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Utilization of the EPRI Depletion Benchmarks for Burnup Credit Validation

2012 TECHNICAL REPORT

Utilization of the EPRI Depletion Benchmarks for Burnup Credit Validation

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1025203
Final Report, April 2012

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Acknowledgments

The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

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This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Utilization of the EPRI Depletion Benchmarks for Burnup Credit Validation.
EPRI, Palo Alto, CA: 2012.
1025203.

Abstract

Pressurized water reactor (PWR) burnup credit validation is demonstrated using the benchmarks for quantifying fuel reactivity decrements, published as *Benchmarks for Quantifying Fuel Reactivity Depletion Uncertainty*, Electric Power Research Institute (EPRI) report 1022909. This demonstration uses the depletion module TRITON (Transport Rigor Implemented with Time-Dependent Operation for Neutronic Depletion) available in the SCALE 6.1 (Standardized Computer Analyses for Licensing Evaluations) code system, followed by criticality calculations using KENO-V.a and MCNP (Monte Carlo N-Particle Transport Code System).

The difference between predicted depletion reactivity and benchmark's depletion reactivity is a bias for the criticality calculations. The uncertainty in the benchmarks is the depletion reactivity uncertainty. This depletion bias and uncertainty is used with the bias and uncertainty from fresh UO_2 critical experiments to determine the criticality safety limits on the neutron multiplication factor, k_{eff}.

The analysis shows that SCALE 6.1 with the ENDF/B-VII 238-group cross-section library supports the use of a depletion bias of only 0.0015 in Δk at peak reactivity after discharge from the core. This peak reactivity occurs after 100 hours of cooling. If credit is taken for more cooling, the bias should be increased to 0.0025. Reliance on the ENDF/B-V cross-section library produces larger disagreement with the benchmarks. Using MCNP for the criticality calculations rather than KENO-V.a produces essentially the same results if the same ENDF/B cross-section library is used.

The analysis covers numerous combinations of depletion and criticality options. Since prediction of the Δk of depletion is within a few tenths of a percent in k, it is possible to discern the impact of small modeling changes on the accuracy of the predictions of the changes in k. The uncertainty associated with the chemical assays is too large to allow discriminating among many methods. In all cases, the historical uncertainty of 5% of the Δk of depletion is shown to be conservative for fuel with burnup greater than 30 gigawatt-days per metric ton of uranium (GWD/MTU).

Keywords
Burnup credit
Depletion uncertainty
Nuclear criticality analysis
Reactivity depletion
Spent fuel cask
Spent fuel pool

Executive Summary

An engineering judgment published in 1998 in a Nuclear Regulatory Commission (NRC) memo written by Larry Kopp [7] has been used for the determination of the uncertainty in the change in fuel assembly reactivity with depletion for criticality analyses of spent fuel pools at light water reactors (LWRs). The NRC has recently limited the use of this historical engineering judgment and will likely require that criticality analysis be based on well-documented data. The Electric Power Research Institute (EPRI) reactivity depletion benchmarks provide data, based on measurements, to allow determination of bias and uncertainty in the change of the neutron multiplication factor, k, with respect to burnup. These benchmarks can be used for criticality calculations for spent fuel pools as well as spent fuel casks.

The reactivity depletion benchmarks are to be analyzed using the criticality tools that will be used for the final criticality analysis of the spent fuel pool or cask. This report shows the impact of the new benchmarks on criticality by using the TRITON (Transport Rigor Implemented with Time-Dependent Operation for Neutronic Depletion) sequence of the SCALE 6.1 (Standardized Computer Analyses for Licensing Evaluations) code system followed by KENO-V.a. Two cross-section libraries are used, the 238-group ENDF/B-VII library and the 44-group ENDF/B-V library.

The benchmarks consist of 11 conditions at six different burnups and three different cooling times. (Cooling for 100 hours maximizes k so the true "zero" cooling-time benchmarks are ignored.) The total number of cases is 198 burned cases and 6 fresh fuel cases. These cases are analyzed, and the Δk's of depletion are determined. These Δk's are then compared to the values inferred from the reactor measurements, as reported in the benchmarks. The predicted depletion reactivity (Calculated Decrement) minus the benchmark's depletion reactivity (EPRI Benchmark Decrement) is the bias of the set of criticality tools being evaluated. Table ES-1, in which a negative bias is conservative, illustrates this process.

Table ES-1
Sample Calculation of Biases for Case 3 and 100-Hour Cooling

Burnup GWD/MTU	Calculated k	Monte Carlo σ	Calculated Decrement	EPRI Benchmark Decrement	Bias Calc – EPRI Decrement
0	1.4712	0.0001			
10	1.3484	0.0002	0.1228	0.1223	0.0005
20	1.2553	0.0002	0.2159	0.2157	0.0002
30	1.1721	0.0001	0.2991	0.2990	0.0001
40	1.0958	0.0001	0.3754	0.3758	-0.0004
50	1.0267	0.0001	0.4445	0.4445	0.0000
60	0.9688	0.0001	0.5024	0.5029	-0.0005

The analysis of the benchmarks with the ENDF/B-VII 238-group data shows that there is excellent agreement with the benchmarks: the biases are very small. Table ES-2 shows the biases for 100 hours of cooling. The slightly higher positive biases shown for 10, 20, and 30 gigawatt-days per metric ton of uranium (GWD/MTU) burnup for Cases 6 and 7 can be ignored, assuming traditional criticality modeling where no credit for the integral fuel burnable absorbers (IFBAs) is taken. The 5- and 15-year cooling benchmarks show similar results, but with slightly higher biases.

Table ES-2
Bias for the Reactivity Decrement with 100-Hour Cooling Using SCALE 6.1 and the ENDF/B-VII 238-Group Cross-Section Library

		Bias (Calculated Reactivity Decrement – Measured Reactivity Decrement) For 100-Hour Cooling					
		Burnup (GWD/MTU)					
Case	**Lattice Description**	**10**	**20**	**30**	**40**	**50**	**60**
1	3.25% enrichment depletion	-0.0004	-0.0008	-0.0010	-0.0015	-0.0014	-0.0022
2	5.00% enrichment depletion	0.0004	0.0005	0.0003	0.0006	0.0005	0.0008
3	4.25% enrichment depletion	0.0005	0.0002	0.0001	-0.0004	0.0000	-0.0005
4	off-nominal pin depletion	0.0002	-0.0002	-0.0004	-0.0010	-0.0011	-0.0016
5	20 WABA depletion	0.0005	0.0009	0.0007	0.0002	-0.0002	0.0001
6	104 IFBA depletion	0.0016	0.0010	0.0008	-0.0002	-0.0008	-0.0014
7	104 IFBA, 20 WABA depletion	0.0015	0.0016	0.0010	0.0002	-0.0001	-0.0011
8	high boron depletion = 1500 ppm	0.0003	0.0004	0.0001	-0.0001	-0.0001	-0.0004
9	branch to hot rack = 338.7K	-0.0003	-0.0002	-0.0005	-0.0004	-0.0004	-0.0004
10	branch to rack boron = 1500 ppm	-0.0005	-0.0010	-0.0016	-0.0019	-0.0023	-0.0026
11	high power density depletion	0.0001	0.0002	-0.0002	-0.0002	-0.0003	-0.0003

Based on the results presented in Table ES-2, a conservative bias for the criticality analysis is selected. Negative biases, as defined here, are conservative; so the largest positive bias is used. A conservative bias of 0.0015 is determined by reviewing Table ES-2 and recognizing that a high enrichment may accompany other depletion parameter effects. The uncertainty in the bias is the uncertainty in the benchmarks, which is reported as 0.00643 in the benchmark report [1]. With cooling, the bias should be increased to 0.0025. The bias and uncertainty for the 100-hour cooling is compared to the historical approach in Table ES-3. It can be seen that the uncertainty that is obtained by applying the guidance in the Kopp memo and the uncertainty that is derived from the EPRI benchmarks have similar values around a burnup of ~15 GWd/MTU. Table 3 shows that as burnup increases to typical discharge values, the Kopp memo becomes very conservative.

Table ES-3
Comparison Between the EPRI Benchmark Results and the Kopp Memo for Case 3 and 100-Hour Cooling

Burnup (GWD/MTU)	Kopp Uncertainty (Delta k)	EPRI Uncertainty plus Bias (Delta k)
10	0.0061	0.0079
20	0.0108	0.0079
30	0.0150	0.0079
40	0.0188	0.0079
50	0.0222	0.0079
60	0.0251	0.0079

Analysis of the depletion reactivity benchmarks reveals some benefits to this approach for burnup credit validation. These benefits are:

- The depletion modeling for the benchmarks closely matches the depletion modeling needed in the criticality analysis. The impact of modeling assumptions that are used in the final criticality analysis is directly seen in the results of the benchmark analysis. Validation via chemical assays does not have this benefit. Modeling of chemical assays emphasizes modeling a single fuel pin rather than an assembly. Matching the depletion benchmarks results in finding modeling improvements that would have been missed in chemical assay analysis.

- The analysis of the reactivity decrement benchmarks with differing cross-section libraries shows that fairly large differences in reactivity can be due to fairly small differences in isotopic content. The uncertainties in the chemical assays produce

differences in the depletion reactivity of around 1.5%–2.5% in k. The agreement between the predictions and the benchmarks of the depletion reactivity is 10 times closer (0.15%) than the uncertainty effect on k for the chemical assays. The uncertainty in isotopic content found in the chemical assays would make it difficult to ascertain a benefit from one cross-section library over another. With the reactivity decrement benchmarks, ENDF/B-VII is clearly preferred.

- The analysis of the depletion reactivity benchmarks is simple. This simplicity means that it is likely to be performed by the same analyst that does the criticality analysis, as opposed to a specialist. The results are simple to understand for both the analyst and the reviewer. Complex statistical analysis is not needed, and appropriate margins can easily be determined. The chemical assay analyses may be important for some specific purposes, but they do not lend themselves well for direct use in engineering applications.

Table of Contents

List of Figures

List of Tables

Section 1: Introduction

In 2011 EPRI issued the report entitled "Benchmarks for Quantifying Fuel Reactivity Depletion Uncertainty" [1], which provides a set of benchmarks that are to be used for validation of burnup credit.

The present report provides an example analysis of the benchmarks and discusses the application of the benchmarks in burnup credit. The analyses provided in this report use the TRITON (Transport Rigor Implemented with Time-Dependent Operation for Neutronic Depletion) module of SCALE 6.1 (Standardized Computer Analyses for Licensing Evaluations) [2] for the depletion analysis and KENO-V.a [2] and MCNP (Monte Carlo N-Particle Transport Code System) [3] for the determination of the neutron multiplication factor, k. Both ENDF/B-V and ENDF/B-VII libraries are used.

Using depletion reactivity benchmarks for validation of burnup credit is new. Past approaches have used chemical assays, complicated analyses of power reactors, and engineering judgment. Section 2 of this report puts the use of the depletion reactivity benchmarks in relation to past practices as well as ANSI/ANS standards.

The benchmarks needed for this report come from Reference 1. However, to help the reader use this report, the benchmark report [1] is summarized and the benchmark reactivities are presented in Section 3. For convenience, the details to allow analysis of the benchmarks are reproduced from Reference [1] in Appendix B.

Section 4 discusses the modeling of the benchmarks. The modeling requires a depletion analysis followed by a criticality calculation using the isotopic content from the depletion analysis. There are a number of modeling choices that can be made when using SCALE, and Section 4 provides justification for the modeling choices made. Sample input decks are found in Appendix A along with nomenclature rules to aid in using the electronic input decks that are available in an executable file accompanying this report.

The results of the analysis of the benchmarks with the 238-group ENDF/B-VII cross-section library are presented in Section 5. The next section, Section 6, discusses how to utilize the calculated biases in a criticality analysis. This section makes recommendations on the appropriate bias and uncertainty for analysis with the 238-group ENDF/B-VII library.

Since ENDF/B-V is still heavily used and is the licensing basis for most spent fuel pools and casks, Section 7 repeats the analysis using the 44-group ENDF/B-V cross-section library. SCALE 6.1 has two options for the treatment of the resolved resonances, NITAWL and CENTRM. The results of the delta k of depletion strongly depend on which resonance treatment is used. Since Sections 5 and 7 present similar results, but for different methods or cross-section libraries, the results are color coded; red for ENDF/B-VII, green for ENDF/B-V with CENTRM, and orange for ENDF/B-V and NITAWL.

Historically, criticality analysis is often done using depletion codes that do not have the same origin as the Monte Carlo criticality codes. This means the cross-section libraries often differ between the steps. Section 8 of this report looks at combining diverse cross sections and computer codes. This section includes analysis of some of the benchmarks using MCNP for the Monte Carlo criticality analysis.

Finally, the report ends with Section 9 which provides the conclusions from the previous sections as well as some additional observations.

Section 2: Background

Criticality safety analyses are expected to be closely tied to measured data. ANSI/ANS-8.17 [4] requires that the system calculated multiplication factor, k_p, must be less than the multiplication factor calculated for similar criticality experiments, k_c, after reducing the latter (1) for uncertainties in the calculated k of the critical experiments, Δk_c, (2) for the system modeling uncertainties, Δk_p and (3) by a safety margin, Δk_m. The equation in ANSI/ANS-8.17 is:

$$k_p \leq k_c - \Delta k_p - \Delta k_c - \Delta k_m \qquad \textbf{Equation 2-1}$$

For burnup credit, a similar concept is applied, but more terms are required since critical experiments with burned fuel are lacking. Historically, two different approaches have been taken for burnup credit criticality safety. The first approach, which has been used for transport casks, uses chemical assays for validation of the isotopic content and then limits the isotopes used to those where there is some validation of the reactivity of the isotopes. For example, actinide-only burnup credit validated the isotopic content with chemical assays and the reactivity worth with MOX critical experiments. When fission products are added to the isotopes used in this style of burnup credit, the reactivity validation becomes more complex. Recent efforts have included the use of the limited fission–product-containing critical experiments augmented by sensitivity analysis based on the uncertainty in the basic cross-section library [5].

The appropriate limiting k_p for the approach, depending on chemical assays, is documented in the Burnup Credit Standard, ANSI/ANS-8.27 [6]. Equation 2-1 from the burnup credit standard becomes:

$$k_p + \Delta k_p + \Delta k_i + \Delta k_b \leq k_c - \Delta k_c - \Delta k_x - \Delta k_m \qquad \textbf{Equation 2-2}$$

where:

k_p is the calculated multiplication factor of the model for the system being evaluated.

Δk_p is an allowance for the uncertainties in the determination of k_p.

Δk_i is an allowance for the bias and uncertainty in k_p due to depletion uncertainty in the calculated nuclide compositions. This term is computed using the chemical assay data.

Δk_b is an allowance for uncertainty in k_p due to uncertainty in the assigned burnup value.

k_c is the multiplication factor that results from the calculation of the benchmark criticality experiments.

Δk_c is an allowance for uncertainty in calculation of k_c.

Δk_x is an allowance for the bias and uncertainty for the reactivity worth of isotopes not adequately accounted for in the benchmark criticality experiments used for k_c.

Δk_m is a margin for unknown uncertainties.

The chemical assays are used to find Δk_i and the critical experiments with fission products and the cross-section uncertainties are used to find Δk_x.

In the second approach to burnup credit, the terms Δk_i and Δk_x are replaced by Δk_d. The equation becomes:

$$k_p + \Delta k_p + \Delta k_b \leq k_c - \Delta k_c - \Delta k_d - \Delta k_m \qquad \textbf{Equation 2-3}$$

where all the terms are the same as before except for the addition of Δk_d. Δk_d is the bias and uncertainty in the reactivity change from the initial fresh fuel conditions to a depleted condition. In this formulation, it is assumed that the ability to predict the change in reactivity with depletion is separable from the ability to predict the initial conditions (k_c). In order to prove this, separability analysis of a range of conditions is required. In the past, non-conservative burnup credit was taken due to assuming the change in reactivity due to burnup was the same in borated and non-borated systems. The use of Δk_d does not assume constant worth of depletion over differing systems but it does assume that the deviation in computer code performance is constant across different systems. Therefore care should be taken to show the computer codes system performance over a range of conditions is bounded by the selected Δk_d. In particular, it is important to assure that the neutron energy spectrum for the critical system is bounded by the neutron energy spectrum in benchmarks used for the determination of Δk_d.

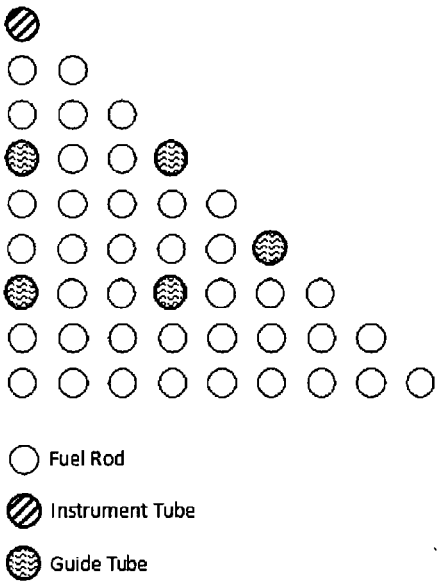
Historically, spent fuel pool criticality analyses used Equation 2-3 (the Δk_d approach) where the Δk_d was approximated by an uncertainty (no bias) of 5% of the delta k of depletion. The technical basis for this approximation presented in the Kopp memo [7] was never documented, but was loosely based on the performance of fuel management codes compared to power reactor conditions. The 5% of the delta k of depletion was viewed as conservative enough to cover the differences between fuel management tools and criticality analysis tools. There was no historical requirement to check this assumption. It was always possible for the analyst to compare the results predicted by fuel management tools to those predicted by criticality codes, but it was unclear which prediction was correct without a clear connection to measured values. The EPRI benchmarks fix this problem by creating a set of benchmarks based on measured evidence that can be calculated by criticality tools. This report shows how to use those benchmarks to determine Δk_d.

Section 3: Summary Review of the EPRI Depletion Benchmarks

The EPRI depletion benchmarks were developed using a large set of power distribution measurements to ascertain reactivity biases. The predicted reactivity of the fuel assemblies was adjusted to find the best match between the predicted and measured power distribution. Once the reactivity adjustment was known, the benchmarks were created with the biased lattice physics code. The fuel management tools used were CASMO-4 and -5 [8] and SIMULATE-3 [9], but other fuel management codes would produce the same benchmarks. However, the bias needed to produce the benchmarks would depend on the fuel management codes used to match the power distribution measurements. This analysis utilizes the benchmarks as "truth" and the uncertainty reported in Reference 1 as the uncertainty we have in our knowledge of "truth." In this approach any difference between the predictions and the benchmarks in the change in k with depletion is a bias and the benchmark uncertainty is the uncertainty in the calculated depletion reactivity. For more details, refer to Reference 1.

The benchmarks are a collection of 11 different conditions for the determination of the delta k of depletion for six different burnups (10, 20, 30, 40, 50, and 60 GWD/MTU). These 66 conditions are then decayed for 100 hours, 5 years, and 15 years. Thus, there are 11*6*3=198 benchmarks used for comparison with calculated delta k's.

The benchmarks are a 2D infinite lattice of 17X17 PWR fuel assemblies with a typical in-core assembly pitch. Figure 3-1 shows the benchmark geometry and the nominal parameters. The first three cases provide depletions corresponding to three different enrichments: 3.25, 5.0 and 4.25 wt% U-235. The 4.25 wt% U-235 enrichment is then used as the base case for the following cases. The next five cases each perturb a single parameter in the depletion: smaller pin diameter, 20 WABA rods, 104 IFBA rods, 20 WABA rods with 104 IFBA rods, and higher soluble boron. This is followed by two cases that use the depletions from Case #3 (4.25 wt% U-235), but perturb only the final conditions (rack). Finally, the last case provides depletions using 1.5 times the nominal specific power. Tables 3-1, 3-2 and 3-3 provide a short description of the 11 cases and the delta k of depletion for all the cases for the three cooling times. To ease the analysis of the benchmarks, the Appendix from Reference 1, which provides all the benchmark specifications, is reproduced in this report as Appendix B.



Physical Description

Number of pins along side	17
Pin pitch	1.2598 cm
Inter-assembly spacing	21.5036 cm
Fuel pellet OR	0.4096 cm
Clad IR	0.4180 cm
Clad OR	0.4750 cm
Guide/instrument tube IR	0.5610 cm
Guide/instrument tube OR	0.6120 cm

Structural Material Description

Material (Zr-4)Density	6.55 (g/cm3)
Temp., unheated	580K
Temp., heated	$0.12*T_{fuel}+0.88*T_{coolant}$
Nuclide	**Number Density**
Zr-4	4.32444E+22

Coolant Description, Depletion (Nominal)

Boron Concentration	900 ppm
Temperature	580 K
Nuclide	**Number Density**
H	4.75756E+22
O	2.37894E+22
B	3.56773E+19

Coolant Description, Cold

Boron Concentration	0 ppm
Temperature	293 K
Nuclide	**Number Density**
H	6.67431E+22
O	3.33738E+22

Figure 3-1
Description of the Nominal Assembly for the EPRI Benchmarks [1]

Table 3-1
Measured Reactivity Decrement with 100-Hour Cooling [1]

		Reactivity Decrement After 100-Hour Cooling (delta k_{inf})					
		Burnup (GWD/MTU)					
Case	**Lattice Description**	**10**	**20**	**30**	**40**	**50**	**60**
1	3.25% enrichment depletion	0.1329	0.2339	0.3211	0.3956	0.4554	0.5002
2	5.00% enrichment depletion	0.1146	0.2021	0.2806	0.3545	0.4238	0.4867
3	4.25% enrichment depletion	0.1223	0.2157	0.2990	0.3758	0.4445	0.5029
4	off-nominal pin depletion	0.1207	0.2176	0.3075	0.3931	0.4715	0.5385
5	20 WABA depletion	0.2045	0.2335	0.2998	0.3717	0.4372	0.4932
6	104 IFBA depletion	0.1736	0.2215	0.2968	0.3726	0.4418	0.5009
7	104 IFBA, 20 WABA depletion	0.2524	0.2418	0.2981	0.3686	0.4343	0.4910
8	high boron depletion = 1500 ppm	0.1216	0.2129	0.2932	0.3662	0.4310	0.4860
9	branch to hot rack = 338.7K	0.1237	0.2171	0.2998	0.3756	0.4432	0.5005
10	branch to rack boron = 1500 ppm	0.0967	0.1784	0.2530	0.3217	0.3826	0.4335
11	high power density depletion	0.1235	0.2149	0.2945	0.3664	0.4299	0.4838

Table 3-2
Measured Reactivity Decrement with 5-Year Cooling [1]

		Reactivity Decrement After 5-Year Cooling (delta k_{inf})					
		Burnup (GWD/MTU)					
Case	**Lattice Description**	**10**	**20**	**30**	**40**	**50**	**60**
1	3.25% enrichment depletion	0.1370	0.2471	0.3447	0.4284	0.4951	0.5445
2	5.00% enrichment depletion	0.1163	0.2086	0.2943	0.3761	0.4529	0.5222
3	4.25% enrichment depletion	0.1247	0.2245	0.3164	0.4018	0.4781	0.5425
4	off-nominal pin depletion	0.1232	0.2263	0.3250	0.4197	0.5063	0.5797
5	20 WABA depletion	0.2069	0.2424	0.3171	0.3974	0.4703	0.5321
6	104 IFBA depletion	0.1760	0.2304	0.3140	0.3984	0.4751	0.5403
7	104 IFBA, 20 WABA depletion	0.2547	0.2507	0.3154	0.3941	0.4672	0.5296
8	high boron depletion = 1500 ppm	0.1241	0.2218	0.3106	0.3922	0.4645	0.5254
9	branch to hot rack = 338.7K	0.1261	0.2257	0.3168	0.4009	0.4759	0.5390
10	branch to rack boron = 1500 ppm	0.0986	0.1858	0.2675	0.3430	0.4096	0.4647
11	high power density depletion	0.1268	0.2245	0.3125	0.3928	0.4636	0.5232

Table 3-3
Measured Reactivity Decrement with 15-Year Cooling [1]

		Reactivity Decrement After 15-Year Cooling (delta k_{inf})					
		Burnup (GWD/MTU)					
Case	**Lattice Description**	**10**	**20**	**30**	**40**	**50**	**60**
1	3.25% enrichment depletion	0.1422	0.2655	0.3768	0.4720	0.5471	0.6021
2	5.00% enrichment depletion	0.1184	0.2184	0.3140	0.4058	0.4918	0.5690
3	4.25% enrichment depletion	0.1277	0.2372	0.3405	0.4369	0.5226	0.5942
4	off-nominal pin depletion	0.1260	0.2385	0.3488	0.4551	0.5516	0.6325
5	20 WABA depletion	0.2102	0.2555	0.3415	0.4325	0.5145	0.5833
6	104 IFBA depletion	0.1792	0.2432	0.3382	0.4334	0.5194	0.5917
7	104 IFBA, 20 WABA depletion	0.2581	0.2639	0.3398	0.4291	0.5111	0.5806
8	high boron depletion = 1500 ppm	0.1273	0.2348	0.3351	0.4276	0.5092	0.5773
9	branch to hot rack = 338.7K	0.1291	0.2384	0.3408	0.4357	0.5198	0.5900
10	branch to rack boron = 1500 ppm	0.1014	0.1971	0.2885	0.3729	0.4468	0.5074
11	high power density depletion	0.1300	0.2377	0.3373	0.4284	0.5084	0.5752

The only item not mentioned yet is the uncertainty in the benchmarks. Reference [1] goes extensively into the determination of the uncertainty. In the end, the uncertainty is shown to be dependent on the specific power. Only two uncertainties are reported: 0.00576 for 38.1 W/gm heavy metal and 0.00643 for 57.2 W/gm heavy metal. The criticality applicant should use the uncertainty from the specific power that bounds the average operation of the fuel. For most plants, the use of 0.00643 for the uncertainty is required. Since the difference in uncertainties is only 0.00067 in k, this is not a significant penalty. **For this report, 0.00643 is used for the uncertainty in the benchmarks.**

Section 4: SCALE 6.1 Modeling of the Benchmarks

SCALE 6.1 [2] is used for the analysis of the benchmarks. SCALE contains modules for numerous applications. For this work, the TRITON module is used for the determination of the isotopic content with depletion, and the CSAS5 module is used for the calculation of the neutron multiplication factor, k, for the benchmark using the TRITON-produced atom densities.

The TRITON module calls several computer codes to do its depletion. It starts with a couple of computer codes for the resonance treatment of the cross sections. BONAMI adjusts the cross sections for the resonance self-shielding in the unresolved energy range. NITAWL or CENTRM adjusts the cross sections of the resonance self-shielding in the resolved resonance energy range. NITAWL does not function with the current ENDF/B cross-section formatting so it only works with ENDF/B-V. Once the cross sections are corrected for resonance self-shielding they need to be collapsed to one-group cross sections for the depletion. The flux calculation to collapse the cross sections can be done in 1D by XSDRNPM, 2D by NEWT or KENO, and 3D by KENO. The benchmarks are 2D infinite lattices so the flux calculations will be done in NEWT or KENO. With the collapsed cross sections, TRITON calls ORIGEN for the actual depletion.

The CSAS5 module which performs the calculation of k also calls several computer codes. Just like TRITON, CSAS5 needs to correct the cross sections for resonance self-shielding. It calls the same BONAMI and NITAWL or CENTRM codes for this. With the corrected cross sections it then calls KENO-V.a for the Monte Carlo determination of k. (SCALE has two versions of KENO, KENO-V.a and KENO-VI; for this work only KENO-V.a is used.)

The SCALE analysis can be done with a number of different cross-section libraries. This report will use the most current ENDF/B-VII 238-group library for the reference calculations, but will also do analysis with the ENDF/B-V 44-group library since it has been used so heavily in the past.

In depletion thousands of isotopes are created. ORIGEN follows 2226 isotopes. Normally only a fraction of those isotopes use cross sections that are updated using problem dependent information. This analysis uses the maximum number of isotopes permitted for updating: 388 isotopes with the ENDF/B-VII libraries. This is set by the input parameter option "addnux=4" in the TRITON

input. (See the SCALE manual [2] for list of isotopes associated with addnux=4.)

The selection of the full set of isotopes has a small impact on the computer run time and due to useful files created by SCALE, the engineering time from dealing with this large set is negligible. SCALE creates isotopic output files called "StdCmpMix00XXX" which has all the isotopes and atom densities in the form needed for future SCALE calculations. XXX is the material number in the depletion analysis. In the depletion analysis for this work the fuel material number is 10 so the file name is"StdCmpMix00010." When burnable absorbers are used, additional files (e.g., "StdCmpMix00050" and "StdCmpMix00060") are saved.

Commercial fuel management codes follow the depletion of each pin in the lattice cell representation. This is needed to accurately predict the pin power. For criticality analysis, small variations in pin burnup are not significant, so the SCALE model used in this work depletes (and adjusts for resonance self-shielding) all the fuel pins using the average flux and composition of the pins. An exception to this was taken for pins with boron coatings, or Integral Fuel Burnable Absorbers (IFBA) pins. For those cases the averaging of the fuel pins was divided into two sets, pins with and pins without boron coating. Wet Annular Burnable Absorbers (WABAs) are treated as though all of the absorber fingers see the same flux and there is no separation of fuel pins close to water holes or WABA pins for depletion with WABAs present.

SCALE 6.1 TRITON has no branching capability, unlike most fuel management lattice tools. For example, the 60 GWD/MTU case does not generate all the lower burnups. Most fuel management tools allow collection of data for all the depletion steps along the way. Unfortunately, separate cases have to be run for 10, 20, 30, 40, 50 and 60 GWD/MTU rather than one 60 GWD/MTU case. Further, cooling time branches are not straightforward. The input decks for this work restart with a near-zero time step to allow additional cooling. This restart uses the "StdCmpMix" output file. The cooling time calculations in SCALE use all the 2226 isotopes in ORIGEN but a restart using the "StdCmpMix" output file is limited to 388 isotopes. The approach taken in this work is to decay for 100 hours before the cooling time restarts. Since most of the missing isotopes between the 2226 and 388 sets have short half-lives the restart approach is successful. This was confirmed by comparison between cooling time restarts for 5 and 15 years cooling and SCALE runs using the ORIGEN cooling. Note that if the 5- and 10-minute cooling times are of interest, this approach does not work since the missing isotopes are important in this time range. One could use this restart approach for the burnup steps, but the loss of the missing isotopes would be a concern. No attempt to use this approach was made. It is expected that these problems will be fixed with the next release of SCALE.

TRITON depletion isotopic output can be retrieved by the "StdCmpMix" output files or by use of the OPUS module that can be called by TRITON. If a limited number of isotopes are of interest and the selected isotopes do not match the

"addnux" options, it may be easier to use "OPUS" output. The depletion decks have OPUS input for a set of isotopes of interest from earlier work. The "OPUS" output was not used for the final work, but the OPUS input is maintained to allow easy transition if a particular set is desired in the future.

The depletion analysis is sensitive to the time steps taken. Small time steps are needed at the beginning of the first cycle (.15, .35, .5, .5, .5, 1, 1, 1, and 1 GWd/T) to correctly get the spectrum effect of Xe and Sm. Larger time steps are appropriate after some burnup. After 6 GWD/MTU, 2-GWD/MTU time steps were found to be adequate. The size of the time steps was varied until no significant change in results was seen. The final time steps may be in excess of what is needed, given that after convergence was found, no attempt was made to find fewer time steps that would still get the same results.

The flux calculations for the depletion can be done with either NEWT which is a 2D transport code or KENO which is a Monte Carlo code. The initial assumption was that NEWT would be much faster. This assumption was based on ENDF/B-V analysis with the 44-group library. The run time for a transport code is proportional to the number of energy groups. ENDF/B-VII has only one group wise library and it uses 238 groups. This means the NEWT analysis using the 238-group ENDF/B-VII library runs 5.4 times slower than analysis with a 44-group library. Monte Carlo analysis run time is independent of the group structure and depends on the number of neutrons per generation and the number of generations. KENO depletion analysis proved to be much faster than NEWT depletion analysis with the 238-group library. (All ENDF/B-V 44-group analyses, however, were still done with NEWT rather than KENO.)

Since 44-group calculations (ENDF/B-V) are faster in NEWT, sensitivities to the spatial mesh in NEWT were investigated. It was found that the depletion analysis is sensitive to the size of the spatial mesh. Initial analyses were done using 4 mesh per pin. When the mesh per pin is increased to 16 mesh per pin, a change of .0024 in the bias is observed. This may seem small, but given the accuracy of the agreement, this mesh discrepancy is too large, and all the NEWT runs were redone with 16 mesh per pin. An attempt was made to again double the x and y meshing (64 mesh per pin), but NEWT failed. KENO depletion atom densities match the much longer run time NEWT atom densities. KENO accuracy was confirmed by increasing the number of neutrons per generation and the number of generations. The depleted atom densities did not change when the number of neutrons was increased by a factor of four thereby confirming the accuracy of the KENO depletion (and the NEWT meshing).

The current version of TRITON also has a potential trap for the casual user. The depletion of burnable absorbers must use the "Flux" option. Although the power option makes no sense for mixtures without fissile material, it is the default in SCALE and will result in erroneous results without any warning. These erroneous results are not so large as to be obvious unless the user knows fairly well the expected results. This is actually a user error, but it is expected that this trap will be fixed in future versions.

The criticality cases are much simpler. The lattice modeling is simple, and all that is needed is to attach the "StdCmpMix" files from the depletions. However, there is one small additional step. The "StdCmpMix" files are at the temperature of the depletion, and the temperature of the criticality is 293 K. A simple "replace all" command in a text editor can quickly fix this prior to use in the criticality runs. For all the KENO V.a criticality runs, 1500 generations are used with 6000 neutrons per generation. No generations in the tally of k were skipped by input, but rather the number of skipped generations was automatically selected by KENO V.a.

Sample input decks are given in Appendix A. Electronic copies of the decks are available in an executable file that accompanies this report. Appendix A describes the decks available.

Section 5: Results of the SCALE 6.1 ENDF/B-VII

With the depletion analysis and criticality calculations done, the next step is to calculate predicted reactivity decrements and compare to the measured decrements. Table 5-1 shows this process with the results of Case 3 100-hour cooling. Column 2 of Table 5-1 is the calculated k's. Column 4 is the difference between the Column 2 values and the first value in Column 2. This calculated decrement is compared to the EPRI measurement-based decrements. The difference between the calculated decrement and the EPRI benchmark value is the bias portion of Δk_d. If the calculated decrement is greater than the measured EPRI decrement, the analysis is non-conservative and a bias needs to be added. On the other hand, if the calculated decrement is less than the measured decrement, the depletion analysis is conservative and the negative calculated bias is conservatively ignored.

Table 5-1
Sample Calculation of Biases for Case 3 and 100-Hour Cooling

Burnup GWD/MTU	Calculated k	Monte Carlo σ	Calculated Decrement	EPRI Benchmark Decrement	Bias Calc-EPRI Decrement
0	1.4712	0.0001			
10	1.3484	0.0002	0.1228	0.1223	0.0005
20	1.2553	0.0002	0.2159	0.2157	0.0002
30	1.1721	0.0001	0.2991	0.2990	0.0001
40	1.0958	0.0001	0.3754	0.3758	-0.0004
50	1.0267	0.0001	0.4445	0.4445	0.0000
60	0.9688	0.0001	0.5024	0.5029	-0.0005

The process of calculating the biases has been performed for all 11 cases, all six burnups, and all three cooling times. The resulting biases for SCALE 6.1 ENDF/B-VII are in Tables 5-2, 5-3, and 5-4.

Table 5-2
Bias for the Reactivity Decrement with 100-Hour Cooling Using SCALE 6.1 and the ENDF/B-VII Cross-section Library

		Bias (Calculated Reactivity Decrement – Measured Reactivity Decrement) For 100-Hour Cooling					
		Burnup (GWD/MTU)					
Case	Lattice Description	10	20	30	40	50	60
1	3.25% enrichment depletion	-0.0004	-0.0008	-0.0010	-0.0015	-0.0014	-0.0022
2	5.00% enrichment depletion	0.0004	0.0005	0.0003	0.0006	0.0005	0.0008
3	4.25% enrichment depletion	0.0005	0.0002	0.0001	-0.0004	0.0000	-0.0005
4	off-nominal pin depletion	0.0002	-0.0002	-0.0004	-0.0010	-0.0011	-0.0016
5	20 WABA depletion	0.0005	0.0009	0.0007	0.0002	-0.0002	0.0001
6	104 IFBA depletion	0.0016	0.0010	0.0008	-0.0002	-0.0008	-0.0014
7	104 IFBA, 20 WABA depletion	0.0015	0.0016	0.0010	0.0002	-0.0001	-0.0011
8	high boron depletion = 1500 ppm	0.0003	0.0004	0.0001	-0.0001	-0.0001	-0.0004
9	branch to hot rack = 338.7K	-0.0003	-0.0002	-0.0005	-0.0004	-0.0004	-0.0004
10	branch to rack boron = 1500 ppm	-0.0005	-0.0010	-0.0016	-0.0019	-0.0023	-0.0026
11	high power density depletion	0.0001	0.0002	-0.0002	-0.0002	-0.0003	-0.0003

Table 5-3
Bias for the Reactivity Decrement with 5-Year Cooling Using SCALE 6.1 and the ENDF/B-VII Cross-section Library

		Bias (Calculated Reactivity Decrement – Measured Reactivity Decrement) for 5-Year Cooling					
		Burnup (GWD/MTU)					
Case	Lattice Description	10	20	30	40	50	60
1	3.25% enrichment depletion	0.0002	-0.0003	-0.0011	-0.0009	-0.0012	-0.0017
2	5.00% enrichment depletion	0.0006	0.0012	0.0011	0.0011	0.0010	0.0009
3	4.25% enrichment depletion	0.0008	0.0005	0.0004	0.0001	0.0002	-0.0001
4	off-nominal pin depletion	0.0007	0.0005	-0.0005	-0.0004	-0.0007	-0.0009
5	20 WABA depletion	0.0009	0.0015	0.0008	0.0007	0.0004	0.0001
6	104 IFBA depletion	0.0017	0.0013	0.0011	0.0006	-0.0001	-0.0009
7	104 IFBA, 20 WABA depletion	0.0016	0.0025	0.0019	0.0012	0.0005	-0.0001
8	high boron depletion = 1500 ppm	0.0007	0.0006	0.0001	0.0007	0.0003	0.0006
9	branch to hot rack = 338.7K	0.0000	0.0003	0.0002	-0.0001	0.0004	0.0003
10	branch to rack boron = 1500 ppm	-0.0004	-0.0006	-0.0013	-0.0015	-0.0018	-0.0022
11	high power density depletion	0.0006	0.0002	0.0003	0.0003	0.0004	0.0006

Table 5-4
Bias for the Reactivity Decrement with 15-Year Cooling Using SCALE 6.1 and the ENDF/B-VII Cross-section Library

		Bias (Calculated Reactivity Decrement – Measured Reactivity Decrement) For 15-Year Cooling					
		Burnup (GWD/MTU)					
Case	Lattice Description	10	20	30	40	50	60
1	3.25% enrichment depletion	0.0004	0.0002	-0.0011	-0.0012	-0.0010	-0.0015
2	5.00% enrichment depletion	0.0011	0.0013	0.0012	0.0012	0.0012	0.0012
3	4.25% enrichment depletion	0.0009	0.0010	0.0002	0.0003	0.0001	0.0000
4	off-nominal pin depletion	0.0008	0.0005	-0.0003	-0.0006	-0.0009	-0.0011
5	20 WABA depletion	0.0017	0.0014	0.0011	0.0010	0.0006	0.0004
6	104 IFBA depletion	0.0026	0.0021	0.0016	0.0008	0.0002	-0.0003
7	104 IFBA, 20 WABA depletion	0.0022	0.0028	0.0021	0.0013	0.0011	0.0001
8	high boron depletion = 1500 ppm	0.0016	0.0009	0.0005	0.0004	0.0002	0.0001
9	branch to hot rack = 338.7K	0.0005	0.0005	0.0002	-0.0001	0.0002	0.0002
10	branch to rack boron = 1500 ppm	0.0004	-0.0004	-0.0011	-0.0018	-0.0018	-0.0020
11	high power density depletion	0.0009	0.0011	0.0005	0.0003	0.0006	0.0004

Section 6: Using the SCALE 6.1 ENDF/B-VII Results in Criticality Applications

With the analysis of benchmarks completed, the criticality application needs to convert the calculated biases to a Δk_d that will be used in the safety analysis. Care must be taken to cover all the depletion and rack conditions. To review the adequacy of the results, Table 5-2, which is for 100-hour decay, is first reviewed; then Tables 5-3 and 5-4 are reviewed for cooling time effects.

First, are the expected enrichments adequately covered? The benchmarks range from 3.25 wt% to 5 wt% U-235. This covers the high range of enrichments, but does not cover the low enrichments from early cycles that would be found in a pool or cask. However, a quick review of the biases shown in Section 5 reveals a slight trend to more negative biases as one goes down in enrichment. Therefore, a bias from the high enrichments would be conservative for the low enrichments. Note that other cross-section libraries could have a trend in the opposite direction, and in that case, the trend would have to be projected and conservatism added.

Next, are the depletion parameters adequately covered? Cases 5, 6, 7, 8, and 11 vary depletion parameters from the base case (Case 3). The Monte Carlo uncertainty used in this analysis is 0.0002. Case 11 increases the power by 50%. The maximum difference in the biases in Table 5-2 between Case 11 and Case 3 is 0.0004. Since the bias is the difference between two Monte Carlo cases each with a 0.0002 uncertainty, the difference in the bias due to a large change in power is insignificant. Similarly the differences between Case 8 and Case 3 where the depletion ppm is changed by 600 ppm (from 900 ppm to 1500 ppm) are insignificant.

The final depletion parameter of interest is burnable absorbers. Statistically, significant differences do exist so the prediction tool is not fully picking up the effects. Case 5 is for depletion with 20 WABA pins. The change in k is between an initial condition without any WABAs [Wet Annular Burnable Absorbers] to the burned state with WABAs in. Thus the change in bias between Case 3 and Case 5 covers both the change in reactivity of the fuel as well as the change in reactivity due to a burned WABA. The WABAs are typically not credited in the criticality analysis, so the criticality analysis is actually done with only the change

in reactivity of the fuel being taken into account. The difference in bias is still small with the maximum difference being 0.0007. Adjusted to cover 24 WABA pins instead of the 20 in the analysis would only be about 0.0001. Even though some of the change in bias may be due to small difficulty with the WABA depletion rather than with the fuel depletion, the final selected biases are chosen to cover possible deficiencies in the depletion model revealed in Case 5. Cases 6 and 7 cover IFBAs and IFBAs with WABAs. Since IFBA stay with the fuel, the criticality analysis could take credit for the IFBA. However, in this report, it is assumed that the more traditional approach is taken, which ignores any residual IFBA boron in the criticality analysis of the cask or pool. In that case, one could compare criticality results with the benchmarks with the boron eliminated. This would produce large negative (conservative) biases for the low burnups. Rather than tabulate the biases calculated in that manner, Table 6-1 is provided and shows that the ignored IFBA boron worth is much greater than the positive biases for burnups 10, 20, and 30 GWD/MTU. At burnups of 40, 50, and 60 GWD/MTU when the boron is gone, the differences in the biases are small (may be Monte Carlo statistical variations) and slightly more negative, which is conservative.

Table 6-1
IFBA Boron Worth

Burnup (GWD/MTU)	Cooling Time	Case 6 (delta k)	Case 7 (delta k)
10	100 hr	0.0533	0.0488
20	100 hr	0.0090	0.0103
30	100 hr	0.0013	0.0017
10	5 yr	0.0531	0.0481
20	5 yr	0.0088	0.0108
30	5 yr	0.0007	0.0018
10	15 yr	0.0537	0.0482
20	15 yr	0.0090	0.0102
30	15 yr	0.0011	0.0014

The range of rack conditions are explored with two cases: Case 9 and Case 10. It should be noted that the geometric parameters of the rack need to be covered in the selection of the fresh fuel critical experiments. The rack condition changes are to explore if the delta k of depletion is impacted by rack conditions. Since this is a fuel effect, the most important concerns are changes in the fuel, so the rack condition changes are a change in the water temperature and density and a change in the boron ppm. Case 9 shows that at elevated temperatures the bias change is small and may not be statistically significant. Case 10, however, shows that the prediction capability is reduced with ppm. Fortunately, the bias becomes more conservative with increasing ppm so using a bias derived from zero ppm is conservative. (Note that results using other code and cross-section libraries may

become less conservative with ppm. This would require the addition of some conservatism to cover rack conditions).

Finally, the bias for the criticality analysis is selected. This bias could be a function of burnup and/or other parameters, but it is recommended to try to keep the bias simple. Reviewing the Table 5-2 results, a bias of 0.001 would cover all the cases. (Note the IFBA boron that was ignored covers the low burnup IFBA cases.) However, the base case for the variations the depletion and rack parameters is 4.25 wt% U-235, and this is slightly non-conservative compared to 5 wt% U-235. Using the delta between 4.25 wt% U-235 and 5 wt% U-235 and adding that delta to the worse case bias (Case 5 20 GWD/MTU), one gets the largest positive bias of 0.0012. It is suggested to round this up to **0.0015** and use this as the bias portion of Δk_d for 100-hour cooling for all burnups.

The measurements do not contain any cooling time information. The reactivity changes for cooling time are based on the computer code (CASMO-5) that was used to generate the benchmarks. CASMO-5/SIMULATE predict startup critical conditions well, and there has been no need to add a bias when the shutdown period varies from hours to many months. The 100-hour cooling time can be considered comparison to measured data, but the 5- and 15-year cooling times should be viewed with caution. Due to the limited number of isotopes changing between 100 hours and 15 years, several approaches may be used to justify the cooling time benefits. One way is to add conservatism in the bias. In this case, it is suggested that the bias be increased by 0.001 to **0.0025** for cooling time credit. A review of Tables 5-3 and 5-4 shows this is sufficient to cover all the calculated biases.

In historical analysis, Δk_d was set by the Kopp memo as 5% of the delta k of depletion. Using the EPRI benchmarks, Δk_d is determined for the criticality code system and cross-section library. In this case with SCALE 6.1 and the 238-group ENDF/B-VII cross-section library, Δk_d is a bias of 0.0015 (or 0.0025 with cooling time credit) and an uncertainty of 0.00643. The uncertainty can be statistically combined with other uncertainties such as manufacturing tolerances on the fuel and rack. Since these other uncertainties are not known at this time, in order to compare to the Kopp memo, the bias and uncertainty will be added together. (This is somewhat unfair to the Kopp approach, but since the bias is so small it is reasonable.) Table 6-2 shows the comparison of the Kopp uncertainty to the EPRI uncertainty plus bias as a function of enrichment at 100-hour cooling. With cooling, the added 0.001 bias makes the 10 GWD/MTU difference a little larger, but is insignificant at higher burnups.

Table 6-2
Comparison Between the EPRI Benchmark Results and the Kopp Memo for Case 3 and 100-Hour Cooling

Burnup (GWD/MTU)	Kopp Uncertainty (Delta k)	EPRI Uncertainty plus Bias (Delta k)
10	0.0061	0.0079
20	0.0108	0.0079
30	0.0150	0.0079
40	0.0188	0.0079
50	0.0222	0.0079
60	0.0251	0.0079

As can be seen in Table 6-2, the Kopp memo guidance is very conservative for normal discharged fuel. Since for simplicity the EPRI approach does not change the bias and uncertainty with burnup, the Kopp uncertainty appears to be non-conservative at very low burnups. However, if all the EPRI benchmark data were reviewed for a bias and uncertainty at 10 GWD/MTU, there would be insignificant differences between the Kopp memo values and the EPRI benchmark values. Since the bias and uncertainty derived with the EPRI benchmarks are so small, the added complexities of a burnup dependent bias and uncertainty are not justified. (However, the data given here for the biases and in Reference 1 for the uncertainties would allow for a burnup dependent bias and uncertainty.)

So far the analysis has not addressed the range of applicability for fuel designs. The measured data came from Westinghouse type 17X17 fuel. The benchmarks cover both Standard (Std) and Optimized Fuel Assembly (OFA) fuel designs. This gives the benchmarks a range of depletion spectrum that covers most PWR fuel designs. The easiest non-calculational way of seeing this is by comparing the wetness of PWR fuel designs. Table 6-3 shows the fuel design parameters of major PWR fuel designs. The last column shows the water-to-pellet volume ratio. As can be seen from Table 6-3, the range of the benchmarks covers the W 15X15, B&W and CE fuel. The Westinghouse 14X14 and 16X16 products will require some extrapolation. As can be seen in Tables 5-2, 5-3, and 5-4, the wetter lattice is slightly more conservatively predicted; so the W 14X14 OFA design is covered. It is suggested to add a 0.001 additional bias for W 14X14 Std and W 16X16 fuel. The analyst should compare a depletion spectrum for the fuel designs used to that spectral parameter from the benchmark analysis; and if it is not in the range of the benchmarks, the analyst needs to conservatively extrapolate the bias.

Table 6-3
Fuel Design Wetness

Fuel Design	Pellet OD (inches)	Clad OD (inches)	Pitch (inches)	Water to Pellet Volume Ratio
W 17X17 Std	0.323	0.374	0.496	1.67
W 17x17 OFA	0.309	0.360	0.496	1.93
W 16X16	0.323	0.374	0.485	1.53
W 15X15	0.366	0.422	0.563	1.68
W 14X14 Std	0.366	0.422	0.556	1.61
W 14X14 OFA	0.344	0.400	0.556	1.97
B&W 15X15	0.369	0.430	0.568	1.66
B&W 17X17	0.323	0.379	0.502	1.70
CE 14X14	0.377	0.440	0.580	1.66
CE 16x16	0.325	0.382	0.506	1.70

Section 7: Analysis with SCALE 6.1 and the ENDF/B-V 44-Group Library

The ENDF/B-V 44-group library is currently the most used library in current safety analyses of casks and racks. Also since it is a 44-group library, depletion run times are faster. The ENDF/B-VII depletion (from Section 4) for Case 3 60 GWD/MTU 100-hour cooling took 4 hours and 56 minutes. The comparable ENDF/B-V 44-group depletion took only 2 hours 23 minutes on the same computer. The key reason for the faster time is due to fewer energy groups allowing the use of NEWT rather than KENO for the depletion flux calculations. If a collapsed 44-group library was made for ENDF/B-VII, similar run times would be expected. Although ENDF/B-V can be run with either NITAWL or CENTRM, the base results for ENDF/B-V were done with CENTRM. The run time for the same Case 3 60 GWD/MTU run using NITAWL rather than CENTRM was 2 hours 3 minutes. Although the CENTRM analysis increased run times by 20% it was deemed acceptable due to the more precise treatment of overlapping resonances.

The results of the ENDF/B-V 44-group library analysis are shown in Tables 7-1, 7-2, and 7-3. A quick comparison between the tables in Section 5 and Tables 7-1, 7-2, and 7-3 shows that the agreement to the benchmarks is much better with ENDF/B-VII. However, the ENDF/B-V results show a maximum deviation of only 0.0180 in k, which is less than 3% of the depletion reactivity (and in a conservative direction). The ENDF/B-V 44-group results produce, in general, more conservative results. Reviewing this section's tables suggests that a very small bias is needed. Due to the positive 0.0010 for Case 11 at 20 GWD/MTU and 100-hour cooling, and the enrichment bias of 0.0014 (Case 2 – Case 3), the suggested bias for the ENDF/B-V is 0.0025. For cases with cooling credit, the bias becomes more negative so the 0.0025 bias can still be used when cooling credit is applied.

Table 7-1
Bias for the Reactivity Decrement with 100-Hour Cooling Using SCALE 6.1 and the ENDF/B-V 44-Group Cross-section Library (CENTRM)

		Bias (Calculated Reactivity Decrement – Measured Reactivity Decrement) for 100-Hour Cooling (CENTRM)					
		Burnup (GWD/MTU)					
Case	Lattice Description	10	20	30	40	50	60
1	3.25% enrichment depletion	-0.0005	-0.0020	-0.0035	-0.0060	-0.0081	-0.0096
2	5.00% enrichment depletion	0.0008	0.0010	0.0002	-0.0009	-0.0025	-0.0044
3	4.25% enrichment depletion	0.0000	-0.0004	-0.0010	-0.0031	-0.0046	-0.0071
4	off-nominal pin depletion	-0.0002	-0.0008	-0.0024	-0.0043	-0.0064	-0.0089
5	20 WABA depletion	-0.0017	-0.0013	-0.0023	-0.0039	-0.0052	-0.0058
6	104 IFBA depletion	0.0027	0.0000	-0.0016	-0.0043	-0.0059	-0.0067
7	104 IFBA, 20 WABA depletion	0.0014	0.0009	-0.0014	-0.0038	-0.0055	-0.0067
8	high boron depletion = 1500 ppm	0.0005	0.0000	-0.0008	-0.0026	-0.0043	-0.0060
9	branch to hot rack = 338.7K	-0.0002	-0.0004	-0.0015	-0.0033	-0.0050	-0.0068
10	branch to rack boron = 1500 ppm	-0.0014	-0.0025	-0.0043	-0.0062	-0.0084	-0.0105
11	high power density depletion	0.0003	0.0010	0.0002	-0.0009	-0.0024	-0.0038

Table 7-2
Bias for the Reactivity Decrement with 5-Year Cooling Using SCALE 6.1 and the ENDF/B-V 44-Group Cross-section Library (CENTRM)

		Bias (Calculated Reactivity Decrement – Measured Reactivity Decrement) For 5-Year Cooling (CENTRM)					
		Burnup (GWD/MTU)					
Case	Lattice Description	10	20	30	40	50	60
1	3.25% enrichment depletion	-0.0001	-0.0025	-0.0058	-0.0093	-0.0121	-0.0142
2	5.00% enrichment depletion	0.0006	0.0004	-0.0010	-0.0034	-0.0058	-0.0084
3	4.25% enrichment depletion	0.0006	-0.0007	-0.0026	-0.0057	-0.0087	-0.0115
4	off-nominal pin depletion	-0.0001	-0.0012	-0.0040	-0.0068	-0.0101	-0.0130
5	20 WABA depletion	0.0000	0.0004	-0.0014	-0.0039	-0.0068	-0.0080
6	104 IFBA depletion	0.0046	0.0017	-0.0011	-0.0042	-0.0069	-0.0089
7	104 IFBA, 20 WABA depletion	0.0029	0.0026	-0.0003	-0.0039	-0.0066	-0.0086
8	high boron depletion = 1500 ppm	0.0008	-0.0005	-0.0023	-0.0049	-0.0076	-0.0103
9	branch to hot rack = 338.7K	0.0000	-0.0010	-0.0029	-0.0055	-0.0084	-0.0109
10	branch to rack boron = 1500 ppm	-0.0010	-0.0024	-0.0046	-0.0077	-0.0106	-0.0127
11	high power density depletion	0.0010	0.0004	-0.0010	-0.0030	-0.0052	-0.0078

Table 7-3
Bias for the Reactivity Decrement with 15-Year Cooling Using SCALE 6.1 and the ENDF/B-V 44-Group Cross-section Library (CENTRM)

		Bias (Calculated Reactivity Decrement – Measured Reactivity Decrement) For 15-Year Cooling (CENTRM)					
		Burnup (GWD/MTU)					
Case	Lattice Description	10	20	30	40	50	60
1	3.25% enrichment depletion	-0.0007	-0.0035	-0.0081	-0.0121	-0.0157	-0.0180
2	5.00% enrichment depletion	0.0010	0.0000	-0.0022	-0.0050	-0.0084	-0.0121
3	4.25% enrichment depletion	0.0006	-0.0015	-0.0042	-0.0079	-0.0119	-0.0152
4	off-nominal pin depletion	-0.0001	-0.0021	-0.0056	-0.0095	-0.0138	-0.0169
5	20 WABA depletion	0.0004	-0.0001	-0.0029	-0.0062	-0.0095	-0.0112
6	104 IFBA depletion	0.0045	0.0016	-0.0024	-0.0063	-0.0099	-0.0119
7	104 IFBA, 20 WABA depletion	0.0031	0.0022	-0.0019	-0.0058	-0.0091	-0.0115
8	high boron depletion = 1500 ppm	0.0004	-0.0010	-0.0036	-0.0075	-0.0109	-0.0142
9	branch to hot rack = 338.7K	0.0002	-0.0016	-0.0043	-0.0078	-0.0112	-0.0144
10	branch to rack boron = 1500 ppm	-0.0010	-0.0029	-0.0060	-0.0092	-0.0123	-0.0148
11	high power density depletion	0.0011	-0.0002	-0.0027	-0.0057	-0.0083	-0.0111

Historical analysis with ENDF/B-V used NITAWL. NITAWL uses the Nordhiem Integral Treatment for resonance self-shielding in the resolved resonance energies using. This approach is limited to a single resonance material combined with two admixed moderators, so that no resonance overlap effects are treated. CENTRM, on the other hand, uses the point wise cross sections from the ENDF/B data to determine the flux as a function of energy for the system and then collapses the cross sections back into the group cross-section structure. The CENTRM approach captures resonance overlap effects. Although CENTRM is an improvement over NITAWL, the effect of the overlaps is small; so it was expected that very similar results would be found if NITAWL was used rather than CENTRM. This, however, is not the case. Tables 7-4, 7-5 and 7-6 show the results of the exact same decks run with the PARM=NITAWL option. Note that the difference in bias is very large. For Case 3, 60 GWD/MTU, 100-hour cooling, the difference in the bias given on Tables 7.1 and 7.4 is 1.57% in k. (This is large, but the Kopp memo uncertainty for this case is 2.51% in k.) This large difference in the delta k of depletion has been investigated.

In the investigation, a small coding error in CENTRM was found. This error occurs when there are isotopes that do not meet a minimum content. Specifically, the error is hit when N(j)/N(tot) < 1.0E-8. Although small isotopic content is generally not followed in criticality analysis it is common in depletion analysis. Isotopes with small initial content become significant with burnup. For this reason, it is normal to model isotopes in analysis of low burnup cases that are below the 1.0E-8 cutoff. The impact of the computer coding error is about 0.1% in k for an infinite lattice analyzed with the ENDF/B-V 44-group library. For high leakage systems tripping the CENTRM error can result in over a 1% in k error. Fortunately, the benchmarks are infinite lattice systems; so the impact of the code error is not significant to this report. Given the accuracy of the ENDF/B-VII results, the user would have been able to detect even this seemingly small error, but this error is insignificant for the ENDF/B-VII results. The impact of the error is smaller with increased number of energy groups. The impact of the error with 238 groups such as used in the ENDF/B-VII analysis is too small to be seen at the level of Monte Carlo uncertainty used in this analysis. The SCALE Help team was informed and will address the issue with a correction made at an appropriate time. For more information please refer to page 78 of the SCALE 6 online notebook.

With the trace elements removed (thereby avoiding the CENTRM error), the difference in k between NITAWL and CENTRM for the same isotopic content is small. Table 7-7 shows the calculated k for the same isotopic content for Case 3 100-hour cooling. It should be noted that the difference in calculated k is less than 0.4% in k, and this difference does not change with burnup. This suggests that almost all of the difference in the delta k of depletion is in the isotopic content and not the direct effect of the processed differences in cross sections.

Table 7-4
Bias for the Reactivity Decrement with 100-Hour Cooling Using SCALE 6.1 and the ENDF/B-V 44-Group Cross-section Library (NITAWL)

		Bias (Calculated Reactivity Decrement – Measured Reactivity Decrement) For 100-Hour Cooling (NITAWL)					
		Burnup (GWD/MTU)					
Case	**Lattice Description**	**10**	**20**	**30**	**40**	**50**	**60**
1	3.25% enrichment depletion	0.0007	0.0024	0.0034	0.0046	0.0056	0.0065
2	5.00% enrichment depletion	0.0004	0.0022	0.0039	0.0059	0.0076	0.0092
3	4.25% enrichment depletion	0.0009	0.0024	0.0041	0.0057	0.0076	0.0086
4	off-nominal pin depletion	0.0004	0.0016	0.0035	0.0046	0.0058	0.0067
5	20 WABA depletion	-0.0006	0.0007	0.0023	0.0043	0.0066	0.0091
6	104 IFBA depletion	0.0037	0.0025	0.0033	0.0045	0.0064	0.0085
7	104 IFBA, 20 WABA depletion	0.0018	0.0024	0.0034	0.0047	0.0064	0.0082
8	high boron depletion = 1500 ppm	0.0011	0.0028	0.0044	0.0064	0.0077	0.0093
9	branch to hot rack = 338.7K	0.0004	0.0020	0.0035	0.0053	0.0066	0.0081
10	branch to rack boron = 1500 ppm	0.0003	0.0009	0.0020	0.0037	0.0042	0.0053
11	high power density depletion	0.0007	0.0031	0.0055	0.0080	0.0100	0.0112

Table 7-5
Bias for the Reactivity Decrement with 5-Year Cooling Using SCALE 6.1 and the ENDF/B-V 44-Group Cross-section Library (NITAWL)

		Bias (Calculated Reactivity Decrement – Measured Reactivity Decrement) For 5-Year Cooling (NITAWL)					
		Burnup (GWD/MTU)					
Case	**Lattice Description**	**10**	**20**	**30**	**40**	**50**	**60**
1	3.25% enrichment depletion	0.0005	0.0010	0.0012	0.0012	0.0014	0.0022
2	5.00% enrichment depletion	0.0008	0.0017	0.0022	0.0028	0.0036	0.0051
3	4.25% enrichment depletion	0.0013	0.0014	0.0022	0.0026	0.0031	0.0041
4	off-nominal pin depletion	0.0003	0.0005	0.0008	0.0011	0.0018	0.0024
5	20 WABA depletion	0.0007	0.0020	0.0033	0.0039	0.0051	0.0068
6	104 IFBA depletion	0.0051	0.0035	0.0035	0.0041	0.0050	0.0064
7	104 IFBA, 20 WABA depletion	0.0038	0.0039	0.0038	0.0046	0.0052	0.0066
8	high boron depletion = 1500 ppm	0.0015	0.0017	0.0025	0.0030	0.0039	0.0048
9	branch to hot rack = 338.7K	0.0003	0.0011	0.0017	0.0025	0.0035	0.0044
10	branch to rack boron = 1500 ppm	0.0006	0.0008	0.0013	0.0018	0.0023	0.0031
11	high power density depletion	0.0016	0.0031	0.0041	0.0053	0.0064	0.0075

Table 7-6
Bias for the Reactivity Decrement with 15-Year Cooling Using SCALE 6.1 and the ENDF/B-V 44-Group Cross-section Library (NITAWL)

		Bias (Calculated Reactivity Decrement – Measured Reactivity Decrement) For 15-Year Cooling (NITAWL)					
		Burnup (GWD/MTU)					
Case	**Lattice Description**	**10**	**20**	**30**	**40**	**50**	**60**
1	3.25% enrichment depletion	0.0007	-0.0001	-0.0011	-0.0019	-0.0019	-0.0017
2	5.00% enrichment depletion	0.0007	0.0008	0.0009	0.0007	0.0006	0.0013
3	4.25% enrichment depletion	0.0010	0.0005	0.0002	-0.0001	0.0001	0.0005
4	off-nominal pin depletion	0.0004	0.0000	-0.0009	-0.0019	-0.0019	-0.0018
5	20 WABA depletion	0.0007	0.0013	0.0017	0.0012	0.0018	0.0036
6	104 IFBA depletion	0.0049	0.0029	0.0018	0.0016	0.0019	0.0031
7	104 IFBA, 20 WABA depletion	0.0036	0.0033	0.0025	0.0021	0.0022	0.0033
8	high boron depletion = 1500 ppm	0.0009	0.0014	0.0008	0.0004	0.0007	0.0010
9	branch to hot rack = 338.7K	0.0005	0.0003	0.0000	-0.0003	-0.0001	0.0008
10	branch to rack boron = 1500 ppm	0.0002	0.0001	-0.0003	0.0001	0.0001	0.0006
11	high power density depletion	0.0013	0.0018	0.0023	0.0026	0.0032	0.0042

Table 7-7
Comparison of NITAWL and CENTRM Calculated k Using the Same Isotopic Content (Case 3, 100-Hour Cooling)

Burnup (GWD/MTU)	NITAWL	CENTRM	Delta k
0	1.4694	1.4658	0.0036
60*	0.9732	0.9700	0.0032

* 60 GWD/MTU isotopic content from the CENTRM depletion for both cases.

Since the difference between the NITAWL and CENTRM results are caused by the difference in isotopic concentration, the isotopic content predictions are reviewed. Table 7-8 shows the 29 isotopes where the absolute value of the difference between the NITAWL and CENTRM isotopic content is greater than 3% (ordered by decreasing differences). At the bottom of the Table 7-8, the U-238 difference is added. The differences shown in Table 7-8 suggest that CENTRM processing increases U-238 capture compared to NITAWL processing. In conversations with Mark Williams, the author of CENTRM, this is an expected result. This increase in U-238 capture also explains the slightly lower k's observed with CENTRM. Since U-238 content is mostly independent of burnup, the constant reduction in k seen in Table 7-7 is expected. The isotopes that follow U-238 capture have a higher concentration with the CENTRM depletion. This means there is more plutonium fission. Since the comparison is for the same burnup the number of fissions is the same; so as expected, there is less U-235 fissions and therefore a higher concentration of U-235 as well as the plutonium. In order to confirm that there is higher U-238 capture, the 44-group U-238 capture cross sections predicted using NITAWL and CENTRM are compared in Table 7-9. The differences between NITAWL- and CENTRM-produced cross sections, shown in Table 7-9, are reasonable for the method difference. However, the percent differences do not tell the whole story since the magnitude of the cross sections vary greatly and so does the flux. The reaction rates when summed show that CENTRM predicts 0.4% more U-238 capture than NITAWL.

It should also be noticed that small differences in the predicted atom densities cause a large change in the delta k of depletion. Table 7-8 shows that a 1.57% change in k is due to isotopic differences in uranium and plutonium of 5% and less. A recent assessment of chemical assay data [10] shows a one-sigma uncertainty of the key plutonium isotopes and U-235 content to be between 4.7% and 6.9%. This means that the origin of any effect of the order of 1.5% in k cannot be separated from the random variations in the chemical assays. For example, the uncertainty in the chemical assays would make it difficult to be certain of an appropriate change in bias for going between ENDF/B-VII and ENDF/B-V. Further, the difference between CENTRM and NITAWL is too small for any certainty on improved results. Finally, smaller impacts of modeling decisions such as the proper spatial and temporal mesh will seem insignificant given the large uncertainty in the results. However, the depletion benchmark

uncertainty is small enough so that all of these effects are significant and the impact of all these decisions can be seen in the agreement with the benchmarks.

Table 7-8
Isotopic Content at 60 GWD/MTU (Case 3, 100-Hour Cooling) as Predicted by NITAWL Versus CENTRM Depletions With the ENDF/B-V 44-Group Library

Isotope	CENTRM (Atoms/Barn-cm)	NITAWL (Atoms/Barn-cm)	% Difference (CENTRM-NITAWL)
Cm-245	3.82761E-07	2.76698E-07	27.7
Cm-246	5.16239E-08	4.18672E-08	18.9
Cf-249	2.26276E-13	1.88115E-13	16.9
Cm-247	8.71040E-10	7.33734E-10	15.8
Bk-249	1.28033E-12	1.07860E-12	15.8
Cf-251	2.35926E-13	2.00678E-13	14.9
Cf-250	3.46856E-13	2.97009E-13	14.4
Cf-252	1.83694E-13	1.63742E-13	10.9
Cm-248	7.99867E-11	7.18602E-11	10.2
Es-253	2.29318E-16	2.08955E-16	8.9
Sm-150	2.09551E-05	1.91529E-05	8.6
Pm-147	8.10072E-06	7.47560E-06	7.7
Am-242m	2.52195E-08	2.34440E-08	7.0
Cd-113	8.71704E-09	8.18196E-09	6.1
Am-241	1.77169E-06	1.66711E-06	5.9
U-235	1.28516E-04	1.22059E-04	5.0
Hf-179	2.45289E-20	2.33062E-20	5.0
Sm-147	4.48454E-06	4.27345E-06	4.7
Pu-241	4.79587E-05	4.60196E-05	4.0
Pu-239	1.58042E-04	1.51712E-04	4.0
B-10	2.47730E-15	2.37820E-15	4.0
Gd-154	2.34800E-07	2.25513E-07	4.0
Kr-82	1.20192E-07	1.15657E-07	3.8
Sn-112	2.62593E-16	2.53360E-16	3.5
Cm-243	3.11024E-08	3.00429E-08	3.4
Pu-240	7.74891E-05	7.49215E-05	3.3
Sr-86	8.17371E-08	7.90836E-08	3.2
Ba-134	6.28727E-06	6.08743E-06	3.2
Cs-134	1.14251E-05	1.10734E-05	3.1
U-238	2.10094E-02	2.10250E-02	-0.074

Table 7-9
Comparison of the U-238 n-γ Cross Section for Case 3 Zero Burnup Treated by CENTRM and NITAWL (ENDF/B-V)

Group Number	CENTRM (barns)	NITAWL (barns)	% Difference	Relative Flux
1	2.33334E-03	2.33334E-03	0.0	0.11481
2	4.28430E-03	4.28430E-03	0.0	0.14847
3	7.29420E-03	7.29420E-03	0.0	0.15666
4	1.46886E-02	1.46886E-02	0.0	0.19377
5	2.46180E-02	2.46180E-02	0.0	0.06045
6	3.02750E-02	3.02750E-02	0.0	0.01515
7	3.95070E-02	3.95070E-02	0.0	0.04778
8	6.20618E-02	6.20618E-02	0.0	0.03024
9	1.05609E-01	1.05609E-01	0.0	0.01029
10	1.21440E-01	1.17309E-01	3.4	0.01373
11	1.31942E-01	1.28237E-01	2.8	0.01415
12	3.29761E-01	3.29761E-01	0.0	0.00663
13	5.01445E-01	5.01445E-01	0.0	0.00146
14	7.77250E-01	7.11060E-01	8.5	0.00636
15	1.17804E+00	1.11752E+00	5.1	0.00629
16	1.89538E+00	1.84782E+00	2.5	0.00682
17	3.36659E+00	3.32213E+00	1.3	0.00455
18	3.38840E+00	3.33821E+00	1.5	0.00420
19	7.82564E-01	7.82906E-01	0.0	0.00354
20	2.67782E+01	2.69163E+01	-0.5	0.00046
21	2.85277E+00	2.81881E+00	1.2	0.00077
22	7.86940E-01	7.83551E-01	0.4	0.00256
23	4.77768E-01	4.77363E-01	0.1	0.00377
24	4.81060E-01	4.81420E-01	-0.1	0.00769
25	5.54032E-01	5.54493E-01	-0.1	0.00696
26	6.59510E-01	6.59711E-01	0.0	0.00806
27	7.33349E-01	7.33070E-01	0.0	0.00146
28	7.55178E-01	7.54940E-01	0.0	0.00170
29	7.79364E-01	7.79110E-01	0.0	0.00202
30	8.22422E-01	8.22142E-01	0.0	0.00500
31	8.73042E-01	8.72620E-01	0.0	0.00282

Table 7-9 (continued)
Comparison of the U-238 n-γ Cross Section for Case 3 Zero Burnup Treated by CENTRM and NITAWL (ENDF/B-V)

Group Number	CENTRM (barns)	NITAWL (barns)	% Difference	Relative Flux
32	9.14282E-01	9.13720E-01	0.1	0.00299
33	9.62422E-01	9.61700E-01	0.1	0.00330
34	1.06187E+00	1.06073E+00	0.1	0.00875
35	1.25740E+00	1.25860E+00	-0.1	0.01641
36	1.50472E+00	1.50496E+00	0.0	0.01871
37	1.77633E+00	1.77702E+00	0.0	0.01813
38	2.03620E+00	2.03720E+00	0.0	0.01060
39	2.30650E+00	2.30830E+00	-0.1	0.01101
40	2.58690E+00	2.58650E+00	0.0	0.00500
41	3.25836E+00	3.27240E+00	-0.4	0.01353
42	4.58441E+00	4.58190E+00	0.1	0.00133
43	5.89597E+00	5.88339E+00	0.2	0.00142
44	1.02840E+01	1.02840E+01	0.0	0.00022

Section 8: Methods Using Diverse Cross Sections and Computer Codes

So far, all the analyses have assumed the application of the same cross-section library and computer code for both the depletion analysis and the criticality calculation. However, this is not the common practice. In many cases, the depletion calculations are performed with fuel management codes based on recent cross-section libraries and the criticality codes (KENO or MCNP) using entirely different libraries. To see the impact of switching libraries, Case 3 with 100-hour cooling was rerun with isotopic content produced by a library different from that used in the criticality calculation. Table 8-1 shows the results of this analysis. The shaded cells come from previous tables (color coded). It may seem desirable to deplete using the fastest method, ENDF/B-V and NITAWL, and then use the most modern library and method, ENDF/B-VII and CENTRM, in the criticality calculations. This would be represented by the fifth column in Table 8.1. As can be seen, this approach gives the worst results. The results are even worse than just staying consistent with the ENDF/B-V and NITAWL for both the depletion and criticality. Taking ENDF/B-V and CENTRM depletion and then using ENDF/B-VII criticality calculations does result in some smaller, and less conservative, biases. Using ENDF/B-VII for all calculations provides the best results by far. The last column in Table 8-1 may be the closest representation of the use of commercial fuel management codes combined with SCALE to what has been done in many license applications. It appears that this combination results in more negative biases, which is conservative. (As shown in Table 7-7, there is a negligible difference in results between using NITAWL or CENTRM for the criticality calculation.)

Table 8-1
Delta k of Depletion Biases for Different Combinations of Libraries and Codes (Case 3, 100-Hour Cooling)

Depletion Method	ENDF/B-V CENTRM	ENDF/B-V CENTRM	ENDF/B-V NITAWL	ENDF/B-V NITAWL	ENDF/B-VII CENTRM	ENDF/B-VII CENTRM
Criticality Calculation	ENDF/B-V CENTRM	ENDF/B-VII CENTRM	ENDF/B-V NITAWL	ENDF/B-VII CENTRM	ENDF/B-VII CENTRM	ENDF/B-V CENTRM
Burnup (GWD/MTU)	Bias (delta k)					
10	0.0000	0.0020	0.0009	0.0027	0.0005	-0.0025
20	-0.0004	0.0024	0.0024	0.0050	0.0002	-0.0041
30	-0.0010	0.0014	0.0041	0.0072	0.0001	-0.0043
40	-0.0031	0.0000	0.0057	0.0086	-0.0004	-0.0046
50	-0.0046	-0.0015	0.0076	0.0109	0.0000	-0.0043
60	-0.0071	-0.0028	0.0086	0.0126	-0.0005	-0.0038

Since MCNP is heavily used in criticality analysis, Case 3, 100-hour cooled, was run with MCNP5 using the ENDF/B-VII depletion atom densities. Table 8-2 compares the biases derived from using MCNP versus KENO for the criticality calculations. As can be seen from Table 8-2, there is good agreement between using KENO with the 238-Group ENDF/B-VII and MCNP5 when using the ENDF/B-VII cross sections.

Finally, using KENO with the continuous energy, ENDF/B-VII cross sections was explored. Unfortunately, the WINDOWS version of SCALE 6.1 did not perform well with the 388 isotope depletion file. Runs with this number of isotopes crashed the WINDOWS computer. It was determined that if the number of isotopes were decreased, the same decks would run. After numerous iterations, it was determined that the continuous energy KENO runs would work with 201 isotopes in the fuel. This conclusion is probably not generic in that these decks would still fail if two cases were run at the same time. This implies some memory conflict that could depend on how the computer is configured. It is hoped that this problem can be resolved in the future to give more stability to the WINDOWS-based analysis. Continuous energy KENO was run using the 201 isotopes, and the results are shown on Table 8-2. Clearly the results are not as good as the 238-group analyses. The reduction in the total isotopes from 388 to 201 isotopes is less than 0.002 in for all the burnups (as shown by analysis with the 238-group cross-section set). The SCALE 6.1 validation report [11] found that the agreement with MOX critical experiments and UO_2 experiments differed by about 0.3% with the continuous energy KENO, but no significant difference was seen with the 238-group analysis (Table 5 of Reference 11). This report is seeing a difference twice that, but the analysis utilizes many more isotopes. The SCALE development team is working on improved CE data libraries, but has not yet set a release date. The 238-group KENO runs took 8.2 minutes. The continuous energy KENO runs took 156 minutes. For the zero burnup case with four fuel isotopes, the continuous energy KENO took 79 minutes. The MCNP runs with all the isotopes took 531 minutes and 57 minutes for the zero burnup case. There does not seem to be any benefit from using continuous energy cross sections, and there clearly is a significant time savings for using group cross sections.

Table 8-2
Delta k of Depletion Biases Using ENDF/B-VII Depletion and Various ENDF/B-VII Criticality Options (Case 3, 100-Hour Cooling)

Burnup (GWD/MTU)	ENDF/B-VII Using 238 Group KENO	ENDF/B-VII Using MCNP5	ENDF/B-VII Using Continuous Energy KENO
10	0.0005	0.0005	0.0033
20	0.0002	0.0008	0.0050
30	0.0001	0.0011	0.0062
40	-0.0004	0.0011	0.0066
50	0.0000	0.0012	0.0065
60	-0.0005	-0.0008	0.0073

Section 9: Summary and Conclusions

The EPRI depletion reactivity benchmarks provide an excellent way to validate criticality methods for burnup credit. They are based on reactivity inferred from 680 flux maps taken over 44 cycles from 4 different pressurized water reactors. These benchmarks represent measured data for the change in reactivity with burnup, i.e., the parameter of direct interest in burnup credit. The benchmarks can be easily calculated with criticality tools and provide more detailed insight into the accuracy of these methods for burnup credit than any other set of validation data.

The depletion reactivity benchmarks have been evaluated using SCALE 6.1 and the 238-group ENDF/B-VII cross sections, and it has been found that the reactivity bias for burnup is very small. The bias for using SCALE 6.1 and the 238-group ENDF/B-VII library for burnup credit not crediting cooling time is found to be only **0.0015**. This bias is independent of burnup. In addition to this bias, there is an uncertainty from the measured benchmarks of 0.00643. For cases where cooling time is also credited, it is suggested to increase this bias to **0.0025** (the uncertainty remains 0.00643). These biases and uncertainty apply for most PWR pools or casks. There is a range of spectrum in the benchmarks which cover most PWR fuel, but this will need to be verified for each application. If the design is not covered in the range of spectrum explicitly considered in the benchmarks, an additional small conservatism (0.001) was determined to be adequate to cover the extrapolation.

The agreement between the predicted depletion reactivity and the benchmarks when analyzed with ENDF/B-V is markedly not as close when compared with the results obtained with ENDF/B-VII. In order to avoid complicated burnup dependent biases, it is therefore recommended to change to the newer (ENDF/B-VII) cross-section library. However, the depletion reactivity benchmarks have also been evaluated using SCALE 6.1 and the 44-group ENDF/B-V library. With this library, it is possible to use a NITAWL or CENTRM treatment of the resonances. Although the differences in this treatment have a fairly small impact on direct calculation of k, the two approaches predict different U-238 capture rates and this produces relatively large impacts on the reactivity of depletion. Using CENTRM generally under predicts the change in k with burnup (conservative), but it was determined that the bias of 0.0025 is needed for CENTRM-based analysis with ENDF/B-V. NITWAL depletion, however, is non-conservative. Since it is not recommended to use NITAWL for burnup credit depletion, coming up with a defensible value for a bias is not proposed. However, historically, analyses for burnup credit have

used a reduced number of isotopes. Early analyses, not reported here, used a reduced set of isotopes and were found to be conservative. This is, in effect, adding a burnup-dependent bias. The applicant would analyze the benchmarks with the reduced isotopic set and then determine the appropriate bias, if any, that are consistent with this reduced isotopic set.

Most current criticality analyses mix cross-section libraries and codes in the depletion and criticality analysis. This is due to using fuel management tools for the depletion analysis with criticality tools for the final determination of k. One might believe that using an improved criticality analysis with historical atom densities would improve the agreement on the depletion reactivity. Using the old classical depletion analysis (ENDF/B-V with NITAWL) followed by criticality analysis using ENDF/B-VII actually produced worse agreement with the measured reactivity decrement. Using ENDF/B-V with CENTRM combined with ENDF/B-VII criticality analysis did slightly improve the agreement, but since it increased the positive bias, it made the results non-conservative with the 0.0015 or 0.0025 bias.

Many criticality analyses are performed using MCNP rather than KENO. Analysis of the benchmarks using ENDF/B-VII depletion and MNCP5 with the ENDF/B-VII cross sections showed excellent agreement with the SCALE 6.1 KENO 238-group analyses. It appears that no change in the bias would be needed if MCNP were substituted for KENO. (Only one of the 11 benchmarks was checked, so this would need to be confirmed by a more complete analysis.) Continuous energy KENO was also used with disappointing results. The agreement with the benchmarks was worse than with the 238-group library, and the run times and stability were unacceptable.

The Kopp memo approach of using an uncertainty of 5% of the delta k of depletion was found to always be conservative at discharge burnups. At 30 GWD/MTU burnup, the Kopp uncertainty is 1.5% in k. The most positive bias for all combinations of codes and libraries is 0.72% in k (ENDF/B-V – NITAWL depletion with ENDF/B-VII k calculations – Table 8.1). To this the uncertainty of 0.0064 needs to be added making the most positive value 1.4% in k. Most combinations of the cross section and codes will produce smaller biases and uncertainty. At higher burnup, the Kopp approach is even more conservative. At low burnups, the Kopp approach may appear to be non-conservative since the recommend bias and uncertainty is not a function of burnup as it is with the Kopp approach. The non-conservatism is small so there would appear to be little concern over historical analyses. Analyses using the EPRI depletion reactivity benchmarks should show a significant benefit of over 1% in k at discharge burnups when compared to the historical Kopp memo approach.

The advantages of using the EPRI depletion reactivity benchmarks for burnup credit validation are:

1. Analyses of the depletion reactivity benchmarks closely match the analysis of the criticality analysis. Since both the criticality analysis and the benchmark analyses use lattice depletion, the modeling should be identical. This should

assure that the validation is properly applied to the criticality analysis. Chemical assays require special modeling in order to match the burnup at a particular point in the assembly. This special modeling forces differences between the validation and final models that could introduce errors. The worth uncertainty modeling is not even close to any models used in the criticality calculations.

2. The analysis of the reactivity decrement benchmarks with differing cross-section libraries showed that fairly large differences in reactivity can be due to fairly small differences in isotopic content. The uncertainties in the chemical assays produce differences in the depletion reactivity of around 1.5% to 2.5% in k. The agreement between the predictions and the benchmarks of the depletion reactivity given by the benchmarks is ten times closer (0.15%) than the uncertainty effect on k for the chemical assays. The uncertainty in isotopic content found in the chemical assays would make it difficult to ascertain a benefit from one cross-section library over another. With the reactivity decrement benchmarks ENDF/B-VII is clearly preferred. Meshing problems should be checked by showing convergence, but if that step were accidently skipped, it would never be seen with the chemical assay validation. (The spatial mesh problem with NEWT was only 0.24% in k.)
3. The analysis of the depletion reactivity benchmarks is simple. This simplicity means that it is likely to be performed by the same analyst that does the criticality analysis as opposed to a specialist. The results are simple to understand for both the analyst and the reviewer. Complex statistical analysis is not needed, and appropriate margins can easily be determined. The chemical assay analyses may be important for some specific purposes, but they do not lend themselves well for direct use in engineering applications.
4. The measured depletion reactivity produces a lower uncertainty in the depletion reactivity than chemical assays. This allows for more economical design. Further, for cask designs, it may allow higher capacity casks that have an overall public safety advantage due to less shipping and lower dose per assembly.

Section 10: References

1. "Benchmarks for Quantifying Fuel Reactivity Depletion Uncertainty," EPRI, Palo Alto, CA: 1022909 (2011): http://mydocs.epri.com/docs/public/000000000001022909.pdf.
2. Scale: A Comprehensive Modeling and Simulation Suite for Nuclear Safety Analysis and Design, ORNL/TM-2005/39, Version 6.1, June 2011. Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-785.
3. MCNP – A General Monte Carlo N-Particle Transport Code, Version 5, LA-UR-03-1987, Los Alamos National Laboratory, April 24, 2003 (Revised 2/1/2008).
4. ANSI/ANS-8.17-2004, "Criticality Safety Criteria for the Handling, Storage, and Transportation of LWR Fuel Outside Reactors," American Nuclear Society, La Grange Park, Illinois.
5. D. E. Mueller, et al, "An Approach for Validating Actinide and Fission Product Burnup Credit Criticality Safety Analyses – Criticality (keff) Predictions," 9th International Conference on Nuclear Criticality Safety, ICNC 2011, Edinburgh, Scotland, (2011).
6. ANSI/ANS-8.27-2008, "Burnup Credit for LWR Fuel," American Nuclear Society, La Grange Park, Illinois.
7. L. Kopp, NRC memorandum from L. Kopp to T. Collins, "Guidance on the Regulatory Requirements for Criticality Analysis of Fuel Storage at Light-Water Reactor Power Plants," dated August 19, 1998 (ADAMS Accession No. ML003728001).
8. J. Rhodes, et al., "CASMO-5 Development and Applications," PHYSOR-2006, Vancouver, BC, Canada. September 10-14, (2006).
9. J. Cronin, et al., "SIMULATE-3 Methodology Manual," STUDSVIK/SOA-95/18, Studsvik of America, Inc. (1995).
10. I. C. Gauld, G. Ilas, and G. Radulescu, Uncertainties in Predicted Isotopic Compositions for High Burnup PWR Spent Nuclear Fuel, NUREG/CR-7012, Office of Nuclear Regulatory Research, USNRC, Rockville, MD, January 2011.
11. W. J. Marshall and B. T. Rearden, Criticality Safety Validation of Scale 6.1, ORNL/TM-2011/450, Oak Ridge National Laboratory, Oak Ridge, TN, November 2011.

Appendix A: Description of Available Input Decks

The complete set of input decks for the SCALE 6.1 ENDF/B-VII analysis is available from an executable file accompanying the electronic version of this report, which is downloadable from the EPRI web site.

The file naming scheme is as follows:

The depletion deck names are **caseXYYkenoe7g.in** where X is the case number and YY is the burnup. Case 11 is designated "h" rather than 11 so all the file names have the same length. Please note that Cases 3, 9, and 10 use the same depletion analysis, so Cases 9 and 10 decks are not present. These decks use KENO for their depletion hence keno in the file name. They use ENDF/B-VII 238-group cross sections, hence the "e7g." Continuous energy depletion is not available yet in SCALE so the g is not actually useful.

The final k deck names are **bmXbuYYctZke7g.in** where X is the case number, YY is the burnup, and Z is the cooling time of 100, 5, or 15. Also note that for these decks X goes from 1 to 11 (not h). The initial condition deck name follows the same convention, but ctZk is removed since it is not relevant for the initial condition.

The depletion decks write atom density files in the directory of the SCALE input deck. This is done with a SHELL command. The SHELL commands in the input decks are for WINDOWS. If these decks are to be run under UNIX, the copy command needs to be changed to the UNIX command. The file names of the atom density files are **caseXYYZkenoe7g.txt**. Here X and YY follows the convention of the depletion decks. Z is 5, 15, or 100.

Before running the final k calculations, the temperature in the atom density files must be changed from the hot full power temperature to the cold condition, 293K. The user simply needs to open each file with a text editor and do a simple "change all" command to fix the temperature and then save and close.

The final k decks assume the atom density files are stored at c:\epri\e7dep\. If the user stores the atom density files at a different directory, this will need to be changed for each input deck.

Sample depletion and criticality decks follow.

Table A-1
Sample Depletion Input Deck For Case 7

```
=t5-depl parm=(addnux=4)
EPRI Benchmark Case 7 60 GWD/MTU 100 hours
v7-238
read comp
uo2 10 den=10.340 1 900 92234 0.034
92235 4.25
92238 95.716 end
uo2 11 den=10.340 1 900 92234 0.034
92235 4.25
92238 95.716 end
zirc4 20 1 618.4 end
h2o 30 den=0.710909 1 580.00 end
arbmb 0.710909 1 1 0 0 5000 100 30 900e-06 580.00
end
n 40 den=0.00125 1 600 end
zirc4 21 1 618.4 end
h2o 31 den=0.710909 1 580.00 end
arbmb 0.710909 1 1 0 0 5000 100 31 900e-06 580.00
end
n 41 den=0.00125 1 600 end
c 50 0  .00140923 end
o 50 0  0.0623784 end
al 50 0 0.0415904 end
b-10 50 0 .00299030 end
b-10 60 0  .0215913        end
zr  60 0  .0322187        end
end comp
'
read celldata
latticecell squarepitch pitch=1.2598 30
fueld=0.8192 10
gapd=0.836 40
cladd=0.950 20 end
latticecell squarepitch pitch=1.2598 31
fueld=0.8192 11
gapd=0.836 41
cladd=0.950 21 end
end celldata
'
read depletion
10 11 flux 50 60 end
end depletion
'
read burndata
' Steps of 150, 350, 500(3), 1000(4), 2000(2), 2000(x)
power=38.1 burn=3.937 nlib=1 end
power=38.1 burn=9.18635 nlib=1 end
power=38.1 burn=39.37 nlib=3 end
power=38.1 burn=104.9868 nlib=4 end
power=38.1 burn=104.9868 nlib=2  end
power=38.1 burn=262.4671 nlib=5  end
power=38.1 burn=262.4671 nlib=5  end
power=38.1 burn=262.4671 nlib=5  end
power=38.1 burn=262.4671 nlib=5  end
power=38.1 burn=262.4671 nlib=5 down=4.16667 end
end burndata
'
read opus
units=atoms
symnuc= o-16 u-234 u-235 u-236 u-238 np-237
pu-238 pu-239 pu-240 pu-241 pu-242 am-241
am-242m am-243 cm-242 cm-243 cm-244 cm-245 cm-
246 cm-247
kr-83 zr-93 zr-95 mo-95 mo-96 mo-97 mo-98 mo-99
mo-100
tc-99 ru-101 ru-102 ru-103 ru-104 ru-106 rh-103
pd-105 pd-107 pd-108 ag-109
cd-113 te-129m i-129 xe-131 la-139 la-140
cs-133 cs-134 cs-135 cs-137
nd-143 nd-144 nd-145 nd-146 nd-148 nd-150
eu-151 eu-153 eu-154 eu-155
ce-143 ce-144 sb-125 pm-147 pm-148m
sm-147 sm-148 sm-149 sm-150
sm-151 sm-152 sm-154
gd-155 gd-156 gd-157 b-10 end
matl=10 11 50 60 end
end opus
'
'
read model
read parm   tme=900.0  gen=1000 npg=4000 run=yes
plt=no
 htm=no    far=no  NB8=500
                end parm
                read geom
                unit 1
                com='fuel rod'
cylinder  10  1    0.4096  1.0  0.
cylinder  40  1    0.418  1.0  0.
cylinder  20  1    0.475  1.0  0.
cuboid    30  1  4p0.6299  1.0  0.
unit 4
com='fuel rod with IFBA'
cylinder  11  1    0.4096  1.0  0.
cylinder  60  1    0.4106  1.0  0.
cylinder  0  1    0.418  1.0  0.
cylinder  21  1    0.475  1.0  0.
cuboid    31  1  4p0.6299  1.0  0.
unit 2
com='guide-tube'
cylinder  30  1     0.561  1.0  0.
cylinder  20  1     0.612  1.0  0.
cuboid    30  1  4p0.6299  1.0  0.
unit 5
com='guide-tube waba'
cylinder 30  1 .2860  1.0  0.
cylinder 20  1 .3390  1.0  0.
cylinder 0  1  .3530 1.0  0.
cylinder 50  1  .4040 1.0  0.
cylinder 0  1  .4180 1.0  0.
cylinder 20  1  .484  1.0  0.
cylinder  30  1     0.561  1.0  0.
cylinder  20  1     0.612  1.0  0.
cuboid    30  1  4p0.6299  1.0  0.
unit 3
com='fuel assembly'
array 1 3*0.0
'
global unit 99
com='CASMO single assembly model'
cuboid 30 1 21.5036 0.0  21.5036 0.0  1.0  0.
hole 3 0.0434999999999999 0.0434999999999999 0.0
end geom
read array
ara=1   com='layout of pins in the assembly'
      nux=17   nuy=17   nuz=1
 fill
4 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 4
1 1 1 1 1 4 1 1 4 1 1 4 1 1 1 1 1
1 1 1 4 4 5 4 4 5 4 4 5 4 4 1 1 1
1 1 4 5 4 4 1 1 4 1 1 4 4 5 4 1 1
1 1 4 4 1 4 1 1 4 1 1 4 1 4 4 1 1
1 4 5 4 4 2 4 4 5 4 4 2 4 4 5 4 1
1 1 4 1 1 4 1 1 4 1 1 4 1 1 4 1 1
1 1 4 1 1 4 1 1 4 1 1 4 1 1 4 1 1
1 4 5 4 4 5 4 4 2 4 4 5 4 4 5 4 1
1 1 4 1 1 4 1 1 4 1 1 4 1 1 4 1 1
1 1 4 1 1 4 1 1 4 1 1 4 1 1 4 1 1
1 4 5 4 4 2 4 4 5 4 4 2 4 4 5 4 1
1 1 4 4 1 4 1 1 4 1 1 4 1 4 4 1 1
1 1 4 5 4 4 1 1 4 1 1 4 4 5 4 1 1
1 1 1 4 4 5 4 4 5 4 4 5 4 4 1 1 1
1 1 1 1 1 4 1 1 4 1 1 4 1 1 1 1 1
4 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 4
 end fill
end array
read bnds   xfc=mirror  yfc=mirror  zfc=mirror  end bnds
end data
end model
end
=shell
copy StdCmpMix00010 %RTNDIR%\Case760100kenoe7gf.txt
copy StdCmpMix00011 %RTNDIR%\Case760100kenoe7gif.txt
copy StdCmpMix00050 %RTNDIR%\Case760100kenoe7gwf.txt
copy StdCmpMix00060 %RTNDIR%\Case760100kenoe7gbf.txt
end
=t5-depl parm=(addnux=4)
EPRI Benchmark Case 7 60 GWD/MTU 5 years KENO Deplete
v7-238
read comp
< StdCmpMix00010
< StdCmpMix00011
zirc4 20 1 618.4 end
h2o 30 den=0.710909 1 580.00 end
arbmb 0.710909 1 1 0 0 5000 100 30 900e-06 580.00 end
n 40 den=0.00125 1 600 end
```

```
zirc4 21 1 618.4 end
h2o 31 den=0.710909 1 580.00 end
arbmb 0.710909 1 1 0 0 5000 100 31 900e-06 580.00 end
n 41 den=0.00125 1 600 end
< StdCmpMix00050
< StdCmpMix00060
end comp
'
                read celldata
                latticecell squarepitch pitch=1.2598 30
                fueld=0.8192 10
                gapd=0.836 40
                cladd=0.950 20 end
                latticecell squarepitch pitch=1.2598 31
                fueld=0.8192 11
                gapd=0.836 41
                cladd=0.950 21 end
                end celldata
                '
                read depletion
                10 11 flux 50 60 end
                end depletion
                '
                read burndata
                power=00.1 burn=.0002 nlib=1 down=1822.08 end
                end burndata
                '
                read opus
                units=atoms
                symnuc= o-16 u-234 u-235 u-236 u-238 np-237 pu-
                238 pu-239
                pu-240 pu-241 pu-242 am-241 am-242m am-243 cm-
                242
                cm-243 cm-244 cm-245 cm-246 cm-247
                kr-83 zr-93 zr-95 mo-95 mo-96 mo-97 mo-98 mo-99
                mo-100
                tc-99 ru-101 ru-102 ru-103 ru-104 ru-106 rh-103
                pd-105 pd-107 pd-108 ag-109
                cd-113 te-129m i-129 xe-131 la-139 la-140
                cs-133 cs-134 cs-135 cs-137
                nd-143 nd-144 nd-145 nd-146 nd-148 nd-150
                eu-151 eu-153 eu-154 eu-155
                ce-143 ce-144 sb-125 pm-147 pm-148m
                sm-147 sm-148 sm-149 sm-150
                sm-151 sm-152 sm-154
                gd-155 gd-156 gd-157 b-10 end
                matl=10 11 50 60 end
                end opus
                '
                '
                read model
                read parm  tme=900.0  gen=500 npg=1000 run=yes
                plt=no
                 htm=no   far=no  NB8=500
                end parm
                read geom
                unit 1
                com='fuel rod'
                cylinder  10  1   0.4096  1.0  0.
                cylinder  40  1   0.418  1.0  0.
                cylinder  20  1   0.475  1.0  0.
                cuboid   30  1  4p0.6299  1.0  0.
                unit 4
                com='fuel rod with IFBA'
                cylinder  11  1   0.4096  1.0  0.
                cylinder  60  1   0.4106  1.0  0.
                cylinder  0  1   0.418  1.0  0.
                cylinder  21  1   0.475  1.0  0.
                cuboid   31  1  4p0.6299  1.0  0.
                unit 2
                com='guide-tube'
                cylinder  30  1    0.561  1.0  0.
                cylinder  20  1    0.612  1.0  0.
                cuboid   30  1  4p0.6299  1.0  0.
                unit 5
                com='guide-tube waba'
                cylinder 30  1  .2860  1.0  0.
                cylinder 20  1  .3390  1.0  0.
                cylinder 0  1  .3530 1.0  0.
                cylinder 50  1  .4040 1.0  0.
                cylinder 0  1  .4180 1.0  0.
                cylinder 20  1  .484  1.0  0.
                cylinder  30  1    0.561  1.0  0.
                cylinder  20  1    0.612  1.0  0.
                cuboid   30  1  4p0.6299  1.0  0.
                unit 3
                com='fuel assembly'
                array 1 3*0.0
                '
                global unit 99
                com='CASMO single assembly model'
                cuboid 30 1 21.5036 0.0  21.5036 0.0  1.0  0.
                hole 3 0.0434999999999999 0.0434999999999999 0.0
                end geom
                read array
                ara=1   com='layout of pins in the assembly'
                     nux=17  nuy=17  nuz=1
                 fill
                 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 4
1 1 1 1 1 4 1 1 4 1 1 4 1 1 1 1 1
1 1 1 4 4 5 4 4 5 4 4 5 4 4 1 1 1
1 1 4 5 4 4 1 1 4 1 1 4 4 5 4 1 1
1 1 4 4 1 4 1 1 4 1 1 4 1 4 4 1 1
1 4 5 4 4 2 4 4 5 4 4 2 4 4 5 4 1
1 1 4 1 1 4 1 1 4 1 1 4 1 1 4 1 1
1 1 4 1 1 4 1 1 4 1 1 4 1 1 4 1 1
1 4 5 4 4 5 4 4 2 4 4 5 4 4 5 4 1
1 1 4 1 1 4 1 1 4 1 1 4 1 1 4 1 1
1 1 4 1 1 4 1 1 4 1 1 4 1 1 4 1 1
1 4 5 4 4 2 4 4 5 4 4 2 4 4 5 4 1
1 1 4 4 1 4 1 1 4 1 1 4 1 4 4 1 1
1 1 4 5 4 4 1 1 4 1 1 4 4 5 4 1 1
1 1 1 4 4 5 4 4 5 4 4 5 4 4 1 1 1
1 1 1 1 1 4 1 1 4 1 1 4 1 1 1 1 1
4 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 4
 end fill
end array
read bnds   xfc=mirror  yfc=mirror  zfc=mirror  end bnds
end data
end model
end
=shell
copy StdCmpMix00010 %RTNDIR%\Case7605kenoe7gf.txt
copy StdCmpMix00011 %RTNDIR%\Case7605kenoe7gif.txt
copy StdCmpMix00050 %RTNDIR%\Case7605kenoe7gwf.txt
copy StdCmpMix00060 %RTNDIR%\Case7605kenoe7gbf.txt
end
=t5-depl parm=(addnux=4)
EPRI Benchmark Case 7 60 GWD/MTU 15 years KENO Deplete
v7-238
read comp
< StdCmpMix00010
< StdCmpMix00011
zirc4 20 1 618.4 end
h2o 30 den=0.710909 1 580.00 end
arbmb 0.710909 1 1 0 0 5000 100 30 900e-06 580.00 end
n 40 den=0.00125 1 600 end
zirc4 21 1 618.4 end
h2o 31 den=0.710909 1 580.00 end
arbmb 0.710909 1 1 0 0 5000 100 31 900e-06 580.00 end
n 41 den=0.00125 1 600 end
< StdCmpMix00050
< StdCmpMix00060
end comp
'
read celldata
latticecell squarepitch pitch=1.2598 30
fueld=0.8192 10
gapd=0.836 40
cladd=0.950 20 end
latticecell squarepitch pitch=1.2598 31
fueld=0.8192 11
gapd=0.836 41
cladd=0.950 21 end
end celldata
'
read depletion
10 11 flux 50 60 end
end depletion
'
read burndata
power=00.1 burn=.0002 nlib=1 down=3652.50 end
end burndata
'
read opus
units=atoms
symnuc= o-16 u-234 u-235 u-236 u-238 np-237 pu-238 pu-239
pu-240 pu-241 pu-242 am-241 am-242m am-243 cm-242
cm-243 cm-244 cm-245 cm-246 cm-247
kr-83 zr-93 zr-95 mo-95 mo-96 mo-97 mo-98 mo-99 mo-100
tc-99 ru-101 ru-102 ru-103 ru-104 ru-106 rh-103
pd-105 pd-107 pd-108 ag-109
cd-113 te-129m i-129 xe-131 la-139 la-140
cs-133 cs-134 cs-135 cs-137
nd-143 nd-144 nd-145 nd-146 nd-148 nd-150
eu-151 eu-153 eu-154 eu-155
ce-143 ce-144 sb-125 pm-147 pm-148m
sm-147 sm-148 sm-149 sm-150
sm-151 sm-152 sm-154
gd-155 gd-156 gd-157 b-10 end
matl=10 11 50 60 end
end opus
```

```
'
'
read model
read parm  tme=900.0  gen=500 npg=1000 run=yes  plt=no
 htm=no   far=no  NB8=500
end parm
read geom
unit 1
                com='fuel rod'
                cylinder  10  1   0.4096  1.0  0.
                cylinder  40  1   0.418  1.0  0.
                cylinder  20  1   0.475  1.0  0.
                cuboid   30  1  4p0.6299  1.0  0.
                unit 4
                com='fuel rod with IFBA'
                cylinder  11  1   0.4096  1.0  0.
                cylinder  60  1   0.4106  1.0  0.
                cylinder  0  1   0.418  1.0  0.
                cylinder  21  1   0.475  1.0  0.
                cuboid   31  1  4p0.6299  1.0  0.
                unit 2
                com='guide-tube'
                cylinder  30  1    0.561  1.0  0.
                cylinder  20  1    0.612  1.0  0.
                cuboid   30  1  4p0.6299  1.0  0.
                unit 5
                com='guide-tube waba'
                cylinder 30  1  .2860  1.0  0.
                cylinder 20  1  .3390  1.0  0.
                cylinder 0  1  .3530 1.0  0.
                cylinder 50  1  .4040 1.0  0.
                cylinder 0  1  .4180 1.0  0.
                cylinder 20  1  .484  1.0  0.
                cylinder  30  1    0.561  1.0  0.
                cylinder  20  1    0.612  1.0  0.
                cuboid   30  1  4p0.6299  1.0  0.
                unit 3
                com='fuel assembly'
                array 1 3*0.0
                '
                global unit 99
                com='CASMO single assembly model'
                cuboid 30 1 21.5036 0.0  21.5036 0.0  1.0  0.
                hole 3 0.0434999999999999 0.0434999999999999 0.0
                end geom

read array
ara=1   com='layout of pins in the assembly'
     nux=17  nuy=17  nuz=1
 fill
 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 4
 1 1 1 1 1 4 1 1 4 1 1 4 1 1 1 1 1
 1 1 1 4 4 5 4 4 5 4 4 5 4 4 1 1 1
 1 1 4 5 4 4 1 1 4 1 1 4 4 5 4 1 1
 1 1 4 4 1 4 1 1 4 1 1 4 1 4 4 1 1
 1 4 5 4 4 2 4 4 5 4 4 2 4 4 5 4 1
 1 1 4 1 1 4 1 1 4 1 1 4 1 1 4 1 1
 1 1 4 1 1 4 1 1 4 1 1 4 1 1 4 1 1
 1 4 5 4 4 5 4 4 2 4 4 5 4 4 5 4 1
 1 1 4 1 1 4 1 1 4 1 1 4 1 1 4 1 1
 1 1 4 1 1 4 1 1 4 1 1 4 1 1 4 1 1
 1 4 5 4 4 2 4 4 5 4 4 2 4 4 5 4 1
 1 1 4 4 1 4 1 1 4 1 1 4 1 4 4 1 1
 1 1 4 5 4 4 1 1 4 1 1 4 4 5 4 1 1
 1 1 1 4 4 5 4 4 5 4 4 5 4 4 1 1 1
 1 1 1 1 1 4 1 1 4 1 1 4 1 1 1 1 1
 4 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 4
 end fill
end array
read bnds   xfc=mirror  yfc=mirror  zfc=mirror  end bnds
end data
end model
end
=shell
copy StdCmpMix00010 %RTNDIR%\Case76015Kenoe7gf.txt
copy StdCmpMix00011 %RTNDIR%\Case76015Kenoe7gif.txt
copy StdCmpMix00050 %RTNDIR%\Case76015Kenoe7gwf.txt
copy StdCmpMix00060 %RTNDIR%\Case76015Kenoe7gbf.txt
end
```

Table A-2
Sample Criticality Input Deck For Case 7 100-Hour Cooling

```
=csas5
EPRI Benchmark 7
v7-238
READ COMPOSITION
< c:\epri\e7dep\case760100kenoe7gf.txt
< c:\epri\e7dep\case760100kenoe7gif.txt
zirc2    2  1.  end
h2o      3  1.  end
zirc2    21  1.  end
h2o      31  1.  end
< c:\epri\e7dep\case760100kenoe7gwf.txt
< c:\epri\e7dep\case760100kenoe7gbf.txt
end comp
READ CELLDATA
LATTICECELL SQUAREPITCH  PITCH=1.2598  3
FUELD=0.8192  10  CLADD=0.95  2
 GAPD=0.836  0  END
LATTICECELL SQUAREPITCH  PITCH=1.2598  31
FUELD=0.8192  11  CLADD=0.95  21
 GAPD=0.836  0  END
END CELLDATA
read parm  tme=900.0  gen=1500 npg=6000 run=yes
plt=no
 htm=no   far=no  NB8=500
end parm
read geom
unit 1
com='fuel rod'
cylinder  10  1   0.4096  1.0  0.
cylinder  0  1   0.418  1.0  0.
cylinder  2  1   0.475  1.0  0.
cuboid   3  1  4p0.6299  1.0  0.
unit 4
com='fuel rod with IFBA'
cylinder  11  1   0.4096  1.0  0.
cylinder  60  1   0.4106  1.0  0.
cylinder  0  1   0.418  1.0  0.
cylinder  21  1   0.475  1.0  0.
cuboid   31  1  4p0.6299  1.0  0.
unit 2
com='guide-tube'
cylinder  3  1   0.561  1.0  0.
cylinder  2  1   0.612  1.0  0.
cuboid   3  1  4p0.6299  1.0  0.
unit 3
com='fuel assembly'
array 1 3*0.0
'
unit 5
com='guide-tube waba'
cylinder 3  1 .2860  1.0  0.
cylinder 2  1 .3390  1.0  0.
cylinder 0  1  .3530 1.0  0.
cylinder 50  1  .4040 1.0  0.
cylinder 0  1  .4180 1.0  0.
cylinder 2  1  .484  1.0  0.
cylinder  3  1   0.561  1.0  0.
cylinder  2  1   0.612  1.0  0.
cuboid   3  1  4p0.6299  1.0  0.
'
global unit 99
com='CASMO single assembly model'
cuboid 3 1 21.5036 0.0  21.5036 0.0  1.0  0.
hole 3 0.0434999999999999 0.0434999999999999 0.0
end geom
read array
ara=1   com='layout of pins in the assembly'
                                        nux=17  nuy=17  nuz=1
fill
4 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 4
1 1 1 1 1 4 1 1 4 1 1 4 1 1 1 1 1
1 1 1 4 4 5 4 4 5 4 4 5 4 4 1 1 1
1 1 4 5 4 4 1 1 4 1 1 4 4 5 4 1 1
1 1 4 4 1 4 1 1 4 1 1 4 4 4 1 1 1
1 4 5 4 4 2 4 4 5 4 4 2 4 4 5 4 1
1 1 4 1 1 4 1 1 4 1 1 4 1 1 4 1 1
1 1 4 1 1 4 1 1 4 1 1 4 1 1 4 1 1
1 4 5 4 4 5 4 4 2 4 4 5 4 4 5 4 1
1 1 4 1 1 4 1 1 4 1 1 4 1 1 4 1 1
1 1 4 1 1 4 1 1 4 1 1 4 1 1 4 1 1
1 4 5 4 4 2 4 4 5 4 4 2 4 4 5 4 1
1 1 4 4 1 4 1 1 4 1 1 4 1 4 4 1 1
1 1 4 5 4 4 1 1 4 1 1 4 4 5 4 1 1
1 1 1 4 4 5 4 4 5 4 4 5 4 4 1 1 1
1 1 1 1 1 4 1 1 4 1 1 4 1 1 1 1 1
4 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 4
end fill
end array
read bnds   xfc=mirror  yfc=mirror  zfc=mirror  end bnds
'
' ******** COLORS FOR PLOT **********
'#DEFINE    #WHITE#    255 255 255
'#DEFINE    #BLACK#    0  0  0
'#DEFINE    #RED#      255  0  0
'#DEFINE    #BLUE#     0  0 255
read plot
scr=yes  pic=mat lpi=10
clr=  0    255 255 255
    1    255  0  0
    2    0  0  0
    3     0  0 255
    end color
 ttl='2-d radial cross section'
xul=-.2  yul=21.7036  zul=.5
xlr=21.7036  ylr=-.2  zlr=.5
 ndn=1600
 uax=1 vdn=-1 end
end plot
end data
end
```

ENDF/B-V analysis is not recommended, but the depletion input decks for this analysis are provided electronically. The key reason for supplying these decks is to demonstrate NEWT input. The decks are set up for using CENTRM in the depletions. The depletion decks are named caseXYYdmc.in. The final k decks are not provided since they are the same as the ENDF/B-VII decks except for changing the atom density file names and directory. Also, unless the user wishes to do the final k calculations with ENDF/B-VII, the cross-section file name on the third line of input will need to be adjusted to "44groupndf5."

For those who wish to use MCNP for the benchmark analysis, zero burnup and 60 GWD/MTU burnup input decks are provided electronically. The 60 GWD/MTU deck is useful, so the user will not need to create for themselves the isotope ids. In order to match the SCALE depletion with atom densities with the MCNP, the user will want to sort the atom density file alphabetically by the isotope name and then remove isotopes with very small atom densities. The user will have to take care to make sure the atom densities match the ids. Since the low atom density isotopes are dispersed in the data, there is no simple automated method to describe how to do this.

Appendix B: Reactivity Benchmark Specifications [1]

Eleven experimental benchmarks, based on simplifications of publically-available data for the Westinghouse RFA and OFA assemblies, are described here. They cover a range of

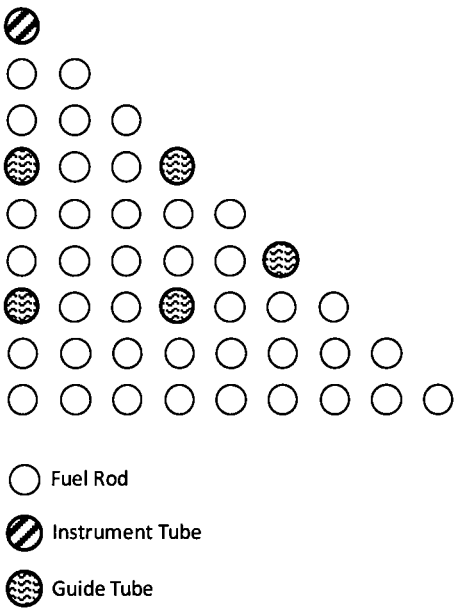
- enrichments
- burnable absorber ladings
- boron concentrations
- fuel and coolant temperatures
- decay times

For each case in Table B-1, a complete geometrical and material description follows.

Note that all lattices are depleted with a power density of 104.5 W/cc (38.1 W/gm heavy metal) – except for Case 11 which is depleted at 156.75 W/cc (150% of nominal power density).

Table B-1
Benchmark Lattice Cases

1	3.25% Enrichment
2	5.00% Enrichment
3	4.25% Enrichment
4	off-nominal pin diameter depletion
5	20 WABA depletion
6	104 IFBA depletion
7	104 IFBA plus 20 WABA depletion
8	high boron depletion = 1500 ppm
9	branch to hot rack (150°F coolant/fuel) = 338.7K
10	branch to high rack boron = 1500 ppm
11	high power depletion (power, coolant/fuel temp)



Physical Description

Number of pins along side	17
Pin pitch	1.2598 cm
Inter-assembly spacing	21.5036 cm
Fuel pellet OR	0.4096 cm
Clad IR	0.4180 cm
Clad OR	0.4750 cm
Guide/instrument tube IR	0.5610 cm
Guide/instrument tube OR	0.6120 cm

Structural Material Description

Material (Zr-4)Density	6.55 (g/cm3)
Temp., unheated	580K
Temp., heated	$0.12*T_{fuel}+0.88*T_{coolant}$
Nuclide	**Number Density**
Zr-4	4.32444E+22

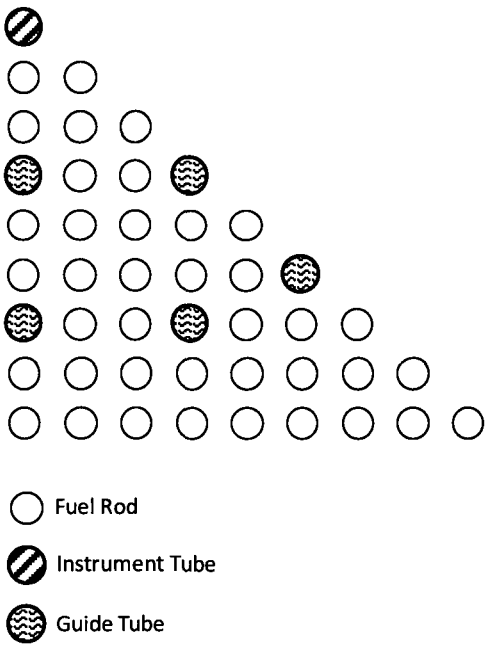
Coolant Description, Depletion (Nominal)

Boron Concentration	900 ppm
Temperature	580 K
Nuclide	**Number Density**
H	4.75756E+22
O	2.37894E+22
B	3.56773E+19

Coolant Description, Cold

Boron Concentration	0 ppm
Temperature	293 K
Nuclide	**Number Density**
H	6.67431E+22
O	3.33738E+22

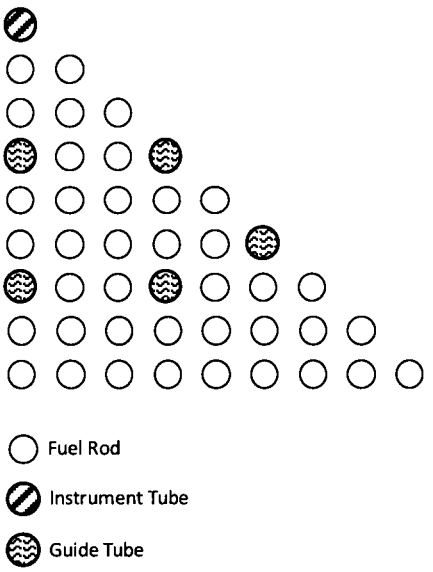
Figure B-1
Nominal Fuel Assembly



Fuel Material Description

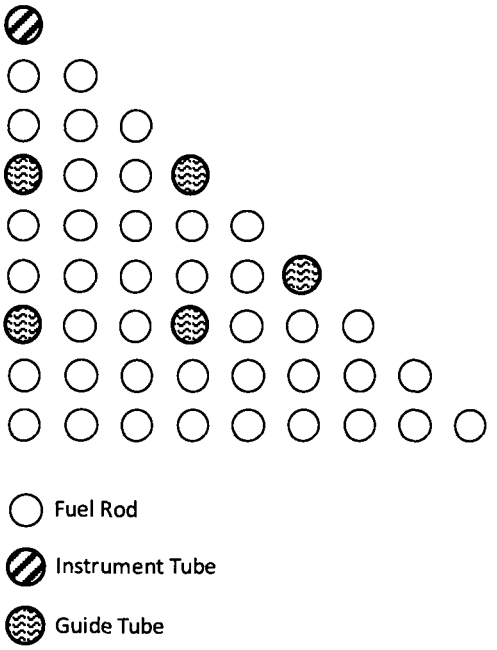
Material Density	10.340 (g/cm3)
Fuel Temperature	900 K
Nuclide	**Number Density**
U-235	7.59010E+20
U-234	6.09917E+18
U-238	2.23037E+22
O	4.61377E+22

Figure B-2
CASE 1: 3.25% Enriched - No Burnable Absorbers



Fuel Material Description	
Material Density	10.340 (g/cm3)
Fuel Temperature	900 K
Nuclide	**Number Density**
U-235	1.16768E+21
U-234	9.38308E+18
U-238	2.18964E+22
O	4.61469E+22

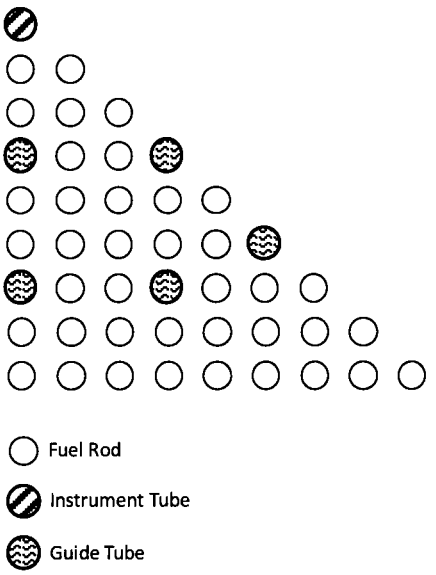
Figure B-3
CASE 2: 5.00% Enriched - No Burnable Absorbers



Fuel Material Description

Material Density	10.340 (g/cm3)
Fuel Temperature	900 K
Nuclide	**Number Density**
U-235	9.92536E+20
U-234	7.97571E+18
U-238	2.20709E+22
O	4.61429E+22

Figure B-4
CASE 3: 4.25% Enriched - No Burnable Absorbers



Physical Description

Number of pins along side	17
Pin pitch	1.2598 cm
Inter-assembly spacing	21.5036 cm
Fuel pellet OR	0.3922 cm
Clad IR	0.4000 cm
Clad OR	0.4572 cm
Guide/instrument tube IR	0.5610 cm
Guide/instrument tube OR	0.6120 cm

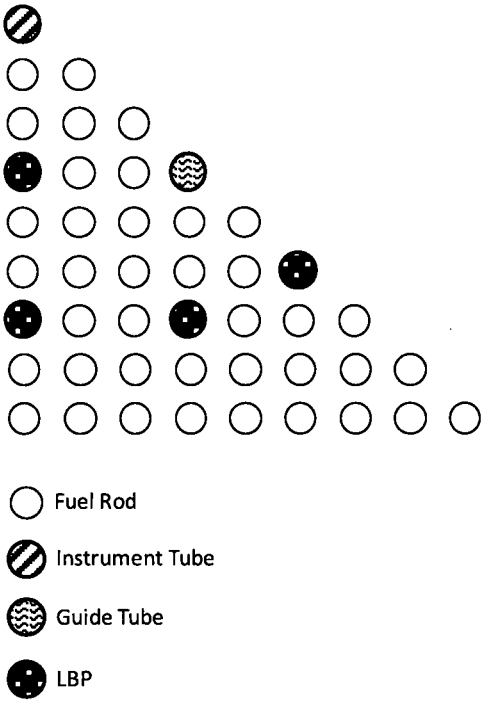
Structural Material Description

Material (Zr-4)Density	6.55 (g/cm3)
Temp., unheated	580K
Temp., heated	$0.12*T_{fuel}+0.88*T_{coolant}$
Nuclide	**Number Density**
Zr-4	4.32444E+22

Fuel Material Description

Material Density	10.340 (g/cm3)
Fuel Temperature	900 K
Nuclide	**Number Density**
U-235	9.92536E+20
U-234	7.97571E+18
U-238	2.20709E+22
O	4.61429E+22

Figure B-5
CASE 4: Small Fuel Pin



Fuel Material Description

Material Density	10.340 (g/cm3)
Fuel Temperature	900 K
Nuclide	**Number Density**
U-235	9.92536E+20
U-234	7.97571E+18
U-238	2.20709E+22
O	4.61429E+22

Lumped Burnable Poison (WABA)

Annular clad IR	0.2860 cm
Annular clad OR	0.3390 cm
Active region IR	0.3530 cm
Active region OR	0.4040 cm
Inner clad IR	0.4180 cm
Inner clad OR	0.4840 cm
Outer clad IR	0.5610 cm
Outer clad OR	0.6120 cm

Active Region

Material Density	3.65 (g/cm3)
Boron Loading	6.03 mg/cm B-10
Nuclide	**Number Density**
C	1.40923E+21
O	6.23784E+22
Al	4.15904E+22
B-10	2.99030E+21

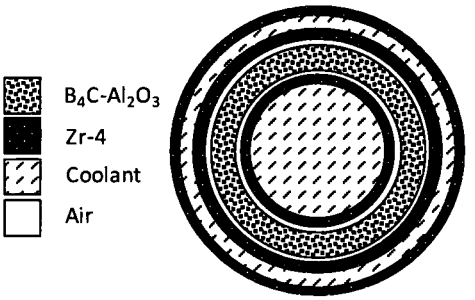
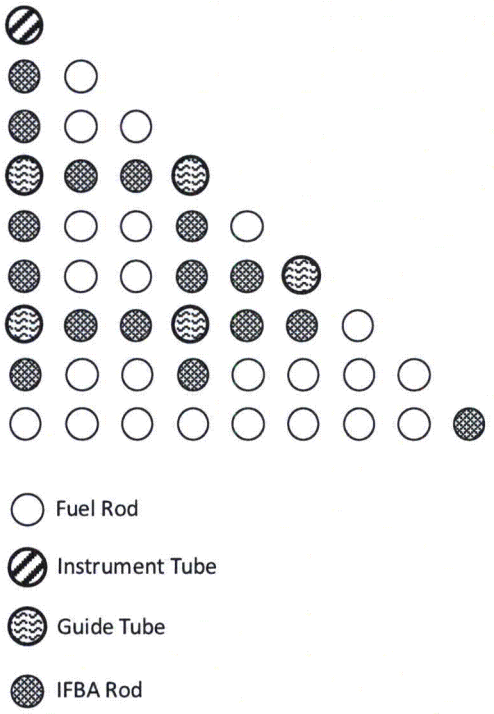
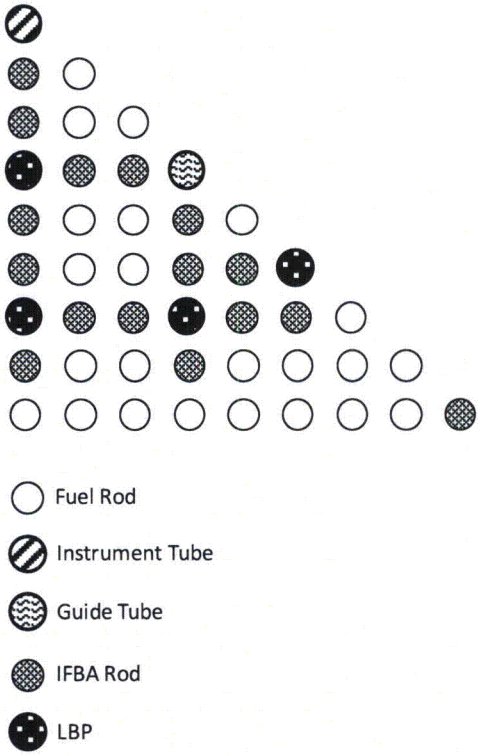


Figure B-6
CASE 5: Lumped Burnable Poison (WABA) Pins



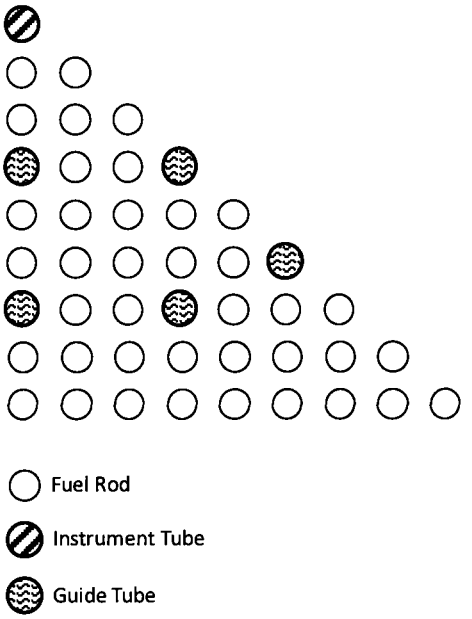
Fuel Material Description	
Material Density	10.340 (g/cm3)
Fuel Temperature	900 K
IFBA Description	
Material Density	6.100 (g/cm3)
Coating Density	0.925 mg/cm B-10
Coating Thickness	0.01 mm
Nuclide	**Number Density**
U-235	9.92536E+20
U-234	7.97571E+18
U-238	2.20709E+22
O	4.61429E+22
Zr-4	3.22187E+22
B-10	2.15913E+22

Figure B-7
CASE 6: 104 Integral Fuel Burnable Absorbers (IFBA) Pins



Fuel Material Description	
Material Density	10.340 (g/cm3)
Fuel Temperature	900 K
IFBA Description	
Material Density	6.100 (g/cm3)
Coating Density	0.925 mg/cm B-10
Coating Thickness	0.01 mm
Nuclide	**Number Density**
U-235	9.92536E+20
U-234	7.97571E+18
U-238	2.20709E+22
O	4.61429E+22
Zr-4	3.22187E+22
B-10	2.15913E+22
Lumped Burnable Poison (WABA)	
Material Density	3.65 (g/cm3)
Boron Loading	6.03 mg/cm B-10
Nuclide	**Number Density**
C	1.40923E+21
O	6.23784E+22
Al	4.15904E+22
B-10	2.99030E+21

Figure B-8
CASE 7: 104 IFBA and 20 WABA Pins



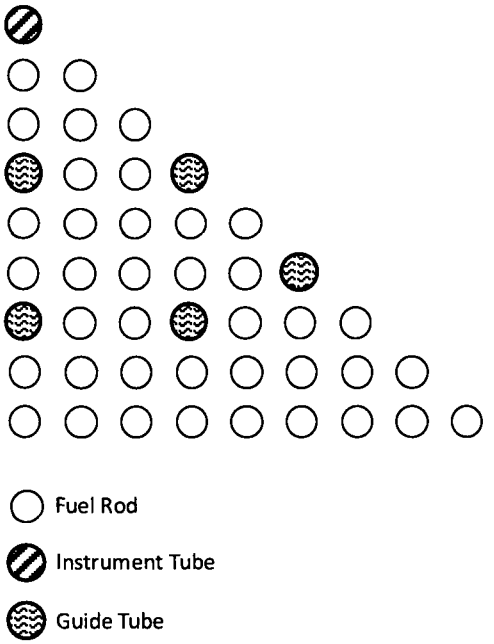
Fuel Material Description

Material Density	10.340 (g/cm3)
Fuel Temperature	900 K
Nuclide	**Number Density**
U-235	9.92536E+20
U-234	7.97571E+18
U-238	2.20709E+22
O	4.61429E+22

Coolant Description, Depletion

Boron Concentration	1500 ppm
Temperature	580 K
Nuclide	**Number Density**
H	4.75756E+22
O	2.37894E+22
B	5.94621E+19

Figure B-9
CASE 8: High Boron Depletion



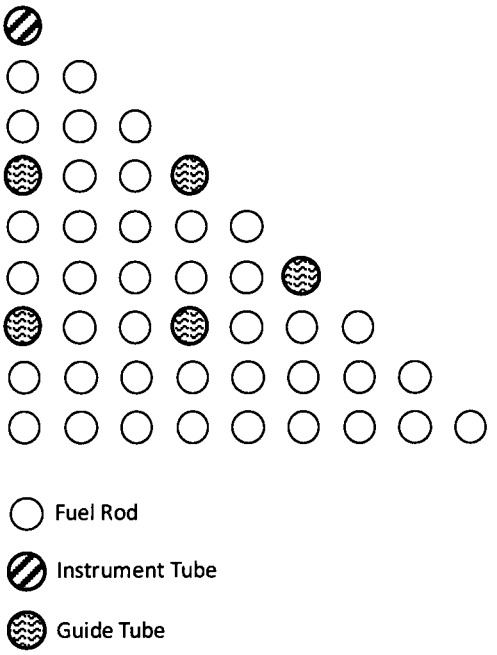
Fuel Material Description

Material Density	10.340 (g/cm3)
Fuel Temperature	900 K
Nuclide	**Number Density**
U-235	9.92536E+20
U-234	7.97571E+18
U-238	2.20709E+22
O	4.61429E+22

Coolant Description, Cold

Boron Concentration	0 ppm
Temperature	338.7 K
Nuclide	**Number Density**
H	6.55262E+22
O	3.27653E+22

Figure B-10
CASE 9: Nominal Case – Branch to Hot Rack Conditions



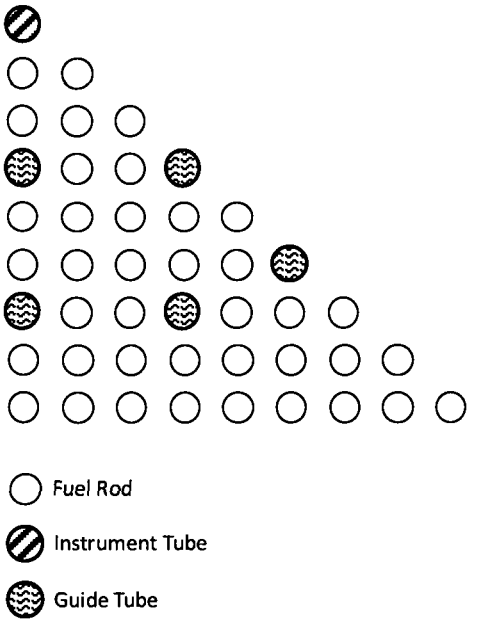
Fuel Material Description

Material Density	10.340 (g/cm3)
Fuel Temperature	900 K
Nuclide	**Number Density**
U-235	9.92536E+20
U-234	7.97571E+18
U-238	2.20709E+22
O	4.61429E+22

Coolant Description, Cold

Boron Concentration	1500 ppm
Temperature	293 K
Nuclide	**Number Density**
H	6.67431E+22
O	3.33738E+22
B	8.34184E+19

Figure B-11
CASE 10: Nominal Case – Branch to High Rack Boron



Fuel Material Description

Material Density	10.340 (g/cm3)
Fuel Temperature	1072.5 K
Nuclide	**Number Density**
U-235	9.92536E+20
U-234	7.97571E+18
U-238	2.20709E+22
O	4.61429E+22

Coolant Description, Depletion

Boron Concentration	900 ppm
Temperature	592.5 K
Nuclide	**Number Density**
H	4.55525E+22
O	2.27778E+22
B	3.41601E+19

Figure B-12
CASE 11: High Power (150% of Nominal) Depletion

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