Depletion Reactivity Benchmarks Derived from Measured Pressurized Water Reactor Flux Maps

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Contributors

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Burnup Credit Standard, ANSI/ANS-8.27

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

k_p is the calculated k from the rack model

Δk_p is the bias and uncertainty in the rack model

Δk_b is the uncertainty in the burnup

k_c is the mean of the critical experiments

Δk_c is the uncertainty about the mean given in k_c

Δk_d is the bias and uncertainty associated with depletion; it includes the uncertainties associated with isotopic content and worth (cross sections)

Δk_m is an administrative margin, typically 5%

Problem Statement

Existing criticality benchmarks have been portrayed as insufficient by regulators in light of operational/licensing changes being sought by utilities

Desired Outcome

Depletion uncertainty approaches that could increase licensee flexibility in addressing spent fuel criticality concerns

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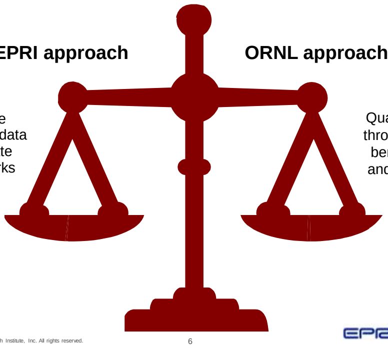
Depletion Uncertainty Quantification



EPRI approach

Leverage operational data to generate benchmarks

ORNL approach

Quantification through critical benchmarks and chemical assays

Basis For The EPRI Uncertainty Methodology

1. Critical LWR cores provide a continuous source of measured reactivities for both fresh and depleted fuel assemblies at full-power conditions
2. Predictions of in-core reaction rate spatial distributions are very sensitive to the accuracy of computed assembly reactivities
3. By examining thousands of in-core measurements (flux maps), the burnup dependence of the error in computed assembly reactivities (and its uncertainty) can be deduced

Goal: Experimental benchmarks of burnup reactivity decrement, which are independent of analysis codes

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Reactor Data

Table 5.1 Reactor and Fuel Data

Unit	Cycles	Cycle Length (EFPD)	Enrichment Range (%)	HZP Boron (ppm)	Maximum LBP # Pins	Maximum IFBA # Pins	Maximum WABA+IFBA # Pins
McGuire-1	10 to 21	363 - 514	3.40 - 4.95	1576 - 2000	24	128	24 + 128
McGuire-2	10 to 20	428 - 512	3.64 - 4.90	1690 - 2037	24	128	24 + 128
Catawba-1	9 to 19	407 - 522	3.45 - 4.75	1501 - 2104	24	128	16 + 128
Catawba-2	8 to 17	451 - 527	3.50 - 4.90	1819 - 2109	24	128	20 + 128

Table 5.2 Feed Fuel Characteristics

Cycle	Enrichment (%)	# of sub batches	Cycle	Enrichment (%)	# of sub batches
McGuire-1			McGuire-2		
10	3.40	4	10	3.85 / 3.95	7
11	3.40 / 3.55	9	11	3.90 / 4.15	7
12	3.67	9	12	3.78	6
13	3.92	8	13	4.09 / 4.39	11
14	4.14 / 4.50	7	14	3.77 / 4.33	7
15	4.40 / 4.75	6	15	4.16 / 4.56	12
16	3.92 / 4.35	7	16	4.37 / 4.67	8
17	4.45 / 4.74	9	17	4.35 / 4.75	8
18	4.01 / 4.64	5	18	4.05 / 4.70	6
19	4.00 / 4.68	7	19	3.90 / 4.80	8
20	4.00 / 4.85	9	20	3.65 / 4.90	9
21	3.60 / 4.95	10			
Catawba-1			Catawba-2		
9	3.86	8	8	3.98	6
10	3.65 / 3.92	6	9	4.32 / 4.42	9
11	4.02	6	10	4.54	5
12	4.50	6	11	3.90 / 4.20	6
13	3.81 / 4.31	6	12	4.35 / 4.66	8
14	4.19 / 4.46	9	13	4.00 / 4.75	8
15	4.18 / 4.53	10	14	4.45 /4.75	8
16	4.42 / 4.67	11	15	3.80 / 4.73	11
17	3.88 / 4.51	9	16	4.38 / 4.90	8
18	4.05 / 4.51	8	17	3.80 / 4.82	9
19	3.96 / 4.75	7			

Involved processing

~1 million measured signals

from 680 flux maps

covering 44 cycles

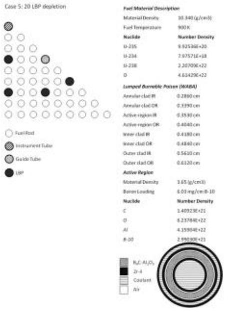
from 4 reactors

Product : 11 Reactivity Decrement Benchmarks for PWR 17 x 17 Design

	Table 13.1 Benchmark Lattice Cases
1	3.25% Enrichment
2	5.00% Enrichment
3	4.25% Enrichment
4	off nominal pin diameter depletion
5	20 LBP depletion
6	104 IFBA depletion
7	104 IFBA plus 20 LBP depletion
8	high boron depletion=1500 ppm
9	branch to hot rack (150F coolant/fuel)=338.7K
10	branch to high rack boron = 1500 ppm
11	high power depletion*(pde, coolant/fuel temp)

Measured Reactivity Decrement

	Burnup (GWd/T)					
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



Utilization – Comparison with SCALE (ENDF/B-VII) Burnup Dependence (Benchmarks 1 thru 3)

- The uncertainty in the benchmarks is 0.00643 in k. The bias depends on the codes and cross sections used in the criticality analysis.
- For SCALE 6.1 and ENDF/B-VII the following is a table of the biases. Negative biases are ignored.

Burnup	Bias (SCALE Δk - Benchmark Δk)		
	3.25 wt% U-235	4.25 wt% U-235	5 wt% U-235
10	-0.0004	0.0005	0.0004
20	-0.0008	0.0002	0.0005
30	-0.0010	0.0001	0.0003
40	-0.0015	-0.0004	0.0006
50	-0.0014	0.0000	0.0005
60	-0.0022	-0.0005	0.0008

Comparison of the Reactivity Decrement Approach to the Kopp Guidance

- Assume the highest bias of all 11 benchmarks and all burnups
  - For ENDF/B-VII (SCALE) and 100-hour cooling, this is <u>0.0015 in k</u>
  - To this, add the uncertainty of 0.00643

Burnup	EPRI	Kopp [Case #3]
10	0.0079	0.0061
20	0.0079	0.0108
30	0.0079	0.0150
40	0.0079	0.0188
50	0.0079	0.0222
60	0.0079	0.0251

← **Small non-conservatism at low burnups**

Large margin at discharge burnups

International Handbook of Evaluated Reactor Physics Benchmark Experiments (IRPhEP)

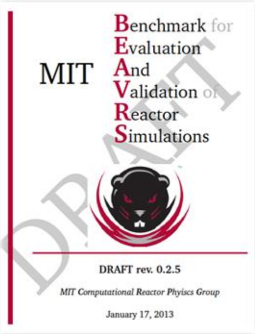
- Contains reactor physics benchmarks
  - Derived from experiments performed at nuclear experimental facilities
  - Intended for use by reactor physics personnel to validate calculational techniques
- 2012 Edition (May 2012)
  - Contains data from 56 different experimental series performed at 32 different reactor facilities
- EPRI-sponsored Benchmarks
  - Accepted as “<u>Draft</u>” by OECD/NEA Committee in October 2012 for publication in the 2013 edition of the Handbook
  - Submitted to OECD-NEA on January 21, 2013
  - Next logical step: Acceptance as “<u>Final</u>” in the 2014 Edition

IRPhEP Review

- Technically very sound reviews
  - Focus should be on Hot Full Power (HFP) conditions
    - Appendix for hot-to-cold conditions
    - *OK!*
  - Use of CASMO-SIMULATE as a reactivity meter
    - Would other tools give the same results?
    - *Only partially addressed! ➔ MIT's "BEAVERS" Project*
  - Derivation of uncertainties
    - Completeness?
    - Provide data set?
    - *Best effort! ➔ MIT's "BEAVERS" Project*
- Report formatting
  - Improvements required
    - *OK!*

MIT's BEAVERS Project

- Opportunity: U. S. Utility made available two cycles of detailed, measured PWR operational data
- By performing core analysis with full-core CASMO models, one can eliminate dependences on nodal models/codes



MIT

Benchmark for
Evaluation
And
Validation of
Reactor
Simulations

DRAFT

DRAFT rev. 0.2.5

MIT Computational Reactor Physics Group

January 17, 2013

Summary

- Experimental benchmarks of burnup reactivity decrement, which are independent of analysis codes, have been created
  - Benchmarks can be used to determine bias and uncertainty of applicant's specific analysis tools
- Ongoing work ongoing at MIT will provide opportunities for other analysts to independently verify the approach retained for creating the depletion reactivity benchmarks
- Regulatory review may be conducted as part of the review of NEI's *Guidance for Performing Criticality Analyses of Fuel Storage at Light-Water Reactor Power Plants* (to be formally submitted in March 2013 in support of a pilot-plant LAR)

EPRI Reports/Documents

1. *“Benchmarks for Quantifying Fuel Reactivity Depletion Uncertainty”* [Report 1022909 (August 2011)]
2. *“Utilization of the EPRI Depletion Benchmarks for Burnup Credit Validation”* [Report 1025203 (April 2012)]
3. *“PWR Fuel Assembly Depletion Reactivity Determination Using PWR Fission Rate Measurements”*
   - Benchmarks accepted as “Draft” for publication in the 2013 Edition of the OECD/NEA International Handbook of Evaluated Reactor Physics Benchmark Experiments [EPRI submittal finalized January 2013]
   - Pursuing OECD/NEA reviews for publication as “Final” in the 2104 Edition [To be finalized by January 2014]
4. *“PWR Fuel Depletion Reactivity Verification and Uncertainty Using Flux Map Data”* [EPRI Report (Planned Publication: Fall 2013)]

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