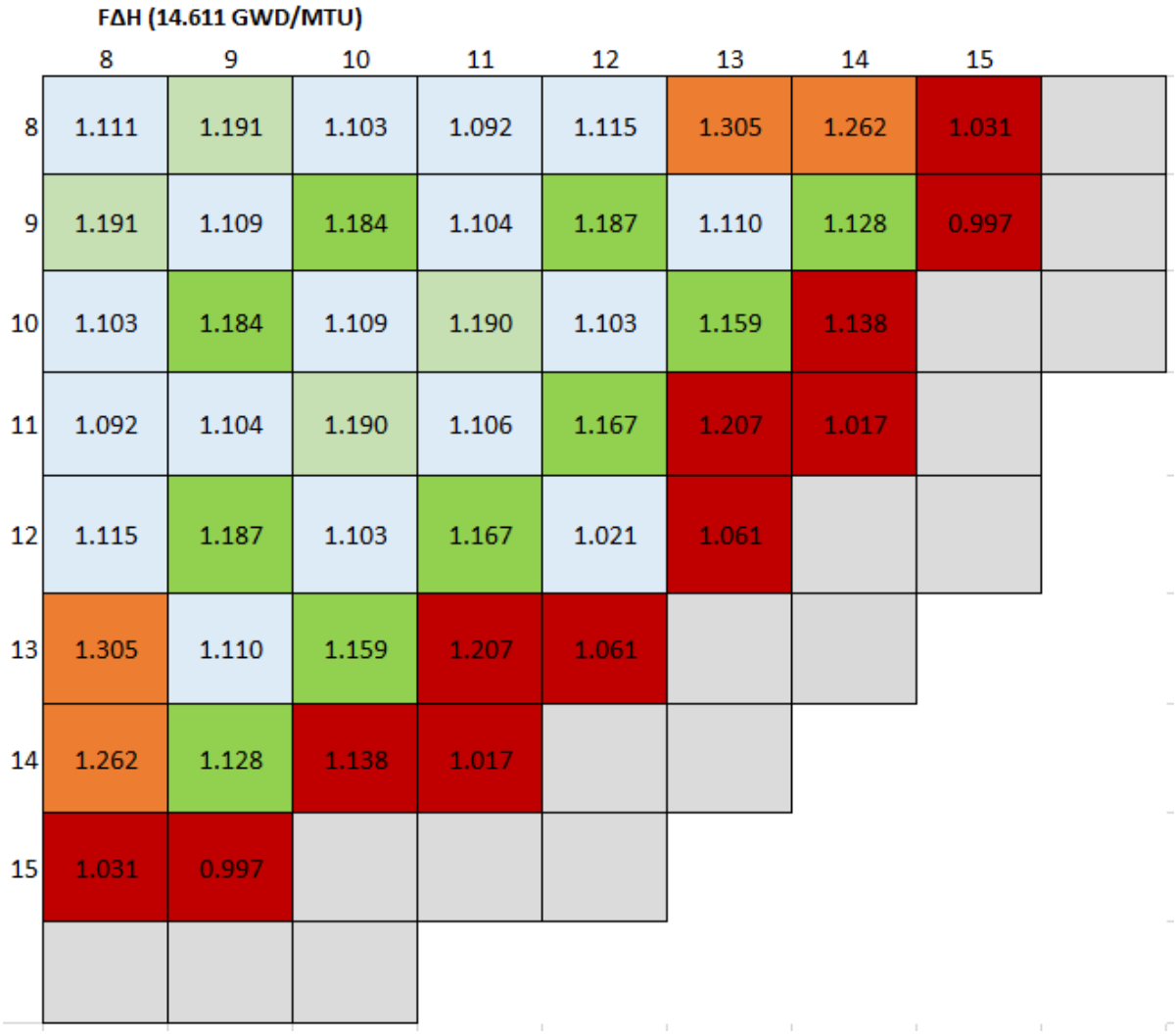

Figure 12 | Core $F_{\Delta H}$ Map at 14.611 GWD/MTU
This figure shows core $F_{\Delta H}$ map for a quarter of the core design at EOC. These peaking factors were found from SIMULATE's 2PIN output edit.

Core F_Q Results

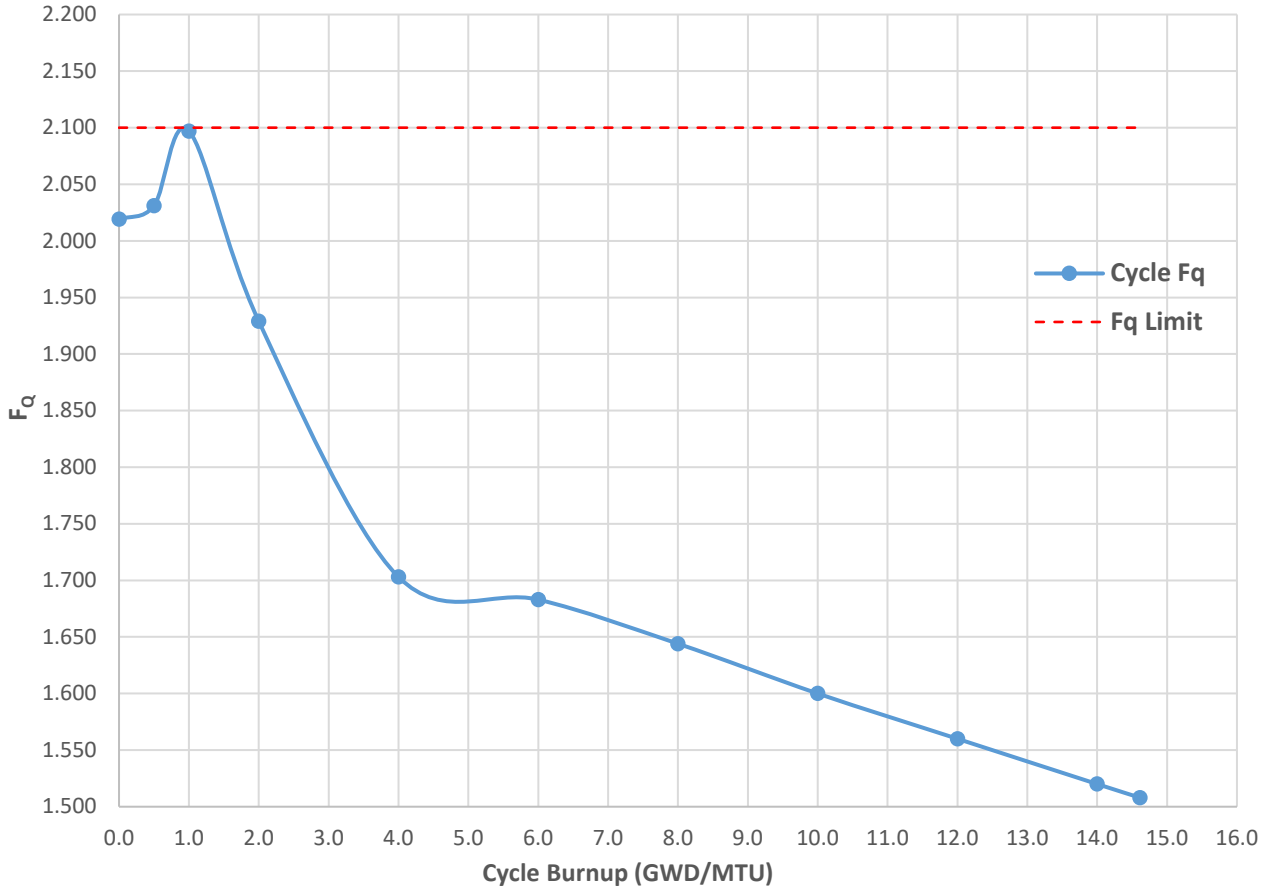

Figure 13 | Core Maximum F_Q vs. Cycle Burnup
This graph shows maximum pin-power peaking factor (including axial intranodal peaking) F_Q for the cycle as a function of burnup. These values were determined in SIMULATE using Eq. 2. The maximum value is shown at 2.097 at 1.00 GWD/MTU, just below the design constraint of 2.1. Near 0.5 GWD/MTU, the effect of the burnable poisons wearing off can be seen as the peaking factor begins to increases before decreasing relatively monotonically until EOC.

CORE BORON RESULTS

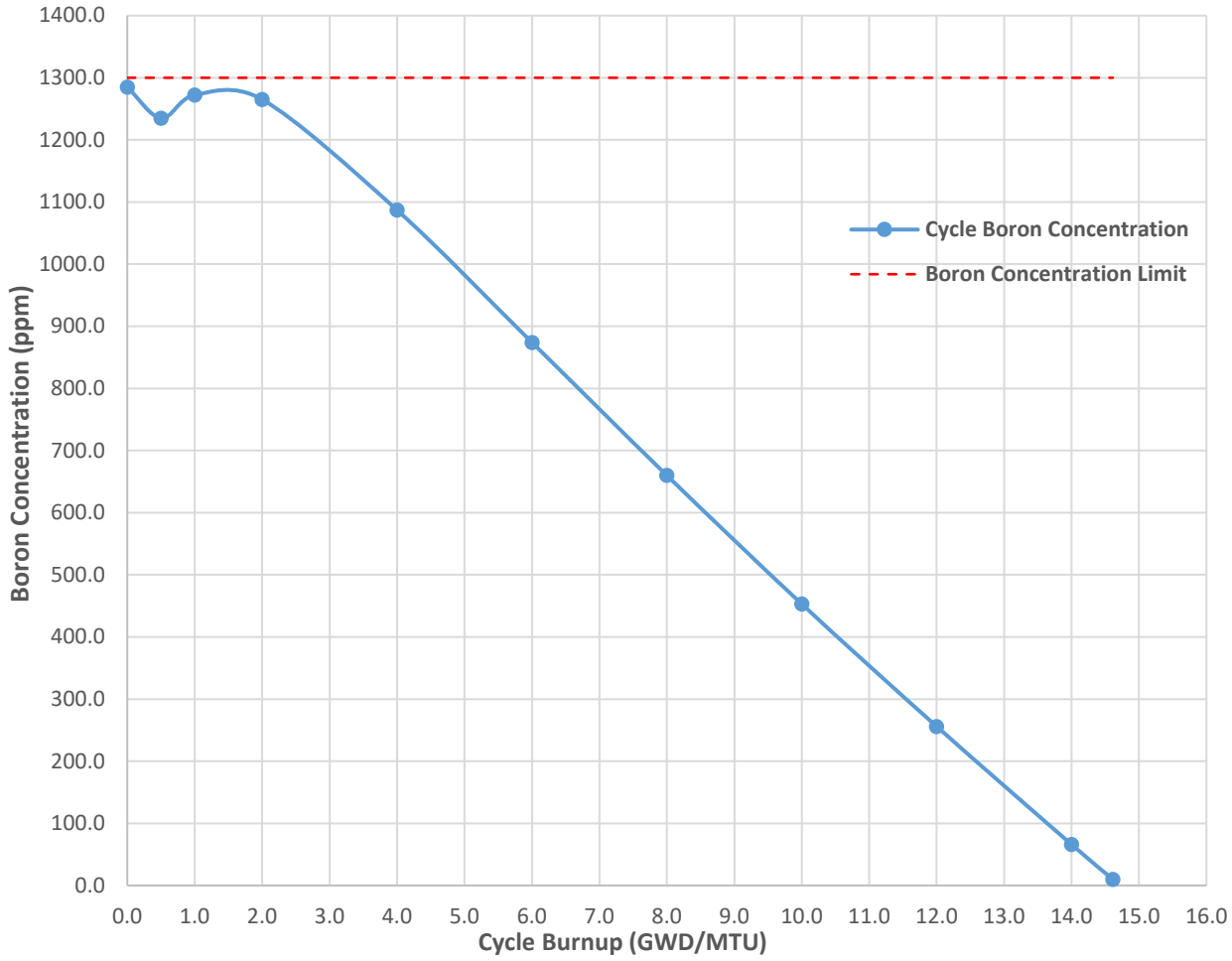

Figure 14 | Core Maximum Boron Concentration vs. Cycle Burnup
This figure shows the boron concentration within the core as a function of cycle burnup. The limiting maximum value is shown to be at BOC with a concentration of 1285.0 ppm, just below the design constraint of 1300 ppm. Similar to the other scalar variables for the core, the trend can be seen to increase near 0.5-1.0 GWD/MTU due to burnable poisons before decreasing steadily to EOC where SIMULATE ends the boron search when the concentration equals 10 ppm, resulting in a EOC burnup of 14.611 GWD/MTU.

CORE AXIAL POWER OFFSET RESULTS

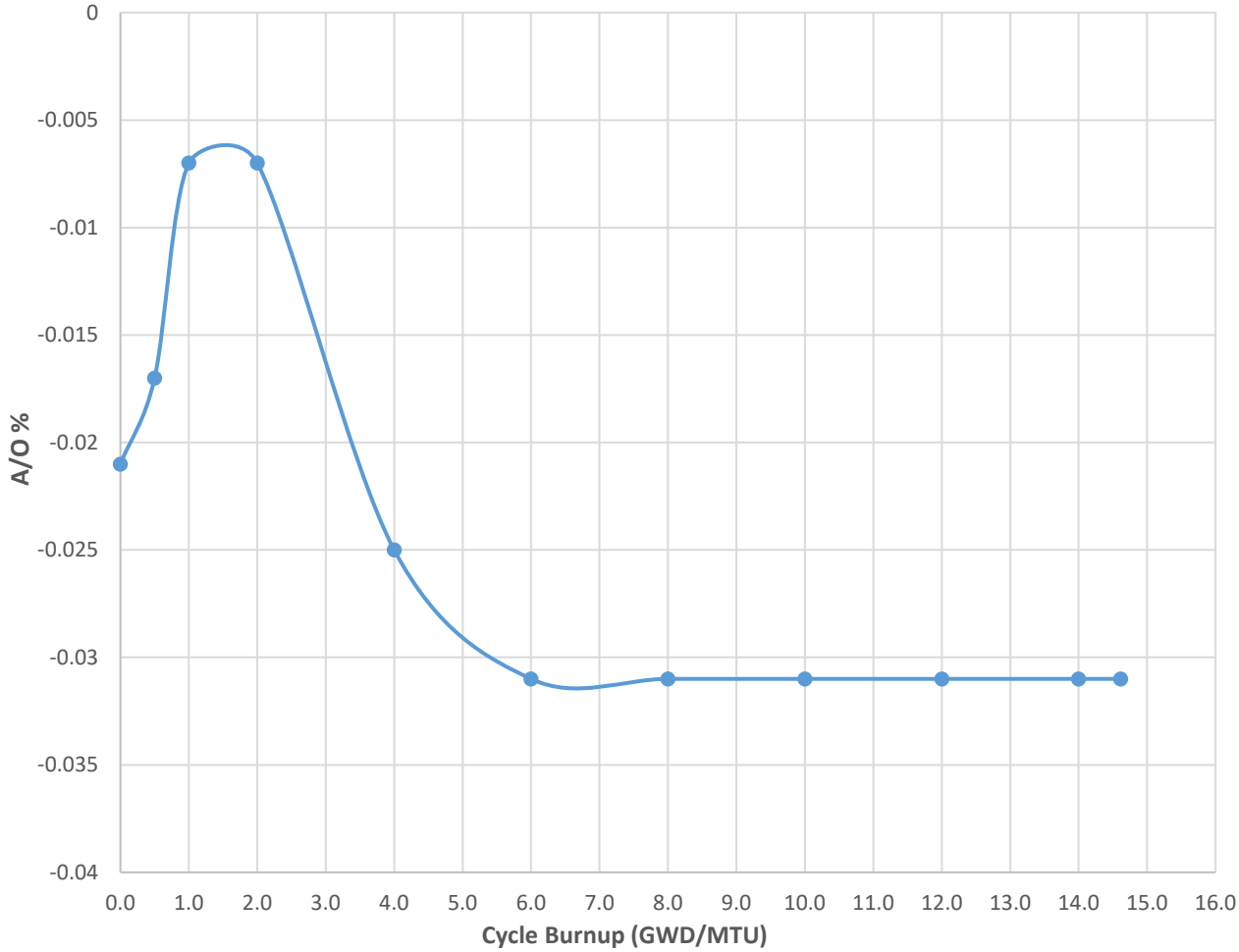

Figure 15 | Core Axial Power Tilt vs. Cycle Burnup
This plot shows the axial power offset as function of cycle burnup. Throughout the cycle, the core is consistently skewed towards bottom peaked, with slight variations throughout the cycle which most likely can be attributed to burnable poisons.

OUTPUT SUMMARY TABLE

P W R S u m m a r y o f S t e a d y - S t a t e S I M U L A T E - 3 V e r s i o n 1 . 0 0 . 0 2

Summary File Name = SUMMARY

Case Step	Step Exp	K-eff	NQ	Bor ppm	Peak Powers AX / K	A-O	Rad	Node	3PIN	Dens g/cc	Power %	Flow %	CRD Pos	Pres psia	Inlet T (F)	Core Exp	Title Exp	Set
1 0	0.000	0.99999	7	1285	1.37/ 7	-0.021	1.26	1.87	1.98	0.715	100.0	100.0	0	2250	546.8	0.000	0.00	0
1 1	0.500	1.00001	4	1235	1.40/ 7	-0.017	1.25	1.81	2.01	0.715	100.0	100.0	0	2250	546.8	0.500	0.00	0
1 2	1.000	0.99999	6	1272	1.44/ 7	-0.007	1.30	1.94	2.07	0.715	100.0	100.0	0	2250	546.8	1.000	0.00	0
1 3	2.000	0.99999	6	1265	1.33/ 7	-0.007	1.37	1.85	1.91	0.715	100.0	100.0	0	2250	546.8	2.000	0.00	0
1 4	4.000	1.00001	5	1087	1.15/ 4	-0.025	1.37	1.61	1.66	0.714	100.0	100.0	0	2250	546.8	4.000	0.00	0
1 5	6.000	1.00000	8	874	1.15/ 3	-0.031	1.34	1.57	1.63	0.714	100.0	100.0	0	2250	546.8	6.000	0.00	0
1 6	8.000	1.00000	9	660	1.14/ 3	-0.031	1.32	1.52	1.58	0.714	100.0	100.0	0	2250	546.8	8.000	0.00	0
1 7	10.000	1.00000	9	453	1.14/ 2	-0.031	1.29	1.50	1.55	0.714	100.0	100.0	0	2250	546.8	10.000	0.00	0
1 8	12.000	1.00000	9	256	1.14/ 2	-0.031	1.27	1.47	1.53	0.714	100.0	100.0	0	2250	546.8	12.000	0.00	0
1 9	14.000	1.00000	9	66	1.13/ 2	-0.031	1.26	1.44	1.50	0.714	100.0	100.0	0	2250	546.8	14.000	0.00	0
1 10	14.611	0.99998	15	10	1.13/ 2	-0.031	1.25	1.43	1.49	0.714	100.0	100.0	0	2250	546.8	14.611	0.00	0

1S I M U L A T E - 3 ** Studsvik CMS Steady-State 3-D Reactor Simulator ** 1.00.02 _BASE INT Created 12/05/08 ** Page 84
Run: RUN NAME ** Project: GENERIC PWR EQUILIBR ** Run Time: 11.29.57.** Date: 2018/11/15 100.0% Flow 100.0% Power
Case 1 Step 0 0.00 ppm 0.000 GWd/MT

Figure 16 | Output Summary
This figure shows the output table produced from SIMULATE in the file project.out, which can be found archived on Page 24.

DISCUSSION

Overall, this core design and loading pattern optimization for Cycle 1 met all design requirements. The final LP design, as seen in Figure 2, is of the Zone Scatter Out-In form, which was utilized to minimize peaking factors within the core. The periphery of the core consists mostly of FA Type 5 (non-BP 3.2%) with some FA Type 6 (16 BP 3.2%), while the middle of the core is a mix of FA Type 2 (2.0%), FA Type 3 (non-BP 2.5%), and FA Type 4 (16 BP 2.5%). This LP design is unlike an equilibrium cycle, as all the fuel is fresh therefore the enrichment (lower) must take the place of burnup. Although this design choice meets thermal and reactivity limits, neutron leakage in this design would be maximized. Additional design constraints could be applied in order to restrict the leakage, thus requiring a slightly different LP to be designed for the core. Furthermore, the design choice for using burnable poisons in various assemblies will raise the fuel cycle cost for this core design. More advanced optimization methods could be applied to the LP in order to find a design that works with little to no BP.

The k-effective over the cycle (0.00 GWD/MTU to 14.611 GWD/MTU) stays relatively constant as shown in Figure 3 with small variations due to the presence of burnable poisons near the BOC and the boron letdown curve towards EOC. The current mix of FA with and without BP, along with the core geometry, gives a cycle that meets and slightly surpasses the initial LP design in terms of cycle length. Creating a design with excess reactivity could allow for a longer stretch-out for the cycle, but this would require more enrichment and most likely burnable poisons to suppress that added reactivity, both adding to the fuel cycle cost.

For Figures 4 through 7, the core map k-infinities can be seen for chosen burnup steps. As expected, these maps show the highest reactivities in the non-BP 3.2% enriched assemblies near the edge of the core and the lowest reactivities in the 2% enriched assemblies near the middle of the core. Slight increases in reactivity can be seen in the FA with BP as they burn out early into the cycle, but the majority of the reactivities slowly decrease until EOC.

The maximum $F_{\Delta H}$ can be seen in Figure 8 as 1.453 at 0.00 GWD/MTU, which is below the limit of 1.48 with a decent margin. Figures 9 through 12 show the 2D maps of $F_{\Delta H}$ at chosen burnup steps. The highest power peaking factors can be seen in the highest enriched fuel (3.2%) and specifically within the FA without BP near BOC. Adding poisons to some of these higher enriched assemblies may suppress the reactivity near the start of the cycle more and hopefully lead to a better thermal margin.

Looking at Figure 13, we can see that the maximum F_Q for the cycle is 2.097 which just barely meets the design constraint of 2.1. This issue occurs in one of the FA Type 6 assemblies just as the burnable poisons within the fuel begin to burn out and excess reactivity is no longer suppressed. This issue could be solved by adding more BP to the problem FA or reorganizing the LP to prevent peaking around this FA.

Figures 14 shows the boron letdown curve for Cycle 1, which increases slightly near the BOC to offset the lost negative reactivity from the burnable absorbers. The boron then decreases almost linearly as SIMULATE searches on concentration to maintain 100% power and a k-effective of 1.0. The search is set to cut off at 10 ppm when the reactor can no longer maintain full power, as seen in the end of Figure 14. Increased excess reactivity at BOC could promote a longer fuel cycle but would require tougher reactivity control in order to suppress peaking (BP and boron).

CONCLUSION

Overall, this project served as an excellent application of our acquired knowledge of nuclear engineering, specifically reactor design, loading patterns, and reactor kinetics. Using an industry standard computational code SIMULATE-3, we were successfully able to create a core and loading pattern design for an initial cycle for a 3-loop Westinghouse PWR that met all desired design constraints. The application of the theory studied in lecture with Dr. Hou and learning modern nuclear engineering computing environments were vital to the success of this project.

This project was a valuable learning experience, as I have had some experience with core and loading pattern design while at an internship with Framatome, however this was on BWRs. This project showed some of the important differences between the two but generally sought to accomplish the same goals. Furthermore, this project aligned almost exactly with my senior design project on a Westinghouse 3-loop PWR using their Advanced Nodal Code. Connections and realizations were made during this design process that really solidified the methodology and theory.

In summary, this project had no real issues beyond the fairly short introduction to SIMULATE-3. I thought the design requirements matched exactly with what was studied in class. Modifications to the project requirements could be made in order to study further analyses (economic, thermal-hydraulic, mechanic, etc.) if warranted.

FILE ARCHIVE

The relevant files for this project design are shown archived below in the RDFMG cluster:

/home/cgmaras

```
-rw-r--r--  1 cgmaras Senior_Design  122848  Nov 15 11:30 project.cms
-rw-r--r--  1 cgmaras Senior_Design       962  Nov 15 11:29 project.inp
-rw-r--r--  1 cgmaras Senior_Design  294108  Nov 15 11:30 project.out
-rw-r--r--  1 cgmaras Senior_Design  120024  Nov 15 11:30 project.sum
-rw-r--r--  1 cgmaras Senior_Design       231  Nov  6  10:41 simulate.sh
-rw-r--r-- 1 cgmaras  Senior_Design       873  Nov  6  10:09 studsvik.conf
-rw------- 1 cgmaras  Senior_Design   25609   Nov 15 11:30 error.dat
-rw------- 1 cgmaras  Senior_Design     416     Nov 15 11:30 info.dat
-rw-r--r-- 1 cgmaras  Senior_Design 3986312 Nov  6 10:14 cms.pwr-all.lib
-rw-r--r-- 1 cgmaras  Senior_Design  874808  Nov  6 10:14  cycle1.res
```

REFERENCES

1. Studsvik Scandpower Inc., SIMULATE-3 User's Manual. University Release 2009.

2. Dr. Paul J. Turinsky. NE 412 Notes: Nuclear Fuel Cycles I, II, III.

3. Dr. J. Hou. NE 412 Notes: Course Project.

4. Robert G. Cochran and Nicholas Tsoulfanidis, Nuclear Fuel Cycle: Analysis and Management, 2nd Edition, American Nuclear Society, 1999.

APPENDIX A

Table A1: Fuel Type 2 Supplementary Information

TYPE 2 (2.0 w/o)				
Burnup MWD/kg	**k-inf**	**Pin peak**	**U235 w/o**	**Pu (Fissile) w/o**
0.00	1.1188	1.034	2.000	0.000
0.10	1.0811	1.035	1.988	0.002
0.50	1.0748	1.035	1.943	0.026
1.00	1.0729	1.036	1.888	0.059
2.00	1.0665	1.036	1.784	0.117
3.00	1.0572	1.036	1.688	0.167
4.00	1.0468	1.036	1.598	0.211
5.00	1.0362	1.036	1.514	0.250
6.00	1.0256	1.036	1.434	0.286
7.00	1.0153	1.036	1.359	0.318
8.00	1.0053	1.035	1.288	0.347
9.00	0.9956	1.035	1.221	0.373
10.00	0.9861	1.034	1.157	0.397
11.00	0.9770	1.034	1.096	0.419
12.50	0.9639	1.033	1.010	0.449
15.00	0.9434	1.031	0.882	0.491
17.50	0.9240	1.030	0.768	0.525
20.00	0.9057	1.029	0.668	0.553
22.50	0.8887	1.028	0.579	0.576
25.00	0.8727	1.027	0.502	0.595
27.50	0.8579	1.026	0.433	0.610
30.00	0.8442	1.026	0.374	0.623

Table A2: Fuel Type 3 and 4 Supplementary Information

TYPE 3 (2.5 w/o, No BP)					TYPE 4 (2.5 w/o, 16 Gad)				
Burnup MWD/kg	**k-inf**	**Pin peak**	**U235 w/o**	**Pu (Fissile) w/o**	**Burnup MWD/kg**	**k-inf**	**Pin peak**	**U235 w/o**	**Pu (Fissile) w/o**
0.00	1.1873	1.038	2.500	0.000	0.00	1.0329	1.079	2.500	0.000
0.10	1.1470	1.039	2.488	0.002	0.10	1.0074	1.075	2.488	0.002
0.50	1.1388	1.040	2.442	0.024	0.50	1.0228	1.069	2.442	0.025
1.00	1.1349	1.040	2.386	0.053	1.00	1.0602	1.057	2.386	0.057
2.00	1.1265	1.040	2.278	0.108	1.50	1.0953	1.045	2.332	0.086
3.00	1.1159	1.040	2.176	0.155	2.00	1.1096	1.041	2.279	0.112
4.00	1.1047	1.040	2.080	0.198	2.50	1.1132	1.042	2.228	0.137
5.00	1.0933	1.040	1.988	0.237	3.00	1.1121	1.042	2.178	0.160
6.00	1.0820	1.039	1.901	0.273	3.50	1.1084	1.042	2.129	0.182
7.00	1.0710	1.039	1.817	0.305	4.00	1.1035	1.042	2.082	0.202
8.00	1.0603	1.038	1.737	0.335	4.50	1.0980	1.042	2.036	0.222
9.00	1.0499	1.038	1.660	0.363	5.00	1.0925	1.042	1.990	0.241
10.00	1.0398	1.037	1.587	0.389	6.00	1.0813	1.041	1.903	0.276
11.00	1.0300	1.037	1.516	0.412	7.00	1.0703	1.041	1.820	0.308
12.50	1.0160	1.036	1.415	0.444	8.00	1.0596	1.040	1.740	0.338
15.00	0.9938	1.034	1.261	0.491	9.00	1.0492	1.040	1.663	0.366
17.50	0.9727	1.032	1.121	0.529	10.00	1.0392	1.039	1.590	0.391
20.00	0.9527	1.031	0.994	0.561	11.00	1.0294	1.038	1.519	0.414
22.50	0.9337	1.029	0.879	0.587	12.50	1.0154	1.037	1.419	0.446
25.00	0.9157	1.028	0.776	0.609	15.00	0.9933	1.036	1.264	0.492
27.50	0.8987	1.027	0.684	0.627	17.50	0.9723	1.034	1.124	0.530
30.00	0.8825	1.026	0.600	0.641	20.00	0.9523	1.033	0.997	0.562
					22.50	0.9333	1.031	0.883	0.588
					25.00	0.9153	1.030	0.779	0.610
					27.50	0.8983	1.028	0.686	0.628
					30.00	0.8821	1.027	0.603	0.642

Table A3: Fuel Type 5 and 6 Supplementary Information

TYPE 5 (3.2 w/o, No BP)					TYPE 6 (3.2 w/o, 16 Gad)				
Burnup MWD/kg	**k-inf**	**Pin peak**	**U235 w/o**	**Pu (Fissile) w/o**	**Burnup MWD/kg**	**k-inf**	**Pin peak**	**U235 w/o**	**Pu (Fissile) w/o**
0.00	1.2548	1.044	3.200	0.000	0.00	1.1147	1.079	3.200	0.000
0.10	1.2130	1.045	3.188	0.002	0.10	1.0857	1.078	3.188	0.002
0.50	1.2039	1.045	3.141	0.021	0.50	1.0943	1.073	3.141	0.023
1.00	1.1985	1.045	3.084	0.048	1.00	1.1180	1.064	3.084	0.051
2.00	1.1891	1.045	2.972	0.098	1.50	1.1435	1.054	3.028	0.078
3.00	1.1783	1.045	2.866	0.144	2.00	1.1601	1.047	2.973	0.103
4.00	1.1670	1.044	2.763	0.185	2.50	1.1668	1.045	2.919	0.126
5.00	1.1555	1.044	2.664	0.223	3.00	1.1684	1.046	2.867	0.148
6.00	1.1441	1.044	2.569	0.259	3.50	1.1670	1.046	2.815	0.169
7.00	1.1330	1.043	2.477	0.291	4.00	1.1636	1.046	2.765	0.189
8.00	1.1221	1.043	2.388	0.322	4.50	1.1591	1.046	2.715	0.209
9.00	1.1116	1.042	2.302	0.351	5.00	1.1539	1.046	2.666	0.227
10.00	1.1013	1.041	2.219	0.377	5.50	1.1485	1.046	2.618	0.245
11.00	1.0913	1.041	2.138	0.402	6.00	1.1430	1.046	2.571	0.262
12.50	1.0768	1.040	2.022	0.437	7.00	1.1320	1.045	2.479	0.295
15.00	1.0540	1.038	1.839	0.488	8.00	1.1212	1.045	2.391	0.325
17.50	1.0323	1.036	1.670	0.531	9.00	1.1107	1.044	2.305	0.354
20.00	1.0116	1.034	1.514	0.568	10.00	1.1004	1.043	2.221	0.380
22.50	0.9917	1.033	1.369	0.599	11.00	1.0905	1.042	2.141	0.405
25.00	0.9726	1.031	1.235	0.626	12.50	1.0761	1.041	2.025	0.439
27.50	0.9543	1.029	1.112	0.648	15.00	1.0533	1.040	1.842	0.490
30.00	0.9366	1.028	0.998	0.666	17.50	1.0317	1.038	1.674	0.533
					20.00	1.0110	1.036	1.517	0.570
					22.50	0.9912	1.034	1.372	0.601
					25.00	0.9721	1.032	1.239	0.627
					27.50	0.9538	1.031	1.115	0.649
					30.00	0.9361	1.029	1.001	0.667