BENEFITS OF USING EPRI DEPLETION REACTIVITY BENCHMARKS FOR BURNUP CREDIT VALIDATION

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Organization

- Description of the EPRI Depletion Reactivity Benchmarks
- Utilization with SCALE 6.1 and ENDF/B-VII
- Alternative Method – Chemical Assays
- Benefits of the EPRI Depletion Reactivity Benchmarks

EPRI Depletion Reactivity Benchmarks

- Flux maps from 44 cycles of PWR operation were used to determine relative reactivity in the core.
- Since the cores contain fuel of differing burnups it is possible to determine the change of reactivity with burnup.
- The measured data was used to bias a lattice code which was then used to create the benchmarks.
- The benchmarks are independent of the lattice code used (different lattice codes would have different biases to match the same measured data).

EPRI Depletion Reactivity Benchmarks

- Flux maps used were from hot full power.
- TSUNAMI was used to determine a conservative added uncertainty for making the cold benchmarks.
- The correlation coefficient between hot full power condition to cold conditions is better than between normal critical experiments and their application.

The 11 Benchmark Lattice Cases

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)

High Power is 1.5 times average power of 38.1 W/gm
The Nominal Pin diameter is for a W 17x17 fuel. Off-nominal is OFA fuel.

Benchmark Data

Table C-3
Measured Reactivity Decrement – 100 Hour Cooling

Case	10	20	30	40	50	60
1	-0.1329	-0.2339	-0.3211	-0.3956	-0.4554	-0.5002
2	-0.1146	-0.2021	-0.2806	-0.3545	-0.4238	-0.4867
3	-0.1223	-0.2157	-0.2990	-0.3758	-0.4445	-0.5029
4	-0.1207	-0.2176	-0.3075	-0.3931	-0.4715	-0.5385
5	-0.2045	-0.2335	-0.2998	-0.3717	-0.4372	-0.4932
6	-0.1736	-0.2215	-0.2968	-0.3726	-0.4418	-0.5009
7	-0.2524	-0.2418	-0.2981	-0.3686	-0.4343	-0.4910
8	-0.1216	-0.2129	-0.2932	-0.3662	-0.4310	-0.4860
9	-0.1237	-0.2171	-0.2998	-0.3756	-0.4432	-0.5005
10	-0.0967	-0.1784	-0.2530	-0.3217	-0.3826	-0.4335
11	-0.1235	-0.2149	-0.2945	-0.3664	-0.4299	-0.4838

Table C-4
Measured Reactivity Decrement – 5 Year Cooling

Case	10	20	30	40	50	60
1	-0.1370	-0.2471	-0.3447	-0.4284	-0.4951	-0.5445
2	-0.1163	-0.2086	-0.2943	-0.3761	-0.4529	-0.5222
3	-0.1247	-0.2245	-0.3164	-0.4018	-0.4781	-0.5425
4	-0.1232	-0.2263	-0.3250	-0.4197	-0.5063	-0.5797
5	-0.2069	-0.2424	-0.3171	-0.3974	-0.4703	-0.5321
6	-0.1760	-0.2304	-0.3140	-0.3984	-0.4751	-0.5403
7	-0.2547	-0.2507	-0.3154	-0.3941	-0.4672	-0.5296
8	-0.1241	-0.2218	-0.3106	-0.3922	-0.4645	-0.5254
9	-0.1261	-0.2257	-0.3168	-0.4009	-0.4759	-0.5390
10	-0.0986	-0.1858	-0.2675	-0.3430	-0.4096	-0.4647
11	-0.1268	-0.2245	-0.3125	-0.3928	-0.4636	-0.5232

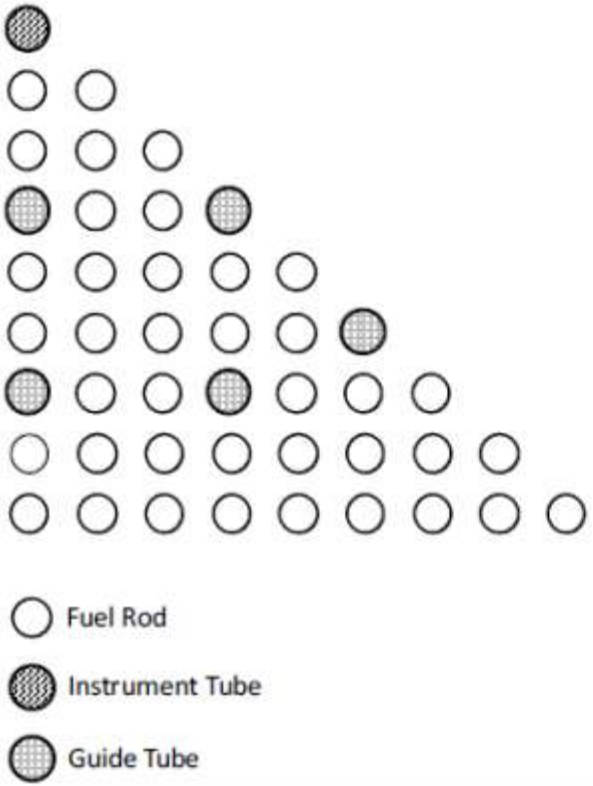
Uncertainty

Case	delta-k
1	0.00576
2	0.00576
3	0.00576
4	0.00576
5	0.00576
6	0.00576
7	0.00576
8	0.00576
9	0.00576
10	0.00576
11	0.00643

Table C-5
Measured Reactivity Decrement – 15 Year Cooling

Case	10	20	30	40	50	60
1	-0.1422	-0.2655	-0.3768	-0.4720	-0.5471	-0.6021
2	-0.1184	-0.2184	-0.3140	-0.4058	-0.4918	-0.5690
3	-0.1277	-0.2372	-0.3405	-0.4369	-0.5226	-0.5942
4	-0.1260	-0.2385	-0.3488	-0.4551	-0.5516	-0.6325
5	-0.2102	-0.2555	-0.3415	-0.4325	-0.5145	-0.5833
6	-0.1792	-0.2432	-0.3382	-0.4334	-0.5194	-0.5917
7	-0.2581	-0.2639	-0.3398	-0.4291	-0.5111	-0.5806
8	-0.1273	-0.2348	-0.3351	-0.4276	-0.5092	-0.5773
9	-0.1291	-0.2384	-0.3408	-0.4357	-0.5198	-0.5900
10	-0.1014	-0.1971	-0.2885	-0.3729	-0.4468	-0.5074
11	-0.1300	-0.2377	-0.3373	-0.4284	-0.5084	-0.5752

Benchmark Description For Benchmark #3 (4.25 wt%)



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

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 (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

Utilization with SCALE 6.1 and ENDF/B-VII

- EPRI Technical Report Number 1025203 demonstrated how to use the benchmarks with SCALE 6.1 with the ENDF/B-VII library. (has now been redone with 6.1.2)
- Depletion analysis is performed using TRITON module t5-depl which calls KENO Va for the flux calculations (not NEWT).
- Criticality calculations use CSAS5 which calls CENTRM, BONAMI, and KENO.Va.

EPRI Benchmark Biases

		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	-0.0008	-0.0017	-0.0024	-0.0037	-0.0040	-0.0044
2	5.00% enrichment depletion	-0.0001	-0.0003	-0.0005	-0.0012	-0.0014	-0.0018
3	4.25% enrichment depletion	0.0002	-0.0004	-0.0010	-0.0018	-0.0026	-0.0029
4	off-nominal pin depletion	-0.0008	-0.0016	-0.0023	-0.0029	-0.0037	-0.0046
5	20 WABA depletion	0.0000	0.0003	-0.0005	-0.0014	-0.0018	-0.0025
6	104 IFBA depletion	0.0009	0.0005	-0.0003	-0.0016	-0.0024	-0.0036
7	104 IFBA, 20 WABA depletion	0.0007	0.0011	0.0000	-0.0008	-0.0019	-0.0031
8	high boron depletion = 1500 ppm	-0.0003	-0.0006	-0.0011	-0.0017	-0.0018	-0.0024
9	branch to hot rack = 338.7K	-0.0004	-0.0007	-0.0008	-0.0017	-0.0019	-0.0025
10	branch to rack boron = 1500 ppm	-0.0009	-0.0019	-0.0027	-0.0036	-0.0044	-0.0049
11	high power density depletion	-0.0002	-0.0012	-0.0016	-0.0022	-0.0026	-0.0032

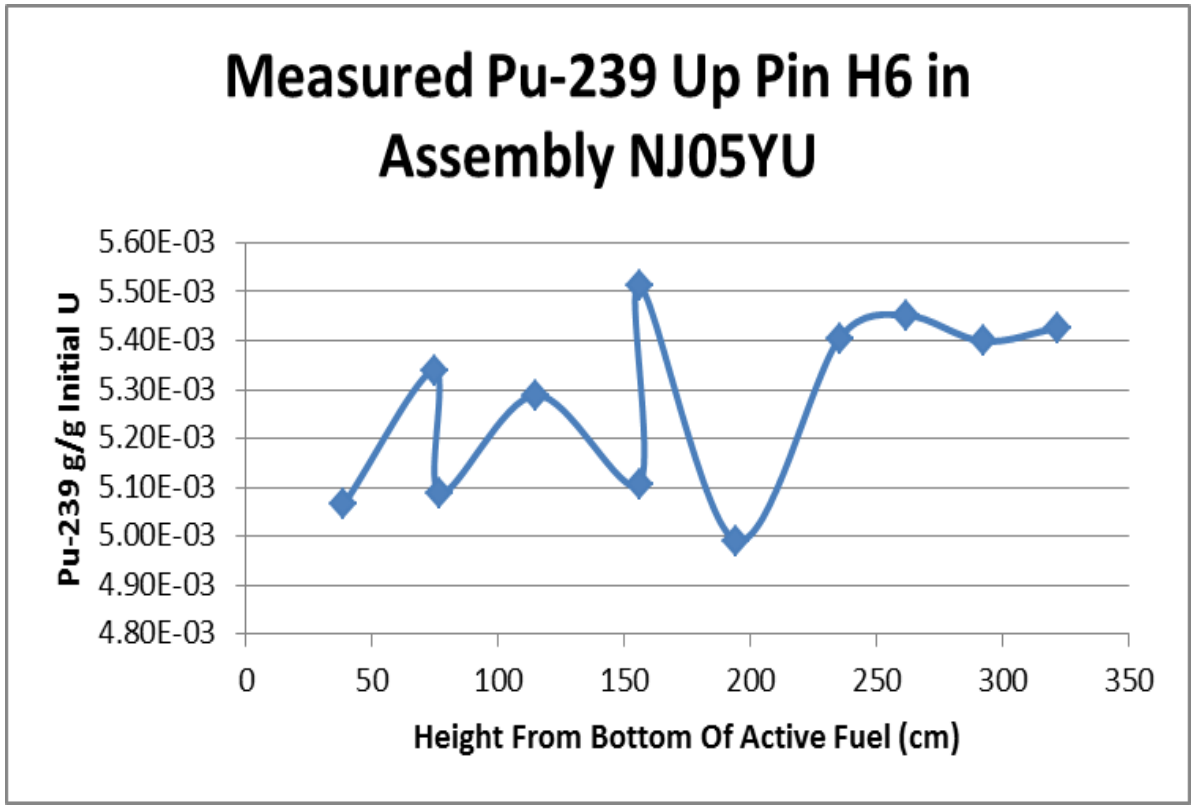
EPRI Benchmark Bias and Uncertainty

- Negative biases are conservative
- Maximum bias from all the cooling times is 0.0026
- For pin diameters larger than the W17X17 (See Difference between Cases 3 and 4) a larger bias is needed.
- **Final Bias for W15x15 is 0.003. The uncertainty is 0.0064**

Alternative Approach – Chemical Assays

- ISG-8 Rev 3 recommends an approach supported by NUREG/CR-7108 and 7109.
- This work follows that approach using direct-difference.
- By inspection of experimental data, we removed 12 TMI chemical assays and one HB Robinson assay (taken from under an Inconel grid which would require 3D methods.)
- Added 5 chemical assays from Vandellós II which were not included in NUREG/CR-7108.
- A total of 92 chemical assays are used (NUREG/CR-7108 used 100).

TMI Pu-239 Assays Done By ANL

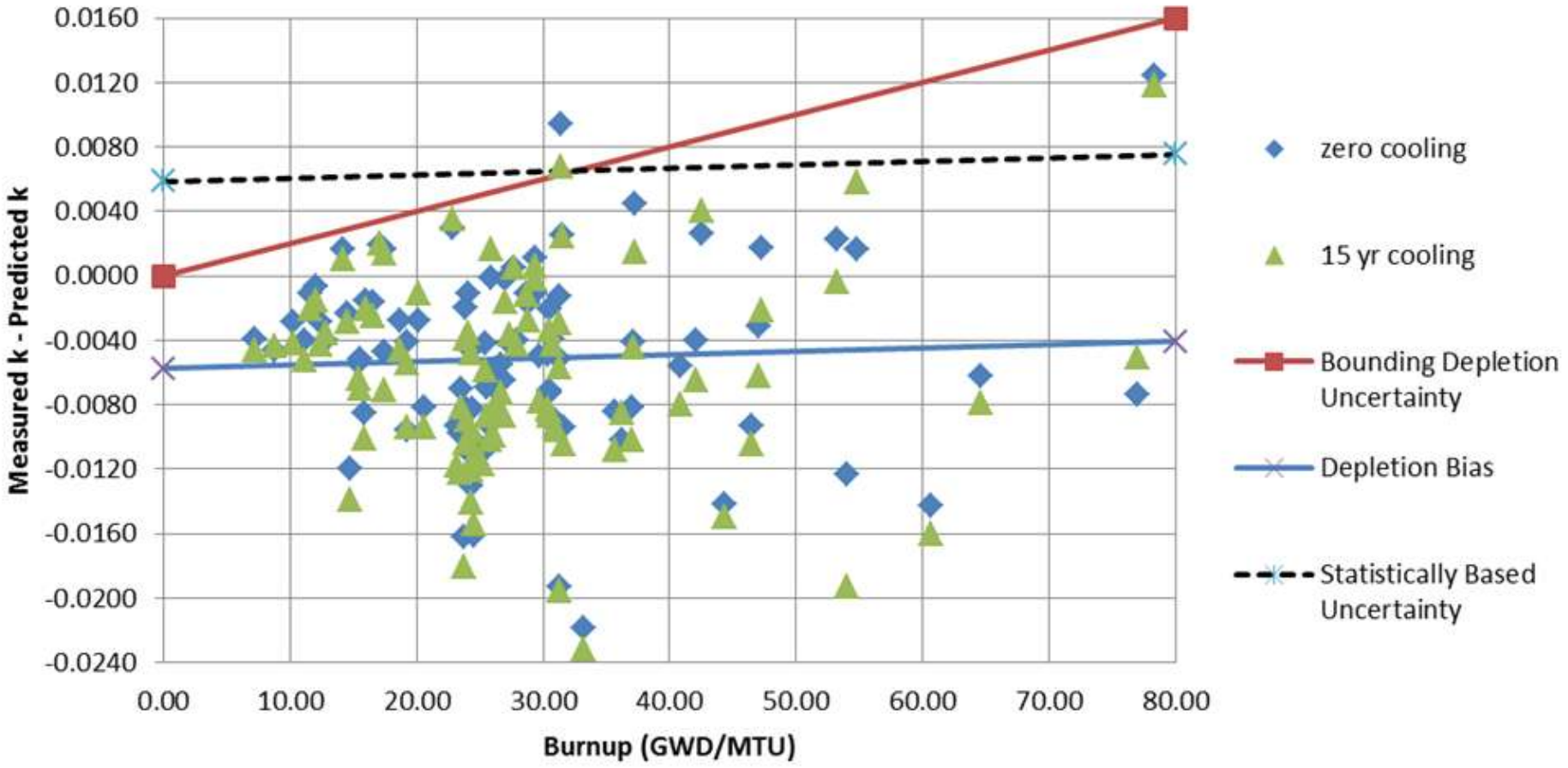


Measured Pu-239 Content Up Pin H6 in Assembly NJ05YU

Chemical Assay Approach

- Determined direct-difference bias as a function of burnup
- Negative bias ignored.
- Statistical uncertainty did not show physical knowledge of 0 bias and uncertainty at 0 burnup.
- Applied engineering uncertainty. See graph.

Direct-Difference Bias and Uncertainty



Chemical Assay Approach

- Much better results due to removing bad experimental data and correcting NUREG/CR-7108 errors.
- Since the chemical assays cover only 28 isotopes and the criticality analysis will be performed using 185 isotopes the EPRI benchmarks are used to confirm none of the added isotopes produces a large unexpected reactivity.

Minor Actinide and FP Worth Bias

- Analyzed HTC criticals and 63 MOX critical experiments
- Mean k
  - 0.9978 for UO_2 criticals
  - 0.9988 for HTC criticals
  - 0.9984 for MOX criticals
- In the chemical assay approach, **UO_2 (most limiting),** HTC and MOX criticals cover the major actinides.
- **Added a bias of 1.5% of the minor actinides and fission product worth** to cover possible bias and uncertainty in the reactivity worth of the minor actinides and fission products (See NUREG/CR-7109 and ISG 8 Rev. 3).

Comparison of Bias and Uncertainty for Burned Fuel

- The chemical assay bias is zero. And the worth bias is about 0.0015. The EPRI benchmark bias is 0.003.
- The EPRI uncertainty is 0.0064. The chemical assay uncertainty does not reach this until 32 GWd/T.
- The net effect is the **EPRI benchmark approach is more limiting** to about 45 GWd/T.
- There is significant agreement between the two methods now that the bad data and errors are removed.

Benefits of the EPRI Depletion Reactivity Benchmarks

- ISG-8 Rev 3 specifies 28 isotopes for credit. These isotopes have the highest worth but using all isotopes is a significant benefit.

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

Benefits of the EPRI Depletion Reactivity Benchmarks

- ISG-8 Rev. 3 states:

  Use of actinide and fission product compositions associated … outside these specifications (sic 28 isotopes) *should be accompanied by the measurement data and/or justified extrapolation techniques necessary to extend the isotopic validation and quantify or bound the bias and bias uncertainty.*

- **EPRI Benchmarks provide the measured data to go beyond 28 isotopes.**

Benefits of the EPRI Depletion Reactivity Benchmarks

- EPRI Depletion Reactivity Benchmarks Models Closely Match Design Models
  - Chemical Assay models must emphasize the sampled pin rather than assembly. K_{eff} is a global parameter not sensitive to pin effects.
  - A large fraction of the chemical assays are from non-standard fuel (Trino) or reconstituted fuel (Vandellòs and Gösgen).
  - EPRI benchmarks are standard lattice models used in most depletion calculations.

Benefits of the EPRI Depletion Reactivity Benchmarks

- EPRI Depletion Reactivity Benchmarks Help in Model Refinements
  - Agreement between benchmarks and predictions are excellent.
  - With such good agreement small modeling imperfections are visible (For example depletion of burnable absorbers using constant flux versus constant power)
  - Chemical assay agreement is so bad that 1D models agree almost as well as 2D models. Also the benefit of ENDF/B-VII over ENDF/B-V is not clear at this level.

Benefits of the EPRI Depletion Reactivity Benchmarks

- Analysis of the EPRI Depletion Reactivity Benchmarks Is Easy
  - Although there are 66 cases per cooling time, the analysis of the EPRI benchmarks requires no special skills or large amount of source research.
  - Analysis of the chemical assays is much more time consuming and requires non-standard modeling.
  - The chemical assay analysis would likely be contracted out whereas the EPRI benchmark analysis would be done by in-house staff.

Benefits of the EPRI Depletion Reactivity Benchmarks

- EPRI Depletion Reactivity Benchmarks Include the Reactivity Due To Assembly Dimensional Changes
  - These effects are negligible but included in the measured data.
- Possibly less shipments due to using higher capacity casks is possible by crediting all isotopes rather than 28. Less shipments is a safety advantage.

Summary

- EPRI Depletion Benchmarks is measured data the supports the use of all isotopes (rather than 28 isotopes).
- There is good agreement between the EPRI depletion benchmarks and chemical assays.
- The EPRI benchmarks are easy to perform and supply sufficient validation of depletion reactivity.
- It is recommended that license applicants be allowed to use only the EPRI benchmarks. (The chemical assays provide assurance that the EPRI benchmarks are adequate.)