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Developing a Basis for Predicting and Assessing Trends in BWR Core Tracking

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In the process of designing a boiling water reactor (BWR) fuel cycle, it is necessary to estimate the bias eigenvalue trend or nuclear design basis, which has a large effect on the cycle parameters. Currently, the history of previous cycles is used as a basis, but due to increasing demands of higher energy output per cycle, and unexpected events during a cycle, predictions become challenging. To aid in developing a basis for making predictions, various perturbations in the areas of fuel manufacturing and plant measurement were studied in a multicycle analysis. These perturbations have a range of effects on several different cycle parameters. The results of this study are intended to assist in the prediction and assessment of trends in the BWR industry.

KEYWORDS: BWR, Multicycle Sensitivity Analysis, Nuclear Design Basis, Eigenvalue Trends, Cold Criticals, TIP Comparisons, Thermal Margins

1. Introduction

It is beneficial to have the ability of predicting and evaluating changes in bias eigenvalue trends, thermal margin trends, and traversing in-core probe (TIP) bias trends when variations occur in a boiling water reactor (BWR) core from one cycle to another. Currently an educated guess, called the nuclear design basis (NDB), is made on what the trends will be. The NDB is based on previous knowledge of the core or related cores, and it involves engineering judgment for interpreting the available experience base. However, it may be difficult to develop a firm NDB when the previous cycle data is unavailable, or it is not fully relevant due to significant changes in the core. This problem is amplified by the introduction of new fuel designs, power uprates, longer operating cycles, changes in operating philosophy, and functioning in regimes without substantial prior experience. For example, BWR plants are running at increasingly higher capacity factors, with fewer opportunities to benchmark cold calculation models because outage schedules continue to be minimized. Since BWR analysis models are quite sensitive to past history, the integral value of the effect of a perturbation can be larger than expected. If the previous history of the core is incorrect, actual values for the power distribution can be different than the calculated results.

To enable this study, a multicycle benchmark model was created [1]. It is a reference BWR three-dimensional multi-cycle rodded core simulation model, which includes all basic details that a BWR core designer requires from an actual operating reactor, i.e. detailed core loading patterns for four cycles, varying operating conditions and rod patterns, as well as cold critical measurements at the beginning of cycle (BOC), middle of cycle (MOC) and end of cycle (EOC). For cold critical measurements, control rods are pulled until criticality is

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reached. The cold critical calculations include distributed as well as local cold criticals. [Distributed cold criticals have a rod pattern distributed throughout the core, and local cold criticals have a rod pattern where the rods are withdrawn from only one part of the core (locally) and are in close proximity of each other.] Various perturbations in the area of fuel manufacturing and plant measurement were studied using this model. The effects on hot eigenvalue trend, distributed and local cold critical prediction, thermal margins, and changes in TIP bias were evaluated for the transition from the original cycle through a future equilibrium cycle. Interesting results have been obtained through these efforts, and further investigations would result in even more insights.

The basis of these studies involves perturbations. The perturbations are done to evaluate the effects of varying certain input parameters, which are used in cycle calculations, within realistic uncertainties. These uncertainties are related to manufacturing, methods, instrument readings, and other possible components. This type of analysis is useful when considering that typical BWR industry uncertainty on the core eigenvalue is ± 0.003, which in large plants roughly translates into ± 6 assemblies in a reload batch (or ± 15 days of operation). Therefore, it is valuable to minimize the uncertainties on the eigenvalue trends and other parameters (e.g. thermal margin trends and TIP bias trends), due to their large impact on financial and safety considerations.

2. Purpose

The initial task in this analysis was to provide information on the sensitivity of these parameters as a function of exposure. This information may be applied in new model development activities for assessment of model changes on core simulation results. Additionally, it can assist in the identification of likely causes for the occasional irregularities observed in core tracking. Even if the lattice physics and core simulator codes were consistent in the past for the evaluation of a particular core, there is no absolute guarantee that the existing trends will continue. The ability to predict or analyze the changes in these trends is important. For example, it can provide assistance in more accurately predicting the NDB eigenvalue bias trends. Also, if the NDB trend does not agree with the actual trend during the cycle, this analysis provides a basis to suggest what unrecognized variations might be present, or might have occurred in the core.

3. Methods

There are various perturbation parameters that were considered in this study. Core flow, core pressure, core inlet temperature, and core power variation data was previously analyzed [1]; however, additional data such as cold critical eigenvalues and TIP comparisons for these cases are analyzed in this study. The effects of variations in burnable poison concentration, enrichment, pellet density, cladding dimensions, and in channel dimensions were considered in this analysis. In addition to varying these parameters, the reference multicycle [1] can also be used in the future to study perturbations in core and fuel behavior; such as, variations in fission product model, Xenon model, depletion model (slope of depletion), gadolinium burnout, control rod depletion, control rod design, impact of different types of spacers, impact of plenum regions at bottom / top / middle of the bundle, impact of the use of hot dimensions, and impact of TIP modeling. Studies of the perturbations in physics assumptions will also be possible with this multicycle mode; for example, variations in core axial leakage, core radial leakage, distribution of flows to bundles, calculation of axial void fraction, control rod axial worths, modeling vs. not modeling of spacers, axially varying control rods, and crud build-up.

In the future, studies of the effects of varying all these parameters will assist in the development of a diagnostic tool.

The analysis was performed using the current standard Global Nuclear Fuel (GNF) analysis package and the reference multicycle created in a previous study [1]. The analysis package included the TGBLA06 lattice-physics code and the PANAC11 core-simulator code [2,3]. Even though other BWR code packages have different biases and give different results, all should show similar changes in the overall characteristic trending. The way the reference multicycle was used can be analyzed in several different manners. Throughout most of the project, the multicycle was considered to be the calculated prediction for a plant, and each variation case was considered as the measured plant data. This method allowed for a controlled experiment where effects from individual perturbations could be evaluated. A comparable real life scenario may be that all of the reload bundles are manufactured to a slightly higher enrichment, while the cycle calculations are based on the fuel being within specifications. As a result, the online monitoring system might then track a different eigenvalue trend than predicted. When comparing this real life situation with this study, the calculated cycle would correspond to the reference base case and the online monitoring system values would correspond to the perturbed case. In order to simplify the calculation process used for TIP comparisons, the interpretation is opposite: the base or reference case in this study would correspond to the measured case (from the online monitoring system) and the higher enriched core would be considered as the calculated core.

3.1 Reference Multicycle

As mentioned earlier, the reference multicycle was created in a previous study [1]. The core of the reference multicycle is a 764 assembly General Electric BWR/4 plant, utilizing two year cycles in a control-cell-core loading, with ~37% batch fraction. There is one GE14 (10x10) fuel assembly type loaded in all the cycles. Cycle N is the beginning cycle in the study. Although starting from cycle N of an existing core, these assemblies (bundles) and the core loadings do not reflect the actual operation of any operating BWR, but were constructed to provide some insights on the sensitivity to the methods of variability in the actual data for this mode of operation. [It is recognized that the sensitivities for a two-year high-energy cycle using GNF 10x10 fuel may or may not have any relationship to the sensitivities that would be seen for an annual cycle operation of a BWR, not loaded with similar fuel or not of the same size. Additional studies would be needed to make that generalization.] The input and output characteristics to describe the reference multicycle are shown below. The values of these parameters are typical of a large BWR core, but are set up to approach an equilibrium cycle.

Table 1 General Fuel Cycle Parameters

Cycle	Rated Power MWt	Exposure MWd/MT, Rated 100%P/100%Flow	Full Cycle Exposure MWd/MT	Total Cycle Days	Outage Days	Operating Days	Core Weight MT	MWD Rated	MWD EOC
N	3514	16535	18133	728	20	708	135.15	2234674	2450693
N+1	3514	15763	17913	728	20	708	136.93	2158432	2452764
N+2	3514	16204	17913	728	20	708	136.95	2219197	2453194
N+3	3514	16480	17913	728	20	708	137.03	2258240	2454609

Figure 1 and Figure 2 below illustrate thermal margin trends, and power and flow maps for the multicycle analysis. Vertical lines separate each cycle and the cumulative exposure is used as the parameter for the x-axis. Except where noted, in the analysis these values represent the predicted/calculated cycle parameters values. To make the reference case somewhat realistic, characteristics such as power coast downs are incorporated (see Figure 2 for details).

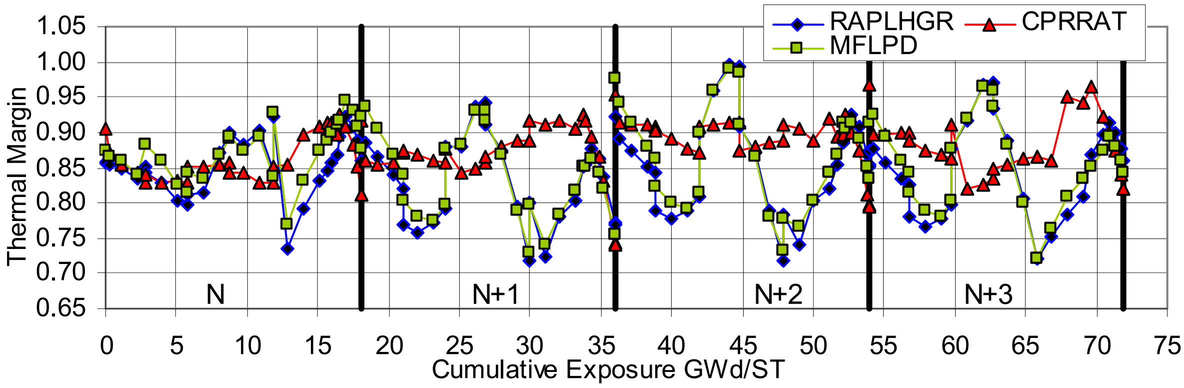


Figure 1 Thermal Margins for Cycles N to N+3

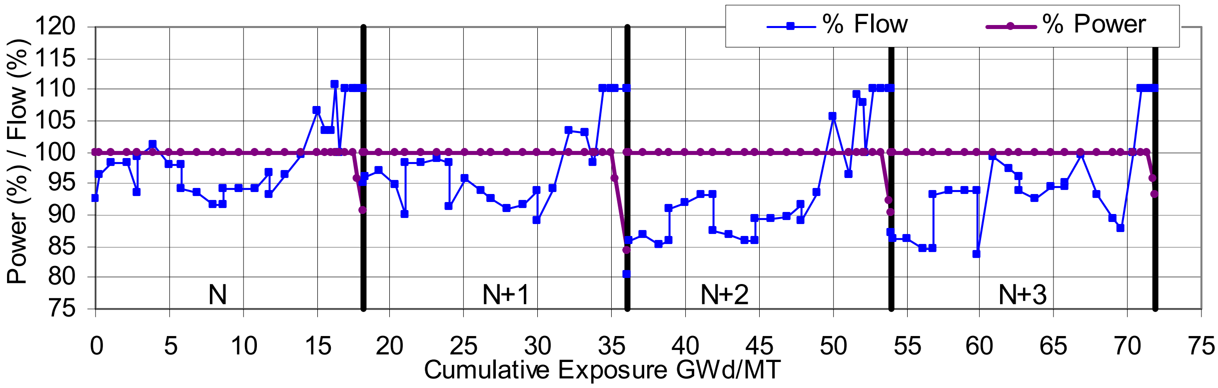


Figure 2 Reactor Power and Core Flow for Cycles N to N+3

Figure 3 illustrates the shapes of the resulting BOC and EOC core average axial relative power, and axial average exposure for Cycle N+3, which is considered to be an equilibrium cycle. This plot is normalized, and to obtain the actual values, there is a multiplier in the legend for each parameter.

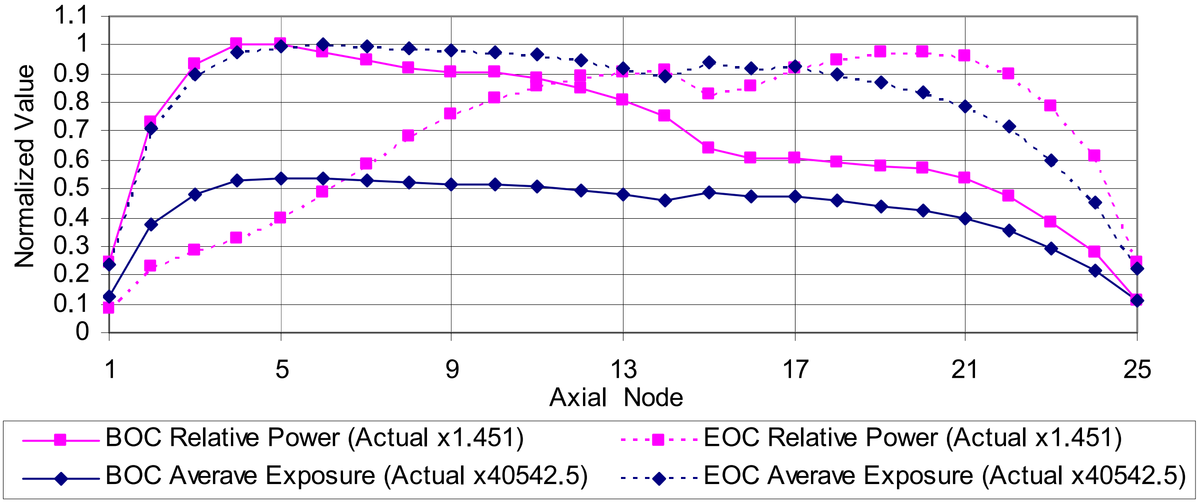
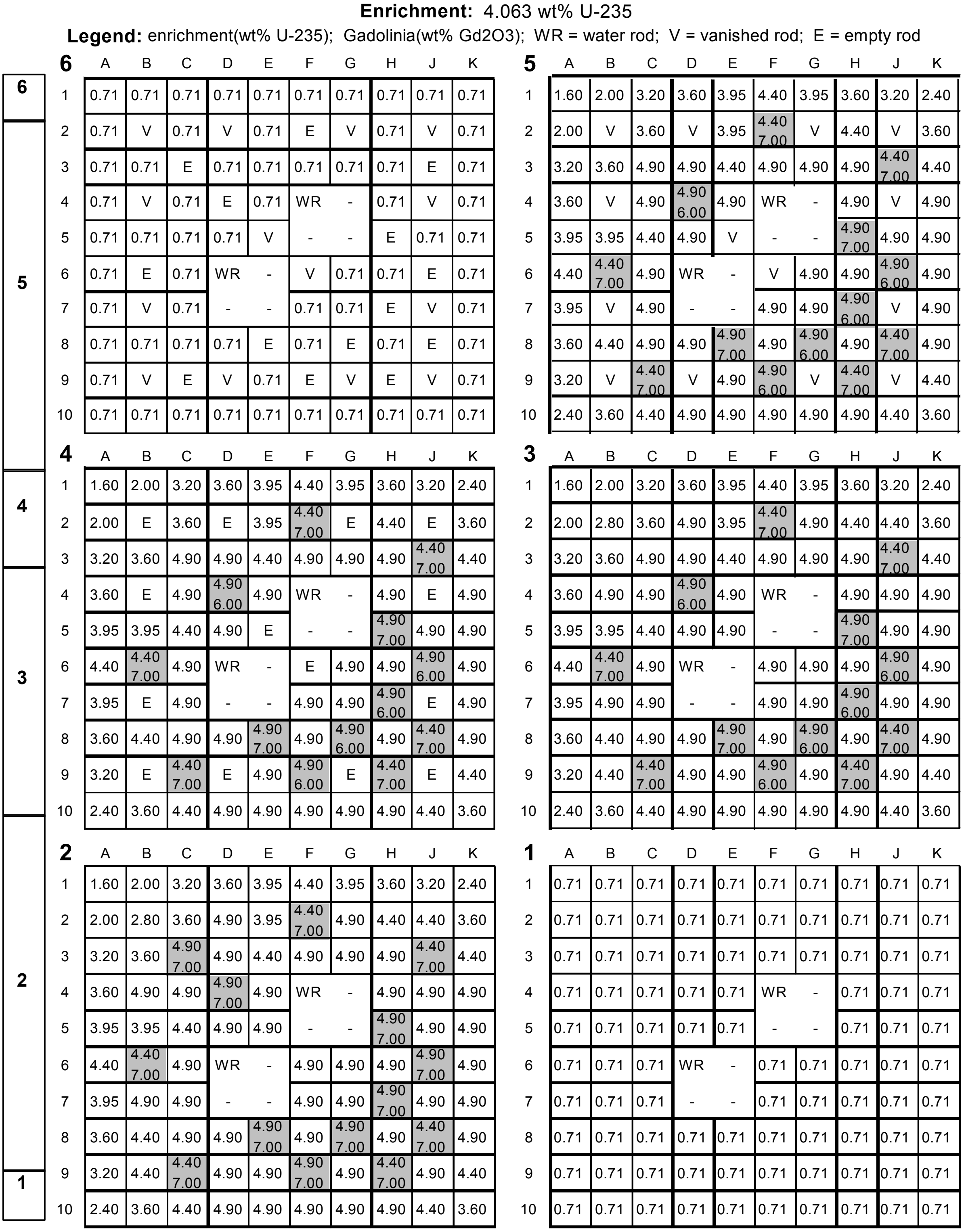


Figure 3 Normalized Axial Core Parameters for Cycle N+3

3.2 Reference Bundle

The reference bundle is a GE14 10x10 fuel bundle. As shown in Figure 4 below, it is composed of six lattices. Lattices 1 & 6 contain natural uranium fuel and lattices 2-5 contain enriched uranium fuel and gadolinium rods. Although this is not an existing fuel bundle, it is typical of what would be in an actual core. This is the fuel bundle that is used as the reload for all the cycles.



Enrichment: 4.063 wt% U-235

Legend: enrichment(wt% U-235); Gadolinia(wt% Gd2O3); WR = water rod; V = vanished rod; E = empty rod

6	A	B	C	D	E	F	G	H	J	K
1	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71
2	0.71	V	0.71	V	0.71	E	V	0.71	V	0.71
3	0.71	0.71	E	0.71	0.71	0.71	0.71	0.71	E	0.71
4	0.71	V	0.71	E	0.71	WR	-	0.71	V	0.71
5	0.71	0.71	0.71	0.71	V	-	-	E	0.71	0.71
6	0.71	E	0.71	WR	-	V	0.71	0.71	E	0.71
7	0.71	V	0.71	-	-	0.71	0.71	E	V	0.71
8	0.71	0.71	0.71	0.71	E	0.71	E	0.71	E	0.71
9	0.71	V	E	V	0.71	E	V	E	V	0.71
10	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71

5	A	B	C	D	E	F	G	H	J	K
1	1.60	2.00	3.20	3.60	3.95	4.40	3.95	3.60	3.20	2.40
2	2.00	V	3.60	V	3.95	4.40 7.00	V	4.40	V	3.60
3	3.20	3.60	4.90	4.90	4.40	4.90	4.90	4.90	4.40 7.00	4.40
4	3.60	V	4.90	4.90 6.00	4.90	WR	-	4.90	V	4.90
5	3.95	3.95	4.40	4.90	V	-	-	4.90 7.00	4.90	4.90
6	4.40	4.40 7.00	4.90	WR	-	V	4.90	4.90	4.90 6.00	4.90
7	3.95	V	4.90	-	-	4.90	4.90	4.90 6.00	V	4.90
8	3.60	4.40	4.90	4.90	4.90 7.00	4.90	4.90 6.00	4.90	4.40 7.00	4.90
9	3.20	V	4.40 7.00	V	4.90	4.90 6.00	V	4.40 7.00	V	4.40
10	2.40	3.60	4.40	4.90	4.90	4.90	4.90	4.90	4.40	3.60

4	A	B	C	D	E	F	G	H	J	K
1	1.60	2.00	3.20	3.60	3.95	4.40	3.95	3.60	3.20	2.40
2	2.00	E	3.60	E	3.95	4.40 7.00	E	4.40	E	3.60
3	3.20	3.60	4.90	4.90	4.40	4.90	4.90	4.90	4.40 7.00	4.40
4	3.60	E	4.90	4.90 6.00	4.90	WR	-	4.90	E	4.90
5	3.95	3.95	4.40	4.90	E	-	-	4.90 7.00	4.90	4.90
6	4.40	4.40 7.00	4.90	WR	-	E	4.90	4.90	4.90 6.00	4.90
7	3.95	E	4.90	-	-	4.90	4.90	4.90 6.00	E	4.90
8	3.60	4.40	4.90	4.90	4.90 7.00	4.90	4.90 6.00	4.90	4.40 7.00	4.90
9	3.20	E	4.40 7.00	E	4.90	4.90 6.00	E	4.40 7.00	E	4.40
10	2.40	3.60	4.40	4.90	4.90	4.90	4.90	4.90	4.40	3.60

3	A	B	C	D	E	F	G	H	J	K
1	1.60	2.00	3.20	3.60	3.95	4.40	3.95	3.60	3.20	2.40
2	2.00	2.80	3.60	4.90	3.95	4.40 7.00	4.90	4.40	4.40	3.60
3	3.20	3.60	4.90	4.90	4.40	4.90	4.90	4.90	4.40 7.00	4.40
4	3.60	4.90	4.90	4.90 6.00	4.90	WR	-	4.90	4.90	4.90
5	3.95	3.95	4.40	4.90	4.90	-	-	4.90 7.00	4.90	4.90
6	4.40	4.40 7.00	4.90	WR	-	4.90	4.90	4.90	4.90 6.00	4.90
7	3.95	4.90	4.90	-	-	4.90	4.90	4.90 6.00	4.90	4.90
8	3.60	4.40	4.90	4.90	4.90 7.00	4.90	4.90 6.00	4.90	4.40 7.00	4.90
9	3.20	4.40	4.40 7.00	4.90	4.90	4.90 6.00	4.90	4.40 7.00	4.90	4.40
10	2.40	3.60	4.40	4.90	4.90	4.90	4.90	4.90	4.40	3.60

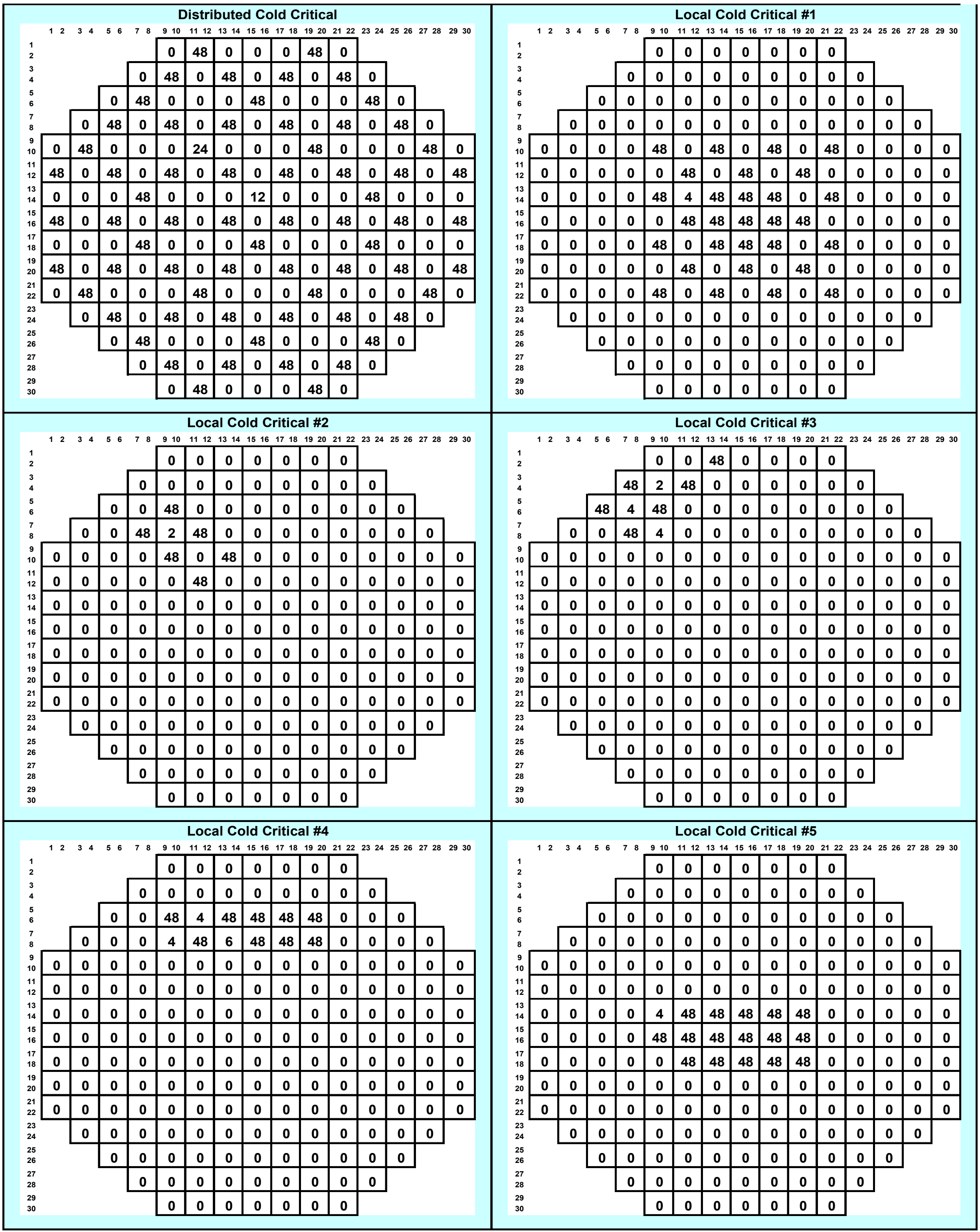
2	A	B	C	D	E	F	G	H	J	K
1	1.60	2.00	3.20	3.60	3.95	4.40	3.95	3.60	3.20	2.40
2	2.00	2.80	3.60	4.90	3.95	4.40 7.00	4.90	4.40	4.40	3.60
3	3.20	3.60	4.90 7.00	4.90	4.40	4.90	4.90	4.90	4.40 7.00	4.40
4	3.60	4.90	4.90	4.90 7.00	4.90	WR	-	4.90	4.90	4.90
5	3.95	3.95	4.40	4.90	4.90	-	-	4.90 7.00	4.90	4.90
6	4.40	4.40 7.00	4.90	WR	-	4.90	4.90	4.90	4.90 7.00	4.90
7	3.95	4.90	4.90	-	-	4.90	4.90	4.90 7.00	4.90	4.90
8	3.60	4.40	4.90	4.90	4.90 7.00	4.90	4.90 7.00	4.90	4.40 7.00	4.90
9	3.20	4.40	4.40 7.00	4.90	4.90	4.90 7.00	4.90	4.40 7.00	4.90	4.40
10	2.40	3.60	4.40	4.90	4.90	4.90	4.90	4.90	4.40	3.60

1	A	B	C	D	E	F	G	H	J	K
1	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71
2	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71
3	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71
4	0.71	0.71	0.71	0.71	0.71	WR	-	0.71	0.71	0.71
5	0.71	0.71	0.71	0.71	0.71	-	-	0.71	0.71	0.71
6	0.71	0.71	0.71	WR	-	0.71	0.71	0.71	0.71	0.71
7	0.71	0.71	0.71	-	-	0.71	0.71	0.71	0.71	0.71
8	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71
9	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71
10	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71	0.71

Figure 4 Reference Bundle Lattice Enrichments and Gadolinium Concentrations

3.3 Cold Criticals

Cold critical eigenvalues are used to calculate the shut down margin (SDM) at different points in a cycle. Below is an illustration of the rod patterns used to calculate the distributed and five different local cold criticals for MOC N+1. Very similar patterns are used for the cold critical calculations at BOC, MOC, and EOC points in each of the four cycles.



Distributed Cold Critical

	1 2	3 4	5 6	7 8	9 10	11 12	13 14	15 16	17 18	19 20	21 22	23 24	25 26	27 28	29 30
1 2					0	48	0	0	0	48	0				
3 4				0	48	0	48	0	48	0	48	0			
5 6			0	48	0	0	0	48	0	0	0	48	0		
7 8		0	48	0	48	0	48	0	48	0	48	0	48	0	
9 10	0	48	0	0	0	24	0	0	0	48	0	0	0	48	0
11 12	48	0	48	0	48	0	48	0	48	0	48	0	48	0	48
13 14	0	0	0	48	0	0	0	12	0	0	0	48	0	0	0
15 16	48	0	48	0	48	0	48	0	48	0	48	0	48	0	48
17 18	0	0	0	48	0	0	0	48	0	0	0	48	0	0	0
19 20	48	0	48	0	48	0	48	0	48	0	48	0	48	0	48
21 22	0	48	0	0	0	48	0	0	0	48	0	0	0	48	0
23 24		0	48	0	48	0	48	0	48	0	48	0	48	0	
25 26			0	48	0	0	0	48	0	0	0	48	0		
27 28				0	48	0	48	0	48	0	48	0			
29 30					0	48	0	0	0	48	0				

Local Cold Critical #1

	1 2	3 4	5 6	7 8	9 10	11 12	13 14	15 16	17 18	19 20	21 22	23 24	25 26	27 28	29 30
1 2					0	0	0	0	0	0	0				
3 4				0	0	0	0	0	0	0	0	0			
5 6			0	0	0	0	0	0	0	0	0	0	0		
7 8		0	0	0	0	0	0	0	0	0	0	0	0	0	
9 10	0	0	0	0	48	0	48	0	48	0	48	0	0	0	0
11 12	0	0	0	0	0	48	0	48	0	48	0	0	0	0	0
13 14	0	0	0	0	48	4	48	48	48	0	48	0	0	0	0
15 16	0	0	0	0	0	48	48	48	48	48	0	0	0	0	0
17 18	0	0	0	0	48	0	48	48	48	0	48	0	0	0	0
19 20	0	0	0	0	0	48	0	48	0	48	0	0	0	0	0
21 22	0	0	0	0	48	0	48	0	48	0	48	0	0	0	0
23 24		0	0	0	0	0	0	0	0	0	0	0	0	0	
25 26			0	0	0	0	0	0	0	0	0	0	0		
27 28				0	0	0	0	0	0	0	0	0			
29 30					0	0	0	0	0	0	0				

Local Cold Critical #2

	1 2	3 4	5 6	7 8	9 10	11 12	13 14	15 16	17 18	19 20	21 22	23 24	25 26	27 28	29 30
1 2					0	0	0	0	0	0	0				
3 4				0	0	0	0	0	0	0	0	0			
5 6			0	0	48	0	0	0	0	0	0	0	0		
7 8		0	0	48	2	48	0	0	0	0	0	0	0	0	
9 10	0	0	0	0	48	0	48	0	0	0	0	0	0	0	0
11 12	0	0	0	0	0	48	0	0	0	0	0	0	0	0	0
13 14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15 16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17 18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19 20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21 22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23 24		0	0	0	0	0	0	0	0	0	0	0	0	0	
25 26			0	0	0	0	0	0	0	0	0	0	0		
27 28				0	0	0	0	0	0	0	0	0			
29 30					0	0	0	0	0	0	0				

Local Cold Critical #3

	1 2	3 4	5 6	7 8	9 10	11 12	13 14	15 16	17 18	19 20	21 22	23 24	25 26	27 28	29 30
1 2					0	0	48	0	0	0	0				
3 4				48	2	48	0	0	0	0	0	0			
5 6			48	4	48	0	0	0	0	0	0	0	0		
7 8		0	0	48	4	0	0	0	0	0	0	0	0	0	
9 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11 12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13 14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15 16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17 18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19 20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21 22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23 24		0	0	0	0	0	0	0	0	0	0	0	0	0	
25 26			0	0	0	0	0	0	0	0	0	0	0		
27 28				0	0	0	0	0	0	0	0	0			
29 30					0	0	0	0	0	0	0				

Local Cold Critical #4

	1 2	3 4	5 6	7 8	9 10	11 12	13 14	15 16	17 18	19 20	21 22	23 24	25 26	27 28	29 30
1 2					0	0	0	0	0	0	0				
3 4				0	0	0	0	0	0	0	0	0			
5 6			0	0	48	4	48	48	48	48	0	0	0		
7 8		0	0	0	4	48	6	48	48	48	0	0	0	0	
9 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11 12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13 14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15 16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17 18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19 20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21 22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23 24		0	0	0	0	0	0	0	0	0	0	0	0	0	
25 26			0	0	0	0	0	0	0	0	0	0	0		
27 28				0	0	0	0	0	0	0	0	0			
29 30					0	0	0	0	0	0	0				

Local Cold Critical #5

	1 2	3 4	5 6	7 8	9 10	11 12	13 14	15 16	17 18	19 20	21 22	23 24	25 26	27 28	29 30
1 2					0	0	0	0	0	0	0				
3 4				0	0	0	0	0	0	0	0	0			
5 6			0	0	0	0	0	0	0	0	0	0	0		
7 8		0	0	0	0	0	0	0	0	0	0	0	0	0	
9 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11 12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13 14	0	0	0	0	4	48	48	48	48	48	0	0	0	0	0
15 16	0	0	0	0	48	48	48	48	48	48	0	0	0	0	0
17 18	0	0	0	0	0	48	48	48	48	48	0	0	0	0	0
19 20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21 22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23 24		0	0	0	0	0	0	0	0	0	0	0	0	0	
25 26			0	0	0	0	0	0	0	0	0	0	0		
27 28				0	0	0	0	0	0	0	0	0			
29 30					0	0	0	0	0	0	0				

Figure 5 Cold Critical Rod Patterns for MOC N+1

4. Experiment Description and Results

In this study the results of many perturbations are discussed. First there is a summary of results for perturbations made on plant measurement parameters [1], and in the section after that there is a summary of results for perturbations made on fuel manufacturing parameters. Even though all cases are shown in the summary tables, detailed plots are shown only for selected high impact perturbations. While reviewing these results, it is important to realize that they are extreme cases, which have a low probability of occurring. However, it is also important to note that each perturbation case only focuses on one parameter, when realistically multiple situations may occur in the core and even if they are individually less drastic, it is possible that their effects are additive or they can cancel each other.

When a perturbation is made it is introduced with the fresh reload bundles. In most cases this perturbation is introduced into all four cycles. As a result of the reload being about one third of the fuel in the core, the core of Cycle N consists of about one third of the reference/perturbed bundles, the core of Cycle N+1 consists of about two thirds of those bundles, and the cores of Cycles N+2 and N+3 consist almost entirely of those bundles.

4.1 Plant Measurement

There is a possibility that instrumentation used to measure plant parameters may fail. In the plant, measurements are taken of parameters such as core flow, pressure, temperature, and power. The plant is run and controlled partially based on these measurements. Due to their importance, these parameters were varied to see their impact on the cycle when no other changes were made. Realistically in the case when the calculated and measured cycles (evaluated by the core monitoring system) do not match, the operations plan is modified and, most likely, the flow and control rod positions are altered to compensate. This type of compensation is not included in this study, which is another factor that makes these perturbations extreme cases. The perturbations considered for the plant measurement parameters are listed in the Table 2. A summary of the results from the perturbation cases is shown in Table 3. In this table the perturbation cases are compared to the base case, where the delta is a result of the base value being subtracted from the perturbed or modified value. For each perturbation the table lists the maximum and minimum resulting hot delta keff, the maximum impact on any of the three thermal margins, and the maximum and minimum delta keff for the distributed and local cold criticals.

Table 2 Description of Plant Measurement Perturbations

Case #	Description
1	Core flow increased 5%
2	Core flow decreased 5%
3	Core pressure increased 2%
4	Core pressure decreased 2%
5	Core temperature increased 0.4%
6	Core temperature decreased 0.4%
7	Core power increased 1.25%
8	Core power decreased 1.25%
9	Core power increased 2.50%
10	Core power decreased 2.50%

Table 3 Summary of Results from Plant Measurement Perturbations

Case #	Range of Impact: Hot Keff		Maximum Impact on Thermal Margin (%)	Range of Impact on Distributed Cold Critical		Range of Impact on Local Cold Critical	
	Maximum	Minimum		Maximum	Minimum	Maximum	Minimum
1	0.00201	0.00026	-2.9	-0.00096	0.00000	-0.00166	0.00000
2	-0.00203	-0.00042	3.1	0.00095	0.00000	0.00163	0.00000
3	0.00168	0.00059	2.1	-0.00056	0.00000	-0.00082	0.00000
4	-0.00175	-0.00063	-2.2	0.00053	0.00000	0.00072	0.00000
5	-0.00150	-0.00055	-1.8	0.00041	0.00000	0.00051	0.00000
6	0.00148	0.00055	1.8	-0.00042	0.00000	-0.00058	0.00000
7	-0.00331	-0.00067	2.7	-0.00118	0.00000	-0.00211	0.00000
8	0.00342	0.00067	-2.7	0.00114	0.00000	0.00197	0.00000
9	-0.00662	-0.00133	5.4	-0.00240	0.00000	-0.00412	0.00000
10	0.00675	0.00135	-5.5	0.00225	0.00000	0.00389	0.00000

There are many conclusions that can be made from the results. The first conclusion is that the variations in the core flow, pressure, and temperature are not as significant as the variations in the power. Figures 6-8 illustrate some of the impacts of cases 9 & 10, where the power is increased and decreased by 2.50%. Figure 6 shows the hot keff of the modified case compared to the base case as a function of continuous burnup over all four cycles. Also, it is important to recognize that the burnup of the modified case is adjusted to the burnup of the base case for this perturbation. This is done because if the instrumentation was giving inaccurate readings, then it would not be know that the burnup is actually different and the comparison below is what would be seen. In this extreme case, the delta keff increases towards EOC for each cycle, reaching a maximum of 0.00675 and 0.00602.

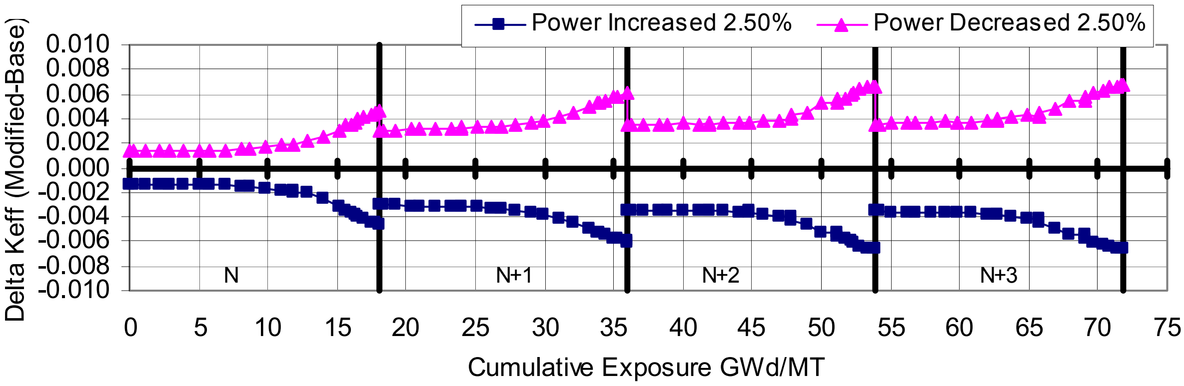


Figure 6 Hot Delta Keff for Varied Power Compared to Base Case

There are two issues that are of concern when looking at the deltas for the cold critical eigenvalues. The first issue is the size of the delta itself. When the delta is positive, it is an indication that the keff for the modified case is higher for the same control rod configuration as in the base case, which means that criticality is reached faster than expected. The second issue is the difference between the changes in the distributed cold criticals compared to the changes in the local cold criticals. This is important because of a bias that has to be maintained between the two values, and when the values vary by different amounts in the perturbation cases, that means the bias may not be maintained. Figure 7 shows the maximum difference between the distributed and any of the five locals within the base case compared to the maximum difference between the distributed and any local within the modified case. In the base case the difference between the distributed cold critical and any local cold critical is roughly designed to maintain the required bias between the two values. As a result, any point in the plot that is above zero indicates that the delta is larger than what the limiting value of the bias should be by that amount. This scenario is not favorable and may result in problems with maintaining an adequate SDM within the cycle.

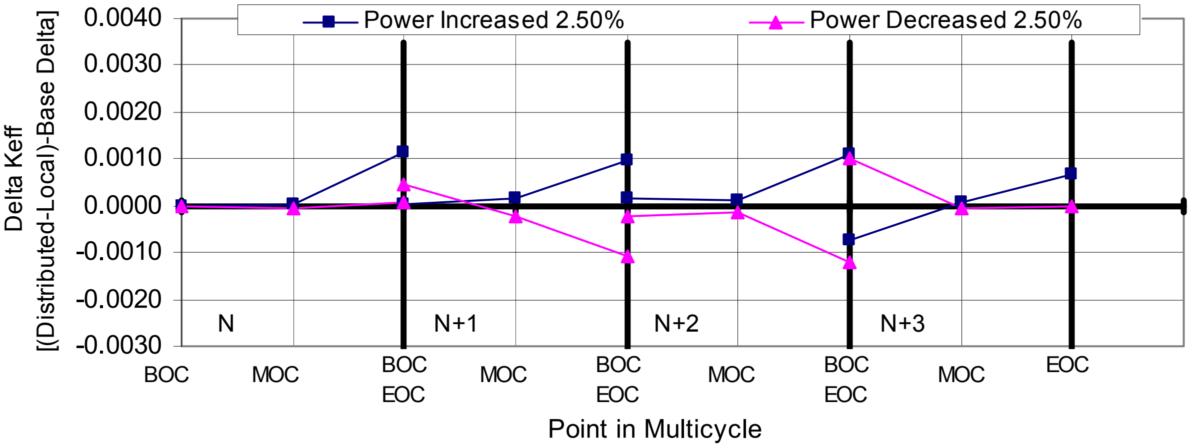


Figure 7 Maximum Delta Keff Between Distributed and Any Local Cold Critical Eigenvalue Compared to Base Case

Figure 8 shows the calculated TIP comparisons between the base case and the perturbation case, where the power is increased by 2.50%. All the RMS values are very small, which means that the difference between the two cases is very small. This indicates that even if the TIP measurements match the calculated TIPs, the plant is not necessarily operating as expected

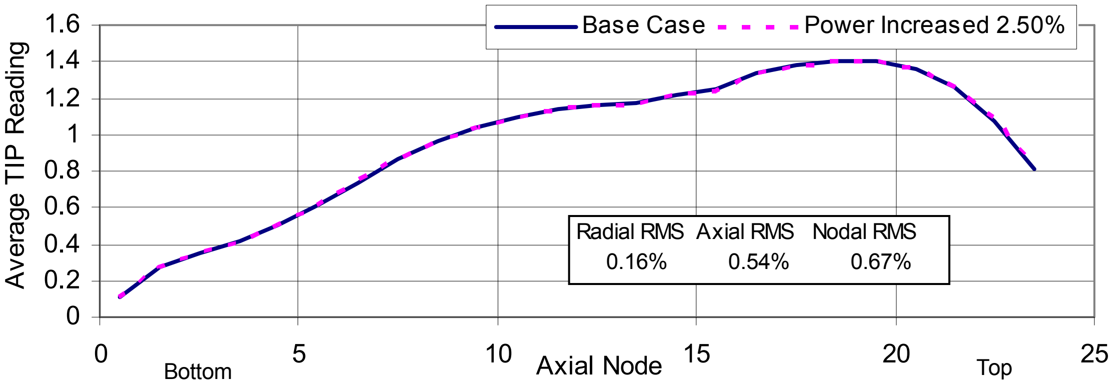


Figure 8 Average Axial TIP Distributions for EOC N+3

As seen by these results, it is important to check the accuracy of the plant equipment since inaccurate measurements used as cycle inputs can greatly effect the way the fuel cycle is designed and operated.

4.2 Fuel Manufacturing

As there are uncertainties in plant measurements, there are also variations in fuel manufacturing. Calculations are always made assuming constant fuel parameters for the standard products that are built by manufacturing. However, the as built parameters for the fuel products are always slightly different from what they are expected or assumed to be. Several perturbations were done in this area to access the effects of fuel manufacturing variations on the fuel cycle. The types of perturbations done are listed in Table 4 and the summary of the results is listed in Table 5. In Table 4, the first four cases of enrichment variations are done by varying the enrichments of entire rods either one level up in enrichment or one level down (using the allowable enrichments that are manufactured) to change the average enrichment of a bundle. This is a very unrealistic scenario and because of the way the perturbation is done (lower enriched rods were replaced with higher enriched rods without varying anything else); the thermal margin effect in case 4 is exceptionally high. In cases 7 & 8 the enrichments were uniformly varied in each pellet by the same percentage to change the average enrichment of the bundle. This uniform variation is also used in cases 13 & 14, where the enrichment is varied uniformly by different percentages in different zones of the bundle.

Table 4 Description of Fuel Manufacturing Perturbations

Case #	Description
1	Average bundle enrichment decreased 1.2% (0.05w%)
2	Average bundle enrichment increased 1.2% (0.05w%)
3	Average bundle enrichment decreased 2.2% (0.09w%)
4	Average bundle enrichment increased 2.2% (0.09w%)
5	Fuel Density increased 0.5%
6	Fuel Density decreased 0.5%
7	Average bundle enrichment uniformly decreased 1.5% (0.06w%)
8	Average bundle enrichment uniformly increased 1.5% (0.06w%)
9	Clad inside diameter increased 0.001 in. and clad thickness decreased 0.003 in.
10	Clad inside diameter decreased 0.001 in. and clad thickness increased 0.003 in.
11	Channel inside dimension decreased 0.015 in.
12	Channel inside dimension increased 0.030 in.
13	Enrichment increased 1.8% in zones 4 & 5 and enrichment decreased 1.2% in zones 2 & 3, average bundle enrichment remained constant
14	Enrichment decreased 1.8% in zones 4 & 5 and enrichment increased 1.2% in zones 2 & 3, average bundle enrichment remained constant
15	Gadolinium concentration increased 0.5w% in Cycle N only
16	Gadolinium concentration increased 0.5w%
17	Gadolinium concentration decreased 0.5w%
18	Gadolinium concentration decreased 0.25w% in Zones 2 & 3 and increased in zones 4 & 5 sufficiently to preserve total gadolinium concentration in the bundle

Table 5 Summary of Results from Fuel Manufacturing Perturbations

Case #	Range of Impact: Hot Keff		Maximum Impact on Thermal Margin (%)	Range of Impact on Distributed Cold Critical		Range of Impact on Local Cold Critical	
	Maximum	Minimum		Maximum	Minimum (Absolute Value)	Maximum	Minimum (Absolute Value)
1	-0.00366	-0.00075	-2.4	-0.00338	0.00102	-0.00349	0.00098
2	0.00374	0.00094	5.2	0.00318	0.00100	0.00335	0.00084
3	-0.00642	-0.00120	4.0	-0.00586	0.00170	-0.00619	0.00161
4	0.00707	0.00186	18.6	0.00640	0.00225	0.00665	0.00180
5	-0.00088	0.00000	-2.7	0.00075	0.00005	0.00109	0.00001
6	-0.00052	0.00000	-0.8	-0.00062	0.00014	-0.00090	0.00002
7	-0.00484	-0.00104	1.8	-0.00432	0.00147	-0.00473	0.00122
8	0.00369	0.00080	1.5	0.00335	0.00111	0.00369	0.00097
9	0.00231	0.00035	1.3	0.00147	0.00013	0.00149	0.00000
10	-0.00190	0.00003	-1.6	-0.00199	0.00009	-0.00204	0.00004
11	0.00082	-0.00001	-0.8	-0.00118	0.00000	-0.00201	0.00001
12	-0.00174	0.00004	1.7	0.00226	0.00001	0.00384	0.00003
13	-0.00128	-0.00002	-6.8	0.00214	0.00049	0.00344	0.00002
14	0.00124	-0.00003	5.2	-0.00172	0.00010	-0.00319	0.00002
15	-0.00521	-0.00002	5.3	-0.00660	0.00000	-0.00646	0.00000
16	-0.00530	-0.00143	6.5	-0.00661	0.00096	-0.00697	0.00078
17	0.00518	0.00118	7.5	0.00692	0.00103	0.00738	0.00080
18	0.00462	-0.00007	-12.4	0.00580	0.00030	0.00735	0.00021

The results of cases 5 & 6, the density variations, and cases 9-12, the clad and channel geometry variations, show less sensitivity than the enrichment and gadolinium concentration variations. There are several plots below that illustrate the effects of these significant perturbation cases. Figures 9-14 show the results of the enrichment variation cases. In Figure 9, the cases where the enrichment is varied by 1.5%, show the most variation in the hot eigenvalue, which increases as more modified fuel is introduced from cycle N to cycle N+2. The axial variation cases, where the average enrichment of the bundle is kept constant, show less variation in the hot eigenvalue and it does not change much from cycle to cycle.

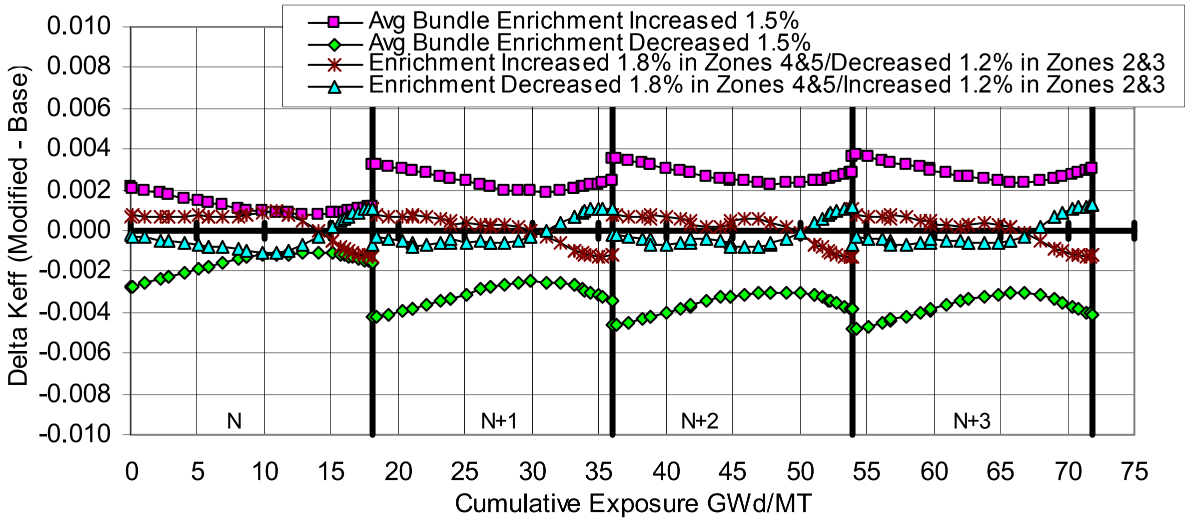


Figure 9 Hot Delta Keff for Enrichment Variation Cases Compared to Base Case

Figures 10 - 12 show the changes in the cold critical eigenvalues. Figure 10 shows that the distributed cold critical eigenvalues vary less in cycle N and then increase in cycles N+1 to N+3. Also, the cases where the enrichment is uniformly changed by 1.5%, show a constant trend in the deltas from cycle to cycle. In the axial variation cases there is an alternating trend from cycle to cycle.

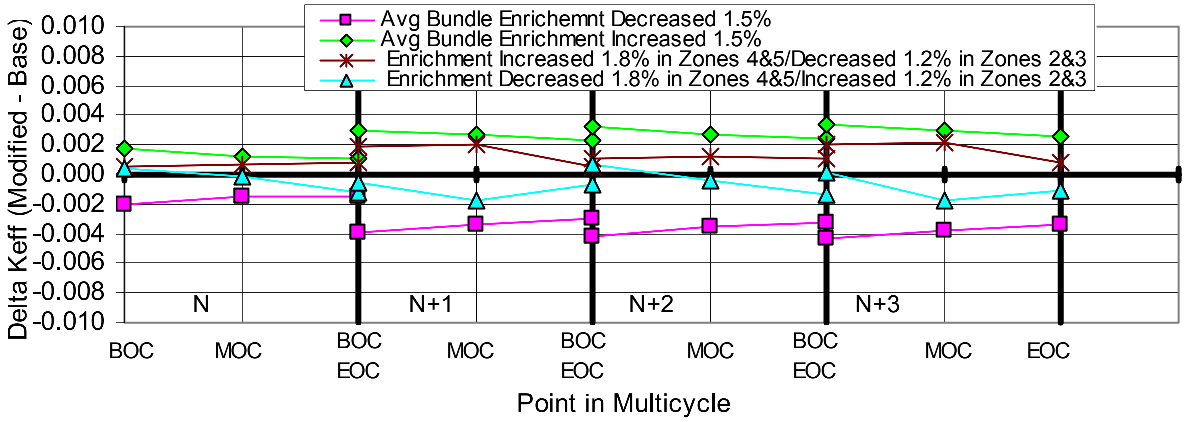


Figure 10 Delta Keff for Distributed Cold Critical Eigenvalues Compared to Base Case

Figure 11 shows the change in the local cold critical eigenvalues for the case where the bundle enrichment is increased by 1.5%. Since the delta is positive in this case, criticality is reached faster by the plotted delta keff. Figure 12 shows that there are very significant changes in the maximum difference between the distributed and local cold critical eigenvalues compared to the base case. These changes are much greater in the cases where the enrichment was axially varied while the average enrichment was kept constant. This also proves that even though the hot eigenvalue might not have much variation, there still might be existing problems with the cycle.

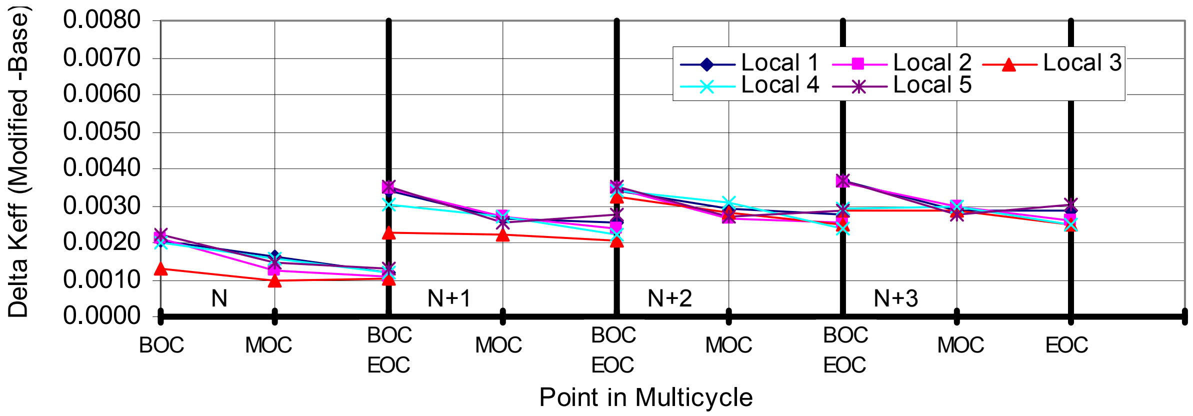


Figure 11 Delta Keff for Local Cold Critical Eigenvalues Compared to Base Case for Avg. Bundle Enrichment Increased 1.5% Case

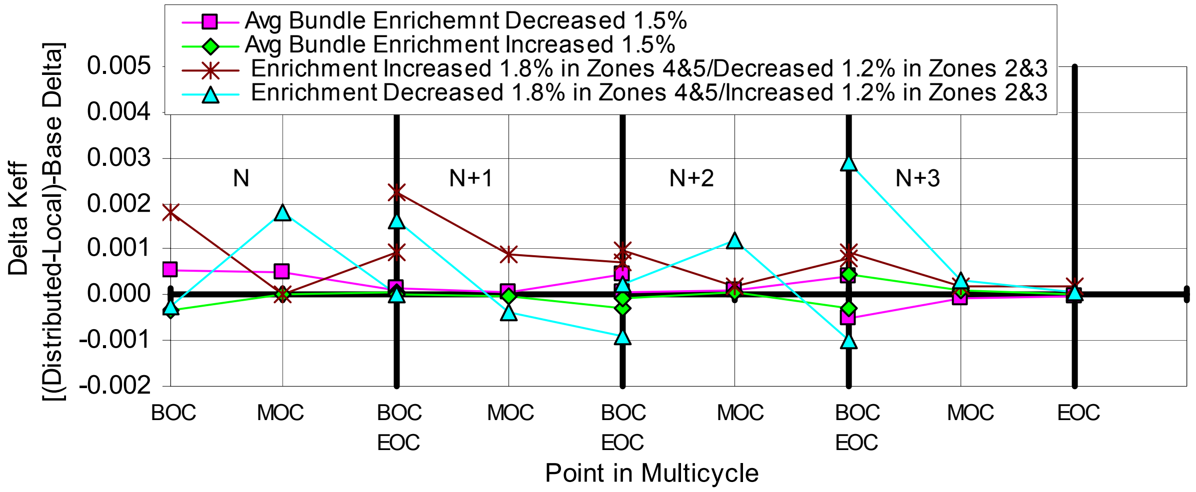


Figure 12 Maximum Delta Keff Between Distributed and Any Local Cold Critical Eigenvalue Compared to Base Case

Once again, Figure 13 shows that there is very almost no variation in the TIP measurements between the base case and the case where the enrichment is decreased 1.5%, even though, this case showed a significant change in the hot and cold eigenvalues.

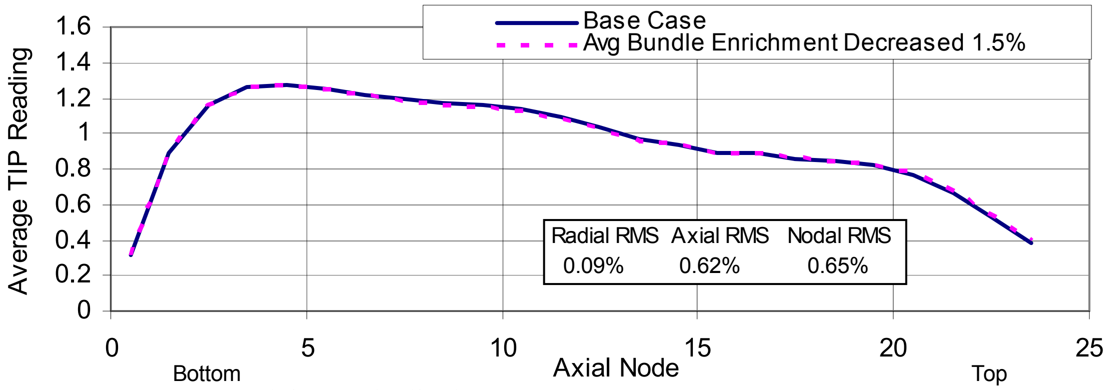


Figure 13 Average Axial TIP Distributions for BOC N+3

Figure 14 shows a recognizable difference in the calculated TIP values between the base case and one of the axially varied enrichment cases. This is an indication that the TIP comparisons are helpful when there is an axial variation in the core as opposed to a uniform variation in the core.

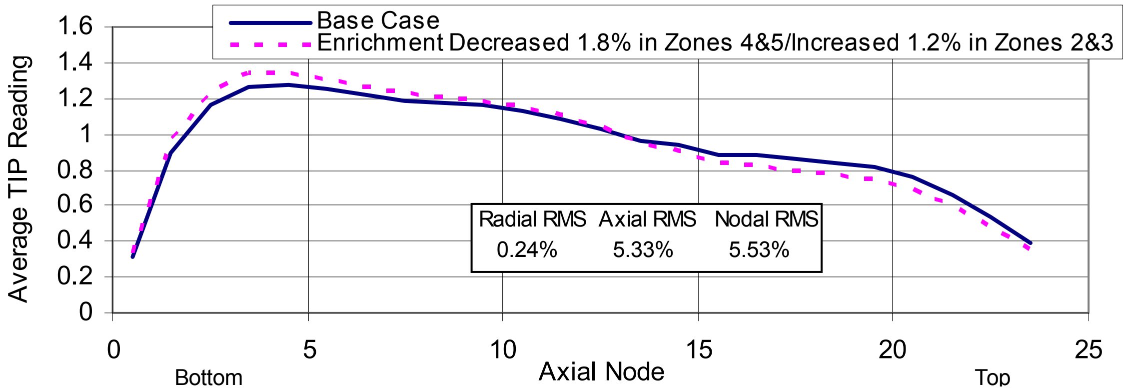


Figure 14 Average Axial TIP Distributions for BOC N+3

Figures 15-21 illustrate the results of the gadolinium concentration variation cases. From the summary table, it is evident that these perturbations have the most impact on the cycle parameters. In figure 15 it is shown that the gadolinium variation has no significant history effect. This can be seen by looking at the case where the gadolinium is varied only in one cycle, after which, the eigenvalue returns to that of the base case. Noticing that the variation from cycle to cycle is constant also recognizes the absence of history effect.

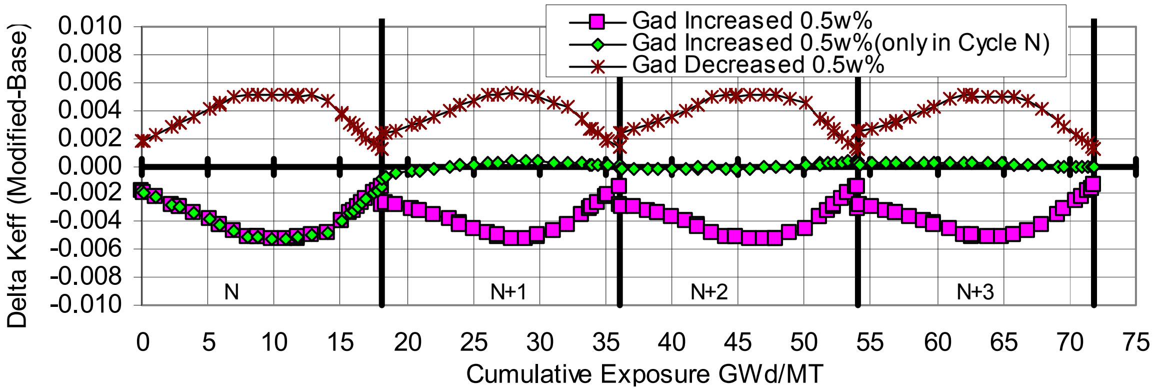


Figure 15 Hot Delta Keff for Gadolinium Concentration Variation Cases Compared to Base Case

Figure 16 shows the case where the gadolinium is varied axially while the bundle average gadolinium is kept constant. Here again, is the phenomenon where there is an alternating trend, and since the trends are not constant from cycle to cycle this axial variation has a history effect on the core.

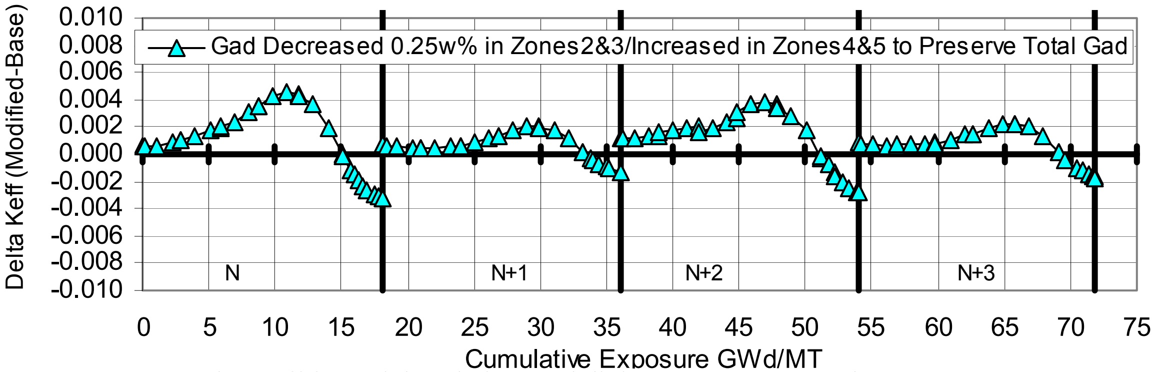


Figure 16 Hot Delta Keff for Axial Variation Gadolinium Case Compared to Base Case

Figures 17-19 show the effects of the gadolinium variations on the cold critical eigenvalues. In Figure 17, the largest changes in the distributed cold critical eigenvalues are seen in the cases where the gadolinium is changed by 0.5w% throughout the bundle.

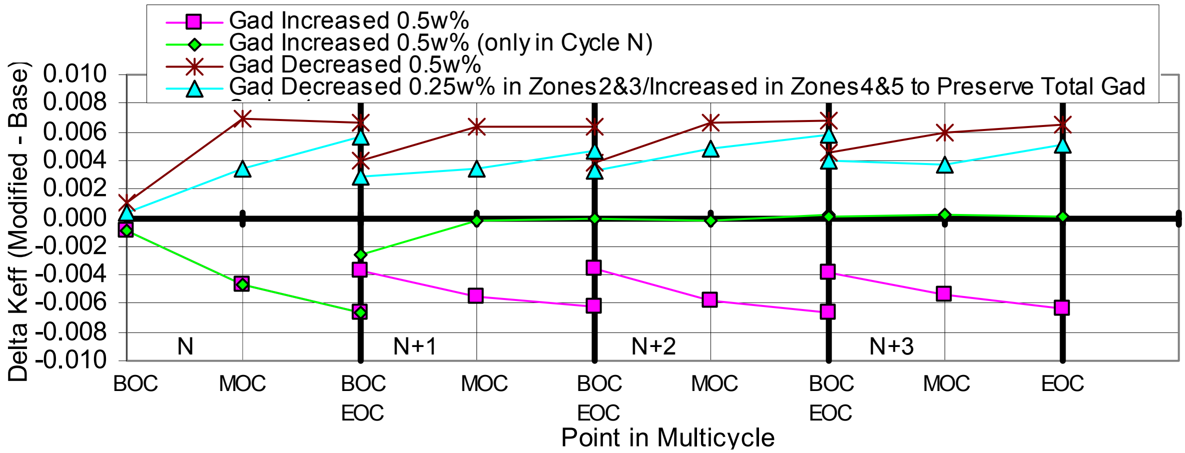


Figure 17 Delta Keff for Distributed Cold Critical Eigenvalues Compared to Base Case

Figure 18 shows the changes in the local cold critical eigenvalues for the case where the gadolinium is decreased by 0.5w% in each reload for each cycle. As the results show, these are very drastic changes that would have a big effect on the SDM for the cycles.

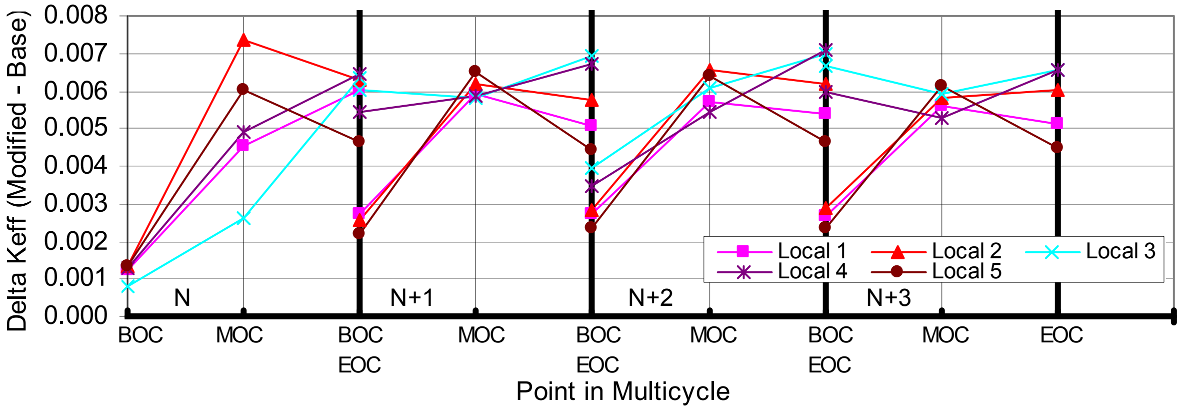


Figure 18 Delta Keff for Local Cold Critical Eigenvalues Compared to Base Case for Decreased Gadolinium Case

Figure 19 illustrates the change in the maximum delta between the local and distributed cold criticals compared to the base case. These are large changes, but there seems to be no trend in the cases. One recognizable aspect is that there is a slight history effect that can be seen cycle N+1 of the gadolinium decreased 0.5w% (only in Cycle N) case. This case did not show history effects previously when looking at other parameters like the hot eigenvalue.

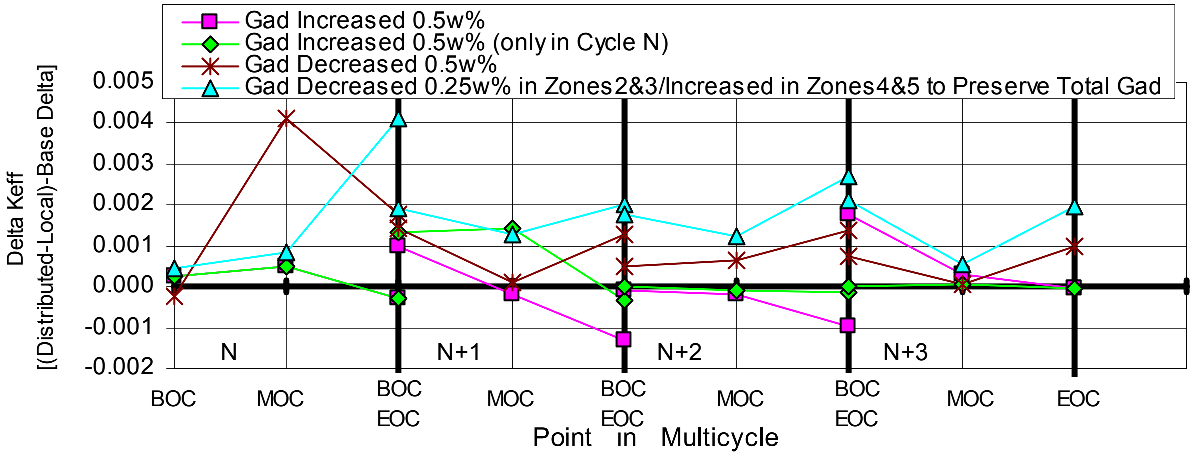


Figure 19 Maximum Delta Keff Between Distributed and Any Local Cold Critical Eigenvalue Compared to Base Case

Figure 20 again shows that there is no noticeable difference in the TIP comparisons for the case where the gadolinium is uniformly increased by 0.5w%. Even though there is a large effect on the eigenvalues and thermal margins, this is not noticeable in the TIP comparisons, since the perturbation was uniform throughout the core.

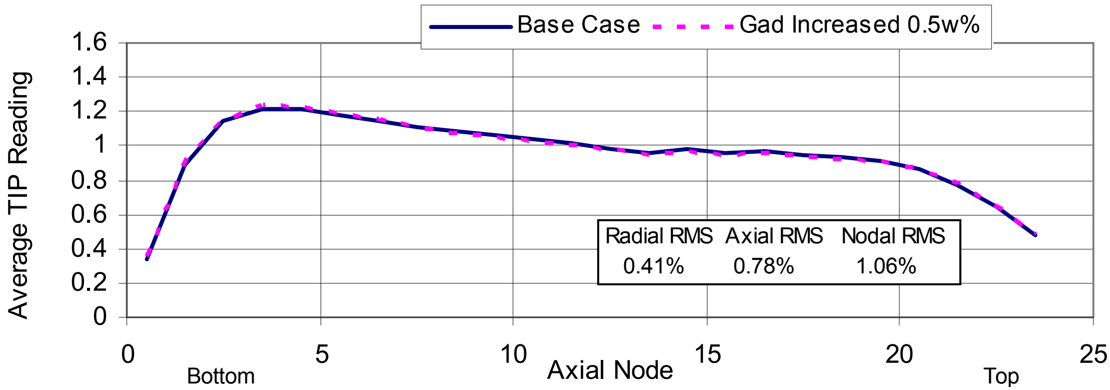


Figure 20 Average Axial TIP Distributions for Cycle N+2 at 9811 MWd/MT

Figure 21 shows the TIP comparisons for the case where the gadolinium was axially varied with the average bundle gadolinium concentration kept constant. Since this is an axial change, there is significant variation between the calculated TIP values.

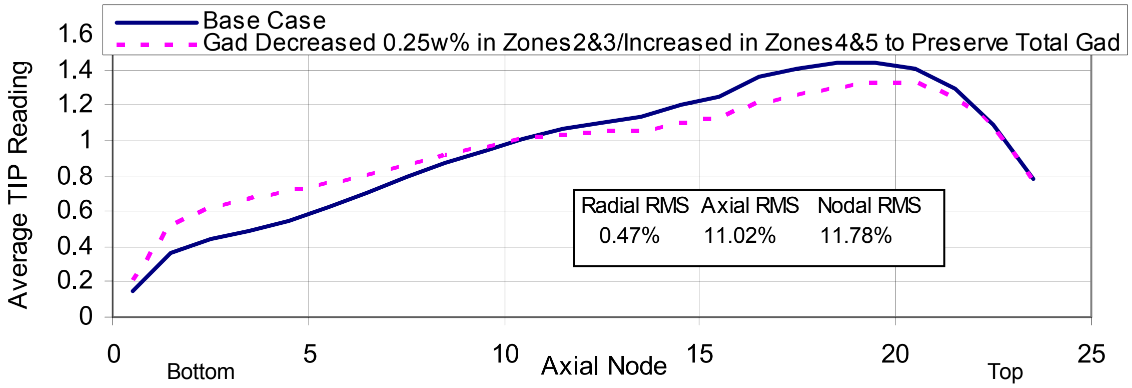


Figure 21 Average Axial TIP Distributions for EOC N

As shown in these results, there are fuel-manufacturing variations that can be ignored, while others that have to be recognized and accounted for.

5. Conclusion

This multicycle analysis contains valuable data that can be used in predictions and assessments of trends in BWR cores. The main realization in this study is that the uncertainties in plant measurement values and in fuel manufacturing parameters may have a significant effect on fuel cycle calculations. One has to recognize that no matter how robust the code is, the level of code accuracy becomes irrelevant if these parameters are not monitored and controlled. However, it also has to be recognized that this study contains extreme individual perturbations. Typically, plant measurement instruments and fuel manufacturing processes are both monitored in order to prevent such extreme scenarios.

There are many additional evaluations necessary to further aid the purpose of this study. There is the aspect of what happens when uncertainties are combined, there are other possible variations and phenomenon that occur in the core, and finally, there are certain methodologies incorporated into the codes that are separately characterized as methods uncertainties. With the continuation of these types of studies, the phenomenon that occur within the BWR core could be better understood, the codes could be tested and improved, and all the procedures and methods that lead up to the final fuel cycle designs in the industry could be refined and enhanced.

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2) A. A. KARVE, B. R. MOORE, J. J. TUSAR, and W. E. CORRELL, “Methods Comparisons for Hot Eigenvalue and TIP Predictions”, Trans. Am. Nucl. Soc., 87, 409 (2002).
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