Determination of a Depletion Uncertainty From Fuel Management Experience

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ABSTRACT:

In the United States, spent fuel pool burnup credit has allowed a depletion uncertainty of 5% of the delta k of depletion. This uncertainty was based on engineering judgment and requires more documentation. It is shown that data from commercial power reactors can be used to validate burnup credit criticality calculations via simplified benchmarks produced by fuel management codes. The accuracy of these simplified benchmarks is established by comparison between the reactor measurements and the fuel management codes. In turn these simplified benchmarks are used to determine a bias between the criticality tools and the fuel management tools. This bias, when added to the bias and uncertainty of the fuel management tools, becomes a basis for a depletion uncertainty. Preliminary analysis shows that depletion uncertainty for a typical criticality code set is less than 2% for the burnups of interest.

BACKGROUND:

Historically, the US NRC has allowed spent fuel pools to use 5% of the delta k of depletion to represent the depletion uncertainty. Recently, there have been requests from the NRC to show the basis of this uncertainty. This paper shows a method that can be used to determine the uncertainty and bias in the delta k of depletion from commercial reactor data.

First, it is important to carefully define terms. Section 4 of the US burnup credit standard, ANSI/ANS-8.27 [1], defines the criteria for subcriticality using equation 1. Here equation 1 is modified to:

$$k_p + \Delta k_p + \Delta k_b \quad \leq \quad k_c - \Delta k_c - \Delta k_d - \Delta k_m \qquad \text{(Eq. 1)}$$

where all the terms are defined to be the same as Equation 1 of the standard except that Δk_d (depletion bias and uncertainty) replaces Δk_i and Δk_x, which represent the uncertainty in the isotopic content and the uncertainty in the cross sections, respectively. Δk_d is the bias and uncertainty associated with the depletion from the initial condition of fresh UO_2 fuel to burned fuel. k_c is derived from fresh fuel critical experiments and addresses the geometric and material concerns not related to burnup. k_p has the appropriate modeling of the axial and horizontal burnup variations. Δk_d only accounts for the bias and uncertainty in the isotopic content and the reactivity worth of that change in the isotopic content. This formulation assumes that the depletion effects are separable from the other phenomena that affect k and so some consideration is necessary to assure that any cross products are covered. For example, the determination of k_c should include spectral indices that cover both the burned and fresh condition of the fuel. The Δk_d should be determined with a range of spectral indices that cover the criticality conditions

expected. From a geometric point of view, the calculated k_p should include conservative distribution of fuel as described in Section 6.2 of the standard.

DETERMINATION OF Δk_d

Knowledge of the bias and uncertainty of the depletion reactivity (Δk_d) is a commercial necessity for power reactors. If it were not possible to predict the change in reactivity with burnup then refueling outages could not be scheduled and fuel costs could not be controlled. Historically, empirical corrections to predictions in reactivity changes were necessary to correctly predict the change in k with depletion. As time progressed (improvements in methods and cross sections), the size and number of these corrections has decreased.

Although Δk_d is well known for power reactors analyzed with fuel management tools, it is less clear how well Δk_d is known for conditions important to casks, pools, and disposal. The tools used in criticality analysis are not generally used for analysis of power reactors. The fuel management tools are generally not used or tested in the conditions important for criticality.

It is proposed to determine Δk_d in a three-step process. First, ascertain the bias and uncertainty in the fuel management tools at reactor conditions. Second, use the fuel management tools to convert this measured data into benchmarks that can easily be calculated with criticality codes. Finally, calculate these benchmarks with the criticality codes. The final Δk_d comes from the bias and uncertainty from step 1 augmented by any uncertainty in going from step 1 to step 2 plus any bias from the criticality codes determined in the analysis of the benchmarks. These steps will now be discussed in more detail.

Step 1 - Depletion Bias and Uncertainty at Reactor Conditions in the Fuel Management Codes

The easiest way to determine the depletion bias and uncertainty from measured reactor data is to collect the data from startup predictions, depletion reactivity (ppm letdown curves for PWRs), and cycle length predictions. The cycle length and startup prediction accuracy will depend on the core average burnup if there is a depletion bias. No such trend is seen using current generation fuel management codes. For PWRs, the ppm letdown curve has the same general slope as predicted from the fuel management codes. At mid cycle, deviations are often observed between the predicted ppm and measured ppm due to B-10 depletion in the soluble boron. When this effect is modeled, the deviations are often eliminated. End of cycle predictions are generally better since the ppm is near zero making any B-10 error in the soluble boron insignificant. Beginning of cycle at power ppm is also better predicted due to the shutdown mixing of the soluble boron which brings the B-10 content back to natural boron. So the bias appears to be zero, but the uncertainty in this result is the uncertainty in the mean of the measurements. For PWRs, one sigma deviation from the mean is about 20 ppm. At 2-sigma this is about 0.4% in k.

The differences between measured and predicted critical conditions are due to a combination of factors, such as the measurement uncertainty, errors in modeling, differences between the actual core conditions and the modeled conditions, and finally, errors in the delta-k due to depletion. For simplicity, it will be conservatively assumed that all the difference between the measured ppm and the predicted ppm is due to errors in the depletion. This is a very conservative assumption since there has been no observed trend with burnup, which implies that most, if not all, of the differences are due to factors that have nothing to do with burnup.

Since the core average burnup is generally less than 20 GWD/MTU, there may be a concern with using the measured core critical conditions for the uncertainty at higher burnups. This is not a problem for absorber credit for BWRs since the peak reactivity condition is less than 20 GWD/MTU. However, for PWR burnup credit, credit is routinely taken for greater than 30 GWD/MTU. In order to determine Δk_d over a range that covers higher burnup, the measured power distribution can be used.

The relative power in a location depends on the relative reactivity imposed on a global shape. The measurement of the power distribution gives information on the local reactivity. For this analysis an approach similar to first order perturbation can be used. At the location of a measured point, the reactivity of that assembly can be adjusted a small amount in the fuel management model and the change in power can be observed. The deviation between the measured power distribution and the predicted power distribution can then be converted into a deviation in reactivity for the fuel management tools. Note that this is like first order perturbation in that it assumes that the local perturbation does not perturb the flux elsewhere in the reactor. Higher order approaches can be developed but are not needed for discussion here. The easiest way to perturb the reactivity is to change the burnup. Our change in reactivity with burnup is what is being validated so the change in reactivity with burnup is known. In reality, the change in reactivity with burnup is initially approximated as the same as predicted with the fuel management tools. The analysis may show a bias in the change in reactivity with burnup. If this is the case the procedure is iterative with the new biased change in reactivity with burnup used to convert a change in burnup to a change in reactivity.

As a test case, the burnup of the central assembly was decreased 5%. The power in the central assembly increased 5.3%. The central assembly burnup was 50 GWD/MTU. The change in reactivity for a 5% change in burnup is predicted to be 2% in k. Suppose the deviation between the measured and predicted power for this assembly was a 1% over prediction. The fuel management code error in reactivity for this 50 GWD/MTU assembly would then be 2%*(1%/5.3%)= **0.38%** in reactivity**.** If this process is repeated for numerous flux maps, numerous assembly positions, and numerous cores it is possible to derive a mean and uncertainty about the mean between predicted and measured reactivity as a function of burnup. Although the deviations can be due to many causes, it can be conservatively assumed that the cause of the deviation is exclusively due to a bias and uncertainty in the ability of the fuel management codes to predict the delta k of depletion. By this process, we now have a conservative determination of Δk_d for the fuel management codes.

Since the Δk_d may depend on the burnup characteristics, it is important to determine Δk_d for assemblies with various burnable absorbers, different moderator temperatures (differing cores), and different average ppm during burnup (differing cycles). It is useful to do the analysis for different fuel designs such as 17X17 and 14X14 fuel designs to see if the pin pitch has an effect. Δk_d may also depend on the conditions at the time of the measurement. For example, ppm at the time of measurement is different than the average depletion ppm. Finally, Δk_d may depend on enrichment.

The accurate determination of Δk_d for the fuel management tools is a large job but the data is available. The Δk_d will depend on the details of the fuel management codes. It is important that all the analysis be performed with the same version of the codes. This means that the effort is not just a collection of data from utilities using their vintage of the fuel management codes but more targeted to a single current version of a set of fuel management tools.

Step 2 – Create the Benchmarks

The next step is to establish benchmark calculations that can be used to translate the known depletion bias and uncertainty determined by measured data from power plants to a depletion bias and uncertainty for the criticality tools, Δk_d. Here the key assumption is that the Δk_d can be separated from spatial effects, which are captured in k_c and k_p. It is important to note that the spatial distribution of the burnup is conservatively handled in the calculation of k_p. This assumption allows the use of simplified benchmarks. Since fuel management codes use lattice physics to determine the nuclide densities and the cross sections then it is logical that the simplified benchmarks are lattice calculations. A check must be performed to assure that the nodal code portion of the fuel management analysis does not introduce any burnup dependent biases.

The bias and uncertainty in the benchmarks may not be the same as the bias and uncertainty for the fuel management tools at core conditions. The benchmarks will be at cold uniform temperatures but the measured conditions were at hot power conditions. BWR's go critical at cold conditions and also predict hot critical conditions. The difference between the predicted and measured power defect can be used to estimate an additional bias and uncertainty for the conversion between hot power and cold conditions. The measured power defect for PWRs only goes between hot zero power to full power so the additional bias and uncertainty needed for PWRs would have two parts, hot zero power to full power and cold to hot zero power. Since the same lattice code is often used for both BWRs and PWRs, some BWR data may be used to establish this second component of the power correction.

The benchmarks would be a large set of lattice calculations. They must cover the enrichment and burnup range of the criticality application. Further they should cover the spectrum of the criticality application. It may not be possible to cover some of the softer spectra of some criticality applications so the benchmarks must show a range of spectra to allow some extrapolation. It is important to note that many criticality applications are heavily borated so although there is more water in the application than in the benchmarks, the actual spectra would fall in the range of the benchmarks. The spectrum range in the benchmarks can be covered with features that are in the power plants such as ppm, burnable absorber, control rods, power level, and a small variation in pin pitch (such as between 14X14 to 17X17). In addition to covering the criticality application spectrum, the benchmarks need to cover a range of depletion characteristics. All of these properties results in a benchmark set of hundreds of calculations. However, since the calculations are simple lattice calculations, producing the benchmarks and calculating the same benchmarks with the criticality codes is not overwhelming.

The benchmarks provide k as a function of burnup along with a bias and uncertainty from the measured reactor data. Δk_d would be the bias and uncertainty in the change in k for a given burnup from the benchmarks plus a bias for the difference in the predicted change in k as a function of burnup between the criticality tools and the benchmarks. There is no required linkage between the criticality tools and the tools used to generate the benchmarks. The criticality tools may use the same lattice code for depletion or deplete with another code. Advances in fuel management tools are expected to reduce the uncertainty and bias in the benchmarks but use of benchmarks based on old fuel management tools should be conservative (contain a higher uncertainty) and are acceptable for criticality benchmarking.

For selected benchmark cases, it is recommended that the nuclide densities and reactivity worths be published. Although there is no measurement confirmation of these values, comparison

between the criticality codes and fuel management codes can identify the trends that should have shown up in the statistical analysis of the benchmarks. Note that this is code to code comparison only so it is not acceptable data for validation but rather can be used for extrapolation only.

Step 3 – Calculate the Benchmarks with the criticality codes

This step is straightforward. The lattice calculations are easy for the criticality code systems to calculate, so generating the hundreds of k's will be a small effort. The delta k of depletion predicted by the criticality codes is compared to the benchmark delta k. Deviations between the benchmarks and the criticality codes are investigated for trends on relevant parameters. If the criticality codes predict a smaller delta k of depletion than the benchmarks, the criticality codes are conservative and the Δk_d is taken straight from the benchmarks. No credit will be allowed for a bias in a non-conservative direction. If the criticality codes are non-conservative, the difference between the criticality codes and the benchmarks is a bias that is added to the bias from the benchmarks. Since this step is a comparison between two codes there is no random variation so the difference is a bias, not an uncertainty.

AN EXAMPLE OF THE DETERMINATION OF Δk_d

At this time the power distribution approach to determining the Δk_d of the benchmarks has not been done. For this example, the core critical predictions are used for the uncertainty and bias in the benchmarks. Further, no analysis has yet been done to assess an additional bias and uncertainty for going from reactor conditions to the benchmark conditions. Thus a great deal of the actual work needed to generate a defendable Δk_d is still in progress. However, sample benchmark calculations have been performed and are provided in Table 1. This table is useful as an example of the type of analysis anticipated. The benchmarks and the criticality tools were well known tools but are not identified here since these results are preliminary.

As can be seen in the last column of Table 1, the delta k of depletion predicted by the criticality tools was always less than that predicted by the fuel management tools. This means that Δk_d is the same as for the benchmarks. As stated before, no trend on burnup has been observed for the fuel management tools, so the bias is zero. And as stated before, the uncertainty (2 sigma) in the fuel management tools is 0.4% in k. In summary Equation 1 can be used to calculate the criticality safety limits using fresh UO2 critical experiments and 0.004 for Δk_d. It is important to note that this is an example where several of the key steps require further analysis.

CONCLUSIONS

It is possible to validate the bias and uncertainty in the delta k of depletion using commercial power reactor data. With the validated delta k of depletion, then the only laboratory criticality experiments needed are fresh UO2. Chemical assays and critical experiments with fission products and non-uranium actinides are useful for research but are not required for validation.

The validation requires establishing benchmarks calculated with fuel management tools. The bias and uncertainty in these benchmarks are determined by measured data. This use of measured data separates this approach from a code-to-code comparison, which is not sufficient for validation.

The benchmarks are simple lattice calculations since the depleted nuclide densities and cross sections for fuel management come from the lattice calculations. Uncertainties due to conversion from the measured conditions to the benchmark conditions must be accounted for.

Power distribution measurements provide measured data that can be used to determine a bias and uncertainty as a function of burnup over the complete range of fuel burnup.

Although the analysis is preliminary, there is strong support to suggest that the depletion uncertainty for burnups greater than one cycle are less than the 5% of the delta k of depletion that has historically been used as engineering judgment in the US.

REFERENCES

[1] ANSI0ANS-8.27-2008, "Burnup Credit for LWR Fuel," American Nuclear Society, La Grange Park, Illinois.

Table 1: Comparison of the Fuel Management Benchmarks with the Criticality Tools (72 hours cooling)

Burnup GWD/MTU	Benchmark k	Δk burnup benchmark	Criticality Codes k	Δk burnup Crit. Codes	difference in Δk
1.8 wt% U-235, 0 ppm					
0	1.2279		1.2258		
10	1.1021	.1258	1.1064	.1194	-.0064
20	1.0142	.2137	1.0170	.2088	-.0049
30	.9498	.2781	.9516	.2742	-.0038
1.8 wt% U-235, 500 ppm					
0	1.1283		1.1251		
10	1.0287	.0996	1.0314	.0937	-.0059
20	.9496	.1787	.9513	.1738	-.0049
30	.8905	.2378	.8911	.2340	-.0038
1.8 wt% U-235, 1000 ppm					
0	1.0451		1.0411		
10	.9660	.0791	.9677	.0734	-.0056
20	.8942	.1509	.8948	.1463	-.0045
30	.8397	.2054	.8395	.2017	-.0038
3.0 wt% U-235, 0 ppm					
0	1.3620		1.3617		
20	1.1334	.2286	1.1392	.2226	-.0061
30	1.0518	.3102	1.0563	.3054	-.0048
40	.9831	.3789	.9869	.3748	-.0041
3.0 wt% U-235, 500 ppm					
0	1.2817		1.2804		
20	1.0755	.2062	1.0798	.2005	-.0057
30	.9968	.2849	1.0004	.2800	-.0049
40	.9305	.3512	.9334	.3470	-.0042
3.0 wt% U-235, 1000 ppm					
0	1.2114		1.2092		
20	1.0244	.1870	1.0276	.1815	-.0055
30	.9485	.2629	.9511	.2581	-.0048
40	.8845	.3269	.8868	.3224	-.0045
4.0 wt% U-235, 0 ppm					
0	1.4199		1.4216		
30	1.1213	.2987	1.1278	.2938	-.0049
40	1.0501	.3698	1.0559	.3657	-.0042
50	.9866	.4333	.9922	.4294	-.0039
4.0 wt% U-235, 500 ppm					
0	1.3511		1.3516		
30	1.0704	.2807	1.0760	.2756	-.0051
40	1.0007	.3503	1.0057	.3459	-.0045
50	.9385	.4126	.9430	.4085	-.0040

Table 2: Comparison of the Fuel Management Benchmarks with the Criticality Tools (72 hours cooling) (Continued)

Burnup GWD/MTU	Benchmark k	Δk burnup benchmark	Criticality Codes k	Δk burnup Crit. Codes	difference in Δk
4.0 wt% U-235, 1000 ppm					
0	1.2894		1.2889		
30	1.0249	.2645	1.0295	.2594	-.0051
40	.9568	.3326	.9610	.3279	-.0048
50	.8959	.3936	.8999	.3890	-.0046
5.0 wt% U-235, 0 ppm					
0	1.4546		1.4582		
40	1.1132	.3415	1.1201	.3382	-.0033
50	1.0526	.4021	1.0586	.3996	-.0024
60	.9966	.4580	1.0025	.4557	-.0023
5.0 wt% U-235, 500 ppm					
0	1.3955		1.3980		
40	1.0695	.3260	1.0754	.3226	-.0034
50	1.0096	.3859	1.0149	.3831	-.0028
60	.9543	.4412	.9596	.4384	-.0028
5.0 wt% U-235, 1000 ppm					
0	1.3417		1.3432		
40	1.0299	.3118	1.0351	.3081	-.0037
50	.9709	.3708	.9754	.3678	-.0030
60	.9163	.4254	.9208	.4223	-.0031