Determination of a Depletion Uncertainty From Fuel Management Experience

Dale Lancaster

NuclearConsultants.com

Charles Rombough

CTR Technical Services

Outline

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Background

- Historically, 5% of the delta k of depletion was used as the depletion uncertainty for USA spent fuel pool analysis.
- This value was a conservative engineering approximation.
- The approximation was based on fuel management code performance against commercial reactor measured data.

Background

- Since the critical experiments were fresh UO2, the depletion uncertainty was to account for the uncertainty in all changes from the fresh UO2 condition to the burned condition (changes in atom densities and cross sections).
- The 5% delta k of depletion uncertainty was then statistically combined with other uncertainties.
- It was assumed that there was no bias or if there was a bias the conservatism in the 5% delta k of depletion was large enough to cover a small bias.

Background

- Recently the regulator is demanding documentation to support using a depletion uncertainty equal to 5% of the delta k of depletion. This paper explores ways to justify the 5% depletion uncertainty.
- Note: There is a separate 5% that is used for burnup uncertainty in pool analysis. This is the uncertainty in the burnup records. This paper does not address this other 5% uncertainty. The depletion uncertainty does not cover burnup records uncertainty.

Definition of Terms

$$k_p + \Delta k_p + \Delta k_d + \Delta k_b \quad \leq \quad k_c - \Delta k_c - \Delta k_m$$

- The above equation is from ANSI/ANS-8.27 where Δk_d is the depletion bias and uncertainty (replaces Δk_i and Δk_x).
- Section 5.2 of the Standard states:

  "The uncertainty in the isotopic content and cross sections is captured in the calculation of the multiplication factor of the criticality experiment with irradiated fuel."

- Δk_d is the bias and uncertainty associated with the depletion from the initial condition of fresh UO_2 to burned fuel.

Definition of Terms

$$k_p + \Delta k_p + \Delta k_d + \Delta k_b \quad \leq \quad k_c - \Delta k_c - \Delta k_m$$

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

How do you determine Δk_d

- To determine Δk_d you must measure the change in reactivity with burnup and determine the accuracy of your codes to reproduce this reactivity change.
- The reactivity change with burnup is required for power plant operation.
- Predictions are compared to measurements on a routine basis.
- If the spatial distribution of burnup is handled conservatively the Δk_d is not spatial and can be determined from lattice or point codes.

Historical Approaches - CRCs

- Historically, a limited set of state points from commercial reactors have been analyzed with criticality codes.
- Due to the limited number of state points it was difficult to determine accuracy as a function of burnup so the critical state points were added to the k_c set and various corrections attempted.
- The analysis of the state points contain the error in calculation of UO_2 cores as well as the error in calculating depletion (atom densities and cross sections).

Proposed Approach

- Use fuel management tools to convert power reactor data to simple benchmarks to be calculated by criticality tools.
- The benchmarks will contain the bias and uncertainty in the fuel management tools.
- The deviation between the benchmarks and the criticality tools analysis is a bias to be added to the the fuel management tools bias.

Simplified Burnup Benchmarks

- Since fuel management tools use lattice codes, the simplified benchmarks will be an infinite sea of unit assemblies.
- The criticality analysis would use uniform burnup for each pin unless pin by pin burnup is used in the criticality application.
- For a set of enrichments benchmarks will be given for 0 burnup and a range of final burnups.
- Δk_d is determined by comparison between the criticality code prediction of the reactivity of depletion and the benchmark prediction.

Simplified Burnup Benchmarks

- The set of benchmarks must cover the spectrum expected in the criticality application.
- Spectral differences can be introduced by using various ppm, burnable absorbers and moderator densities (in the range of power reactor experience).
- The benchmarks should also cover cooling time.

Simplified Burnup Benchmarks

- The simplified benchmarks should also contain data to help determine differences between the benchmarks and the criticality codes. Specifically, the worth and atom density of each isotope.
- Comparisons between benchmarks and criticality tools should contain analysis as to the causes of the differences.

Simplified Burnup Benchmarks

- The simplified burnup benchmarks may be published by organizations separate from the criticality team
- These benchmarks are treated like experimental data but,
  - The benchmarks may contain a bias and will contain an uncertainty that must be used,
  - The differences between the benchmarks and criticality tool analysis does not contain any randomness and must be considered a bias.

Validating the Benchmarks
Easy Approach

- Document results of multiple HZP startup predictions and HFP End of Life (EOL) predictions.
- Make sure that all were performed with the same version of the fuel management codes.
- Show that there is no statistically significant trend with burnup.
- Conservatively assume that all deviation in predictions is due to depletion uncertainty (in reality, deviations are due to all modeling assumptions).

Validating the Benchmarks
Easy Approach

- Using reactor data, show that the power defect is well predicted (therefore we can use HFP EOL with the HZP BOL).
- Confirm that there is no spatial bias introduced in the fuel management analysis.
- Perform and document the benchmark suite of calculations using the validated lattice code.

Validating the Benchmarks
Easy Approach

- Document that the benchmarks are within the range of validation from the reactor data and if not, add appropriate uncertainty for any extrapolation.
- This approach results in no bias and a constant uncertainty independent of burnup.
- A typical (1 sigma) uncertainty would be 0.2% in k.
- Using these values the depletion uncertainty (.4% in k at 2 sigma) from the benchmarks alone would be 5% of the delta k of depletion at 8 GWD/MTU and less than 2% by 20 GWD/MTU.

Validating the Benchmarks
Better Approach

- The easy approach has limitations because the reactor data is based on core average values.
- A better approach would be to use the measured power distribution.
- Power distribution is directly related to assembly reactivity. A reactivity error would result in a difference in the measured power distribution.
- Requires a correlation between reactivity and power.

Validating the Benchmarks
Better Approach – How to do it

1. For selected core locations with incore measurements increase the burnup a small amount (Δbu) in the core model.
2. Record the change in power distribution (Δp).
3. Use the Δbu/Δp to convert the measured error in power to a Δbu.
4. Initially assume the fuel management codes calculated is correct (no bias)
5. Use this Δk/Δbu to convert to a Δk deviation.

Validating the Benchmarks
Better Approach – How to do it

6. Using the predicted to measured power distributions create more than 4000 data points (Δk measured to predicted, burnup).
7. Each monthly flux map produces more than 50 data points. Each ten month cycle could produce 500 data points.
8. Data should be collected over multiple cycles and multiple plants.
9. Analyze the data to establish any trend in Δk deviation as a function of burnup. If there is a statistically significant trend this is a bias in the Δk of depletion.

Validating the Benchmarks
Better Approach – How to do it

10. If a statistically significant trend is observed, adjust the Δk/Δbu used in step 5 (slide 19) and redo steps 5, 6 and 9.
11. If the bias determined in step 9 is the same you are done. Otherwise repeat with new bias until converged.
12. Conservatively assume that all this deviation is due to depletion error (clearly the error comes from all the modeling assumptions).
13. Use this data to determine the depletion bias and uncertainty as a function of burnup.

Validating the Benchmarks
Better Approach – How to do it

14. Check to see if the error is also a function of other parameters such as burnable absorber loading, etc.
15. With the fuel management tools validated with a known bias and uncertainty create the benchmarks.

Validating the Benchmarks
Better Approach

- The power distribution approach to establish the depletion uncertainty has the advantage of a lot of data points with relatively few fuel cycles.
- The use of fewer cycles makes it possible to validate the codes with data taken in a short time so there is less concern about code version changes.

Using the Benchmarks

- With the benchmarks derived from the fuel management tools, the criticality codes are used to calculate the same benchmarks.
- All differences between the fuel management benchmarks and the criticality codes should be evaluated for the root cause.
- Differences are biases. Negative biases should not be used (for conservatism).

Some Preliminary Results

- Only the easy validation approach has been taken so far.
- From operating experience, the benchmarks have no depletion bias and an uncertainty of less than 1% of the delta k of depletion for greater then 20 GWD/MTU.
- The power distribution approach is still under review.

Some Preliminary Results

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

Some Preliminary Results

Burnup GWD/MTU	Benchmark k	Δk burnup benchmark	Criticality Codes k	Δk burnup Crit. Codes	difference in Δk
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

Some Preliminary Results

Burnup GWD/MTU	Benchmark k	Δk burnup benchmark	Criticality Codes k	Δk burnup Crit. Codes	difference in Δk
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
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

Some Preliminary Results

Burnup GWD/MTU	Benchmark k	Δk burnup benchmark	Criticality Codes k	Δk burnup Crit. Codes	difference in Δk
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

Comment

- This approach is **not a code to code comparison**.
- Codes are used to extract the relevant data from the actual measurements to allow measured biases and uncertainty.
- There is manipulation of the data but within the range of actual experience at power plants.

Conclusions

- It is possible to make benchmarks for validation of the delta k of depletion using power reactor data.
- The benchmarks contain the bias and uncertainty from measured data.
- Calculation of these benchmarks with criticality tools establish a bias with the criticality tools.
- Any positive bias from the criticality tools needs to be added to the benchmark bias and uncertainty.

Conclusions

- Preliminary analysis suggest that the depletion bias in fuel management tools is negligible and the uncertainty in the delta k of depletion is less than 1% for burnups greater than 20 GWD/MTU.
- Analysis showed that the criticality tools used in this example under-predicted the delta k of depletion.
- Thus the uncertainty in the delta k of depletion is less than 1% for burnups greater than 20 GWD/MTU.

Conclusions

- Power distributions can be used to estimate the uncertainty in the delta k of depletion.
- The power distribution approach is still under development.

Conclusions

- Comparison between criticality tools and fuel management tools is recommended since it is possible an error in criticality code's fission products could go unobserved without comparison to fuel management tools.
- 5% of the delta k of depletion covers both atom densities and cross sections and is conservative.