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Use of EPRI Depletion Benchmarks for Transport Criticality Burnup Credit

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ABSTRACT

EPRI sponsored the generation of depletion reactivity benchmarks that can be used to validate burnup credit for spent fuel casks. These benchmarks are measurement based using 44 cycles of flux maps to infer the depletion reactivity. The benchmarks have been analyzed using SCALE 6.1 and ENDF/B-VII. The agreement between the 11 benchmarks at burnups from 10 to 60 GWd/T and three cooling times with SCALE calculated values is between -0.0026 and +0.0028 in delta k. The uncertainty in the benchmarks is 0.0064 in delta k. The depletion reactivity bias and uncertainty is much less than the 0.015 delta k uncertainty (approximate since burnup dependent) for just the isotopic content uncertainty for 28 isotopes recently released as part of the US NRC's ISG-8 Rev. 3.

The EPRI benchmarks have a number of advantages for criticality analysis when compared to chemical assay based validation: 1) The benchmarks cover the change in reactivity from all isotopes, not just the 28 where assay data is available. This increased knowledge of reactivity allows for more cost effective cask designs. 2) The benchmark analysis closely matches the criticality safety analysis. The depletion analysis models for the benchmarks can be nearly identical to the depletion models for the cask criticality. The chemical assay depletion models must be tailored to pin details rather than assembly average conditions creating a modeling disconnect between the validation models and the criticality safety models. 3) The uncertainty in the chemical assays is so large that modeling insufficiencies are difficult to see. The uncertainty in the EPRI benchmarks is much smaller, which makes seeing the impact of modeling changes possible. 4) Analysis of the EPRI benchmarks is simple by design. This simplicity makes it more likely that the criticality analyst will do their own validation rather than a specialist which is needed to match the chemical assays. 5) Fewer low capacity casks would be needed to accommodate the existing spent fuel inventory.

INTRODUCTION

Pressurized water reactor (PWR) power distributions are controlled by the reactivity distribution of fuel assemblies. Thus, reactivity distributions can be experimentally inferred from power distributions. PWR power distributions are measured at least once a month, and these measurements can be used to infer reactivity distributions in cores containing fuel of various burnups.

The Electric Power Research Institute (EPRI) sponsored a program to determine the depletion reactivity from measured power distributions [1, 2]. In order to get a high quality determination of this depletion reactivity, power distribution measurements from 4 power plants for a total of 44 cycles of operation were employed. Since the depletion reactivity depends on enrichment, burnable absorber, soluble boron, moderator temperature, etc., the measured data was converted to a lattice code bias. The bias of the lattice code was then used to create benchmarks of depletion reactivity. The computer codes (and cross section library) used to convert data to benchmarks must be able to predict reactor conditions reasonably accurately, but the benchmarks themselves are independent of the computer code/library used. (A different code system would have a different bias that would be applied to its predictions.)

The EPRI depletion reactivity benchmarks are intended to facilitate validation of burnup credit. The benchmarks are a set of depletion reactivities for fuel assembly lattices at burnups of 10, 20, 30, 40, 50, and 60 GWd/T. These depletion reactivities are determined for 11 different conditions and 4 cooling times (0, 100 hours, 5 years, and 15 years). Since the intended application was initially criticality analysis of spent-fuel pools and casks, the benchmarks are defined for reactivity differences under cold conditions. The same data has also been used to generate hot full power benchmarks for the OECD/NEA reactor physics benchmark handbook [3]. Care was taken to establish the uncertainty in these measurement-based benchmarks. Included in the benchmark uncertainty for cold conditions is a conservative estimate of the uncertainty due to adjusting from hot to cold conditions. This uncertainty was determined by use of the TSUNAMI module of SCALE [4]. Table 1 provides one example of the benchmark depletion reactivities for 100-hour cooling. Cases 1 through 10 are at nominal power and the reported uncertainty is 0.00576 in delta-k. Since the uncertainty in the benchmarks is slightly dependent on fuel temperature, the uncertainty for a high power assembly (Case 11) is slightly larger at 0.00643 in delta-k.

APPLICATION OF DEPLETION REACTIVITY BENCHMARKS

With the benchmarks established, their intended application has been demonstrated using SCALE 6.1 [5]. The criticality safety analyst should calculate the delta-k of depletion for all 11 cases using the depletion and criticality modeling intended for final application. In this demonstration, depletion analysis was performed using SCALE 6.1 TRITON and the criticality analysis used SCALE 6.1 CSAS5 (KENO V.a). The difference between the calculated delta-k of depletion and the measurement-based EPRI benchmarks represents a bias in delta-k of depletion that needs to be applied to the final application analysis. The uncertainty in the benchmarks (0.00643) represents the uncertainty of inferring the fuel assembly depletion reactivity. Note that

although there are multiple benchmark calculations, deviations between the benchmarks and the calculations are not statistical and should not be treated as uncertainty. The analyst may develop a bias as a function of parameters such as burnup or enrichment but due to the limited number of calculated deviations it is recommended to determine a single conservative bias that covers all cases.

Table 1. Benchmark Lattice Experimental Depletion Reactivity for 100-Hour Cooling

		Depletion Reactivity (delta k_{inf})					
		Burnup (GWd/T)					
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 2 shows the difference between calculated and benchmark depletion reactivity. The negative biases in Table II are conservative, so the most positive bias should be applied to the criticality analysis. Table II shows positive biases at low burnup for the IFBA cases (Cases 6 and 7). For more accurate IFBA burn-out, model improvements would be needed. However, criticality analysis for pools and casks do not credit boron in IFBAs. (Crediting IFBA boron would require separate loading criteria for each IFBA loading possibility.) The worth of the non-credited boron has been calculated and is much greater than the positive biases at 10 and 20 GWd/T burnup; so these positive biases can be ignored. Now ignoring the positive IFBA biases at 10 and 20 GWd/T, the recommended bias for Westinghouse 17x17 fuel is conservatively selected as 0.0015. Note that some effects such as high enrichment and burnable absorbers can occur at the same time, and the EPRI benchmark cases may not adequately model these cases. However, there are sufficient benchmarks to assert a conservative bias to cover all expected combinations. The bias of 0.0015 in delta-k of depletion is very small, and the impact of the bias and benchmark uncertainty is much less than historical assumptions used for normal, discharged fuel burnups (typically >30 GWd/T).

(Case 4 is for a smaller (OFA) pin diameter and the bias shown in Table 2 decreases. If a larger pin diameter is used (e.g., Westinghouse 15x15 fuel) a higher bias is recommended.)

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

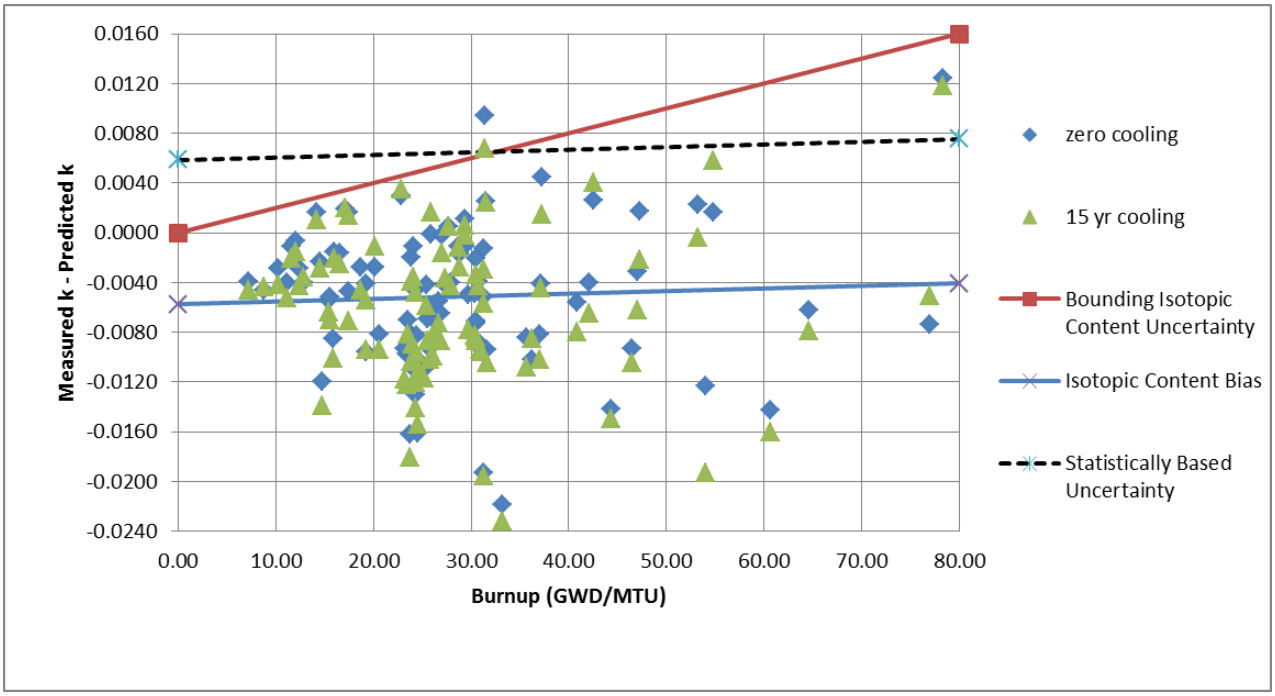
		Bias (Calculated Reactivity Decrement – Measured Reactivity Decrement) For 100-Hour Cooling					
		Burnup (GWd/T)					
Case	Lattice Description	10	20	30	40	50	60
1	3.25% enrichment depletion	-0.0004	-0.0008	-0.0010	-0.0015	-0.0014	-0.0022
2	5.00% enrichment depletion	0.0004	0.0005	0.0003	0.0006	0.0005	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

USE OF CHEMICAL ASSAY DATA

In order to see the benefits of the EPRI depletion reactivity benchmarks, it is important to review the alternative method of validation (validation using chemical assays). NUREG/CR-2010/44 [6] provides information on available PWR chemical assays. NUREG/CR-7108 [7] provides details on how to use the chemical assays in criticality analysis. This NUREG/CR contains two methods for the analysis of the bias and uncertainty due to the isotopic changes with depletion; the Monte Carlo Uncertainty Sampling Method, and the Direct-Difference Method. This article uses the direct-difference method. For a recent criticality analysis the chemical assays were analyzed using the same depletion approach (t5-depl module calling KENO V.a) as was used here for the analysis of the EPRI depletion reactivity benchmarks. The new analysis made some corrections to the previous ORNL work, added the Vandellos chemical assays [8], and removed some poor data (determined by review of the data not by disagreement with analysis: 12 TMI assays and one H. B. Robinson assay).

The direct-difference method requires analysis of the criticality application with the predicted isotopic contents of an assay and then redoing the analysis using the measured isotopic content. For this work, the criticality application is actually a spent fuel pool with boron absorber panels, no flux trap. Figure 1 shows the differences in k_{eff} of the pool from using the predicted versus measured isotopic content. Also shown on Figure 1 is the best fit linear regression. Note that for the fit the measured k_{eff} is higher than the predicted k_{eff}. This is negative bias that will not be used. Figure 1 also shows the statistically determined 95/95 bounding curve for the delta k's.

Both the bias curve and the statistical bounding curve were generated without the knowledge that at zero burnup the bias and uncertainty are zero by definition. Using the knowledge that the uncertainty at zero burnup is zero, a bounding isotopic content uncertainty was graphically determined and is shown on the plot.



In the chemical assay based approach, the reactivity worth of the isotopes needs to be validated as well as the isotopic content. For the major actinides (U-234, U-235, U-238, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, and Am-241) this is done by supplementing the fresh UO_2 critical experiments with MOX critical experiments. Analysis of MOX critical experiments with ENDF/B-VII produces higher k's than analysis of fresh UO_2 critical experiments, so it is conservative to apply the fresh UO_2 critical experiment's bias and uncertainty to the burned fuel. Since there is limited data for minor actinides and fission products, ORNL has used TSUNAMI to determine an uncertainty on the critical system propagated from the uncertainty in the cross section measurements. [9] Since there is insufficient data to establish a bias this uncertainty is used as a bias. The bias selected by ORNL for the 28 isotopes to be credited was 1.5% of the worth of the minor actinides and fission products. This bias has been applied in the US NRC interim staff guidance (ISG-8 Rev.3). [10]

BENEFITS OF THE EPRI DEPLETION REACTIVITY BENCHMARKS

Use of All Isotopes

The current US NRC guidance (ISG-8 Rev.3) [10] allows credit for only 28 isotopes. The reason for this restriction is the chemical assays only cover 28 isotopes. However, the EPRI depletion reactivity benchmarks are based on measured data that include all isotopes. The impact of all isotopes versus 28 isotopes on spent fuel pool costs was studied by Rombough. [11] The cost impact on the spent fuel pools was estimated to be about $1.5 million per pool. The reactivity loss due to reducing the number of nuclides from all to 28 is shown on Table 3. No cost analysis has been made on cask costs but the additional negative reactivity could mean a higher fraction of used fuel can be placed in existing cask designs; therefore, cask costs can be reduced due to less costly absorber panels.

Table 3: Δk of Depletion Comparison – All isotopes versus 28 Isotopes [11]

Burnup (GWd/T)	Δk of Depletion (all isotopes)	Δk of Depletion (28 isotopes)	Difference (all isotopes – 28 isotopes)
10	0.096	0.086	0.010
20	0.178	0.160	0.018
30	0.251	0.228	0.023
40	0.320	0.291	0.029
50	0.380	0.347	0.033
60	0.431	0.395	0.036

It may be desirable to use the chemical assay method and allow credit for all isotopes. This would be reasonable since the 28 isotopes account for about 90% of the depletion reactivity and it would require a large error in any of the remaining isotopes to produce a significant effect on k. However, it is possible that a gross error exists. To confirm that no gross error exists, the EPRI depletion reactivity benchmarks could be analyzed as a backup for the chemical assay method. This would not prove the accuracy of any individual isotope but would show acceptability of the aggregate.

EPRI Depletion Reactivity Benchmarks Models Closely Match Design Models

The reactivity change of interest in cask analysis is the reactivity change of an assembly. The EPRI depletion reactivity benchmarks are the change in reactivity for an assembly. The chemical assays are specific to a fuel pin (except for some Obrigheim cases which are for half of assemblies). The fuel pins in the chemical assays are often not typical of an assembly due to their position relative to the edge of the assembly, burnable absorbers, or guide tubes. Chemical assay modeling must account for the pin location. This makes the chemical assay model different from the design model. This difference in modeling could contain a reactivity difference that is not quantified.

Much of the chemical assay data comes from atypical fuel. The Trino Vercellese reactor, used for about a third of the data, had fuel followers with their control rods which must be modeled for accurate results. These fuel assemblies also used stainless steel clad. The Gösgen and Vandellòs fuel rods which were sampled came from assemblies that were reconstituted. Obrigheim fuel has an assembly support structure that is not like grids used in modern fuel.

EPRI Depletion Reactivity Benchmarks Help in Model Refinements

Since the agreement between the EPRI depletion reactivities and the analysis of these reactivities is so good, about 0.002, model changes make a noticeable difference in performance against the benchmarks. This statement seems to be inconsistent with the uncertainty claimed (0.0064) for the EPRI depletion reactivity benchmarks. Reviewing the report on the development of the benchmarks [1] reveals that only 0.0025 of the uncertainty is due to random error; the rest of the uncertainty is due to conservative treatment of possible error in converting the hot full power measured data to cold conditions.

The chemical assay uncertainty is much larger per experiment. [12] Although the mean error is reasonable, it is not possible to see improvements in individual chemical assays due to modeling changes. Since the models for the chemical assays depend so much on the actual assay it is difficult to see global effects of a model change.

Modeling issues such as 1) NEWT spatial mesh, 2) NITAWL versus CENTRM, 3) ENDF/B-V versus ENDF/B-VII, and 4) burnable absorber depletion with constant flux rather than power were easy to resolve by comparison to the EPRI depletion reactivity benchmarks, but the effects would be too small to see when comparing to chemical assays. [5].

Analysis of the EPRI Depletion Reactivity Benchmarks Is Easy

Since the EPRI depletion reactivity benchmarks are simple lattice models, typical of the models used for the depletion of fuel for cask analysis, the modeling is straightforward for the analyst. Although the time to perform the analysis is not trivial, it takes less than one tenth the time needed to perform the chemical assay analysis. Because of this reduction in effort, it is more likely to be done by the same criticality analyst who will perform the cask safety analysis. The

chemical assay analysis will probably be done by a specialist selling this service. This disconnect is contrary to general criticality safety philosophy.

EPRI Depletion Reactivity Benchmarks Include the Reactivity Due To Assembly Dimensional Changes

Since the EPRI depletion reactivity benchmarks are taken from power reactor measurements they include all the reactivity changes associated with burnup. It has been questioned whether crud, bowing, etc. that occurs during fuel duty has a significant reactivity effect. It is clear from the analysis of the EPRI benchmarks that the effect of these is small since they are not included in the models yet the models agree well with the measured data.

CONCLUSIONS

The EPRI depletion reactivity benchmarks allow using measured reactor data to validate burnup credit calculations for casks as well as for pools. The EPRI benchmarks have been analyzed using SCALE 6.1 and the 238-group ENDF/B-VII library and the bias on the depletion reactivity is very small, less than 0.003 in k. The uncertainty in the analysis is 0.0064. Most of the uncertainty is due to conservative evaluations for the difference between hot and cold conditions.

Chemical assay analysis using similar SCALE modeling shows a negative bias and, if classical statistics are used, shows an uncertainty similar to the EPRI approach. Using a more engineering approach, where it is expected that the uncertainty is zero at zero burnup and the uncertainty should rise with burnup, produces about the same uncertainty at 30 GWd/T but increases for higher burnups.

The chemical assay validation approach is hampered by the limited number of isotopes, 28. This limitation gives the EPRI method of validation a significant advantage. It would be possible to use the EPRI benchmarks as a supplement to the chemical assay analysis to allow the inclusion of all isotopes with the chemical assay approach. This can be justified by noting that the 28 isotopes is about 90% of the depletion reactivity and the EPRI benchmark analysis would assure that no gross error in the extra isotopes exists.

The EPRI depletion benchmarks are easier to analyze and match the design methods much better than the chemical assay analysis. Due to the high precision of the EPRI benchmarks as well as their similarity to design models, it is possible to confirm modeling improvements.

Since there is good agreement between the EPRI depletion reactivity benchmark approach and the chemical assay approach, it is recommended that the validation effort be reduced to just performing the EPRI depletion reactivity benchmark validation and to include all isotopes for future cask criticality analysis.

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