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Depletion Reactivity Benchmarks Derived from Measured Pressurized Water Reactor Flux Maps

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RIC 2013
March 13, 2013
Washington, DC

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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%

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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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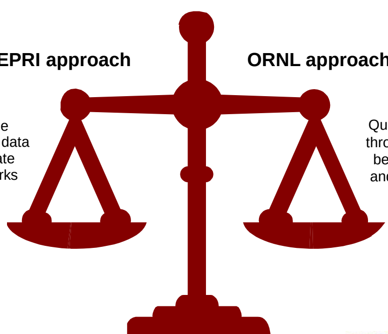
Depletion Uncertainty Quantification

EPRI approach | **ORNL approach**

Leverage operational data to generate benchmarks



Quantification through critical benchmarks and chemical assays

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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

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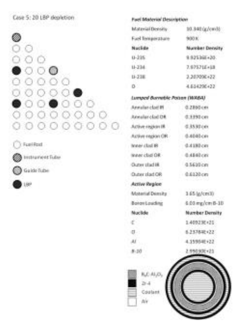
Product : 11 Reactivity Decrement Benchmarks for PWR 17 x 17 Design

	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

Case	Burnup (GWd/T) 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



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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

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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 0.0015 in k
  - To this, add the uncertainty of 0.00643

Burnup	EPRI	Kopp [Case #3]	
10	0.0079	0.0061	← Small non-conservatism at low burnups
20	0.0079	0.0108	
30	0.0079	0.0150	
40	0.0079	0.0188	} Large margin at discharge burnups
50	0.0079	0.0222	
60	0.0079	0.0251	

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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 "Draft" 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 "Final" in the 2014 Edition

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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!*

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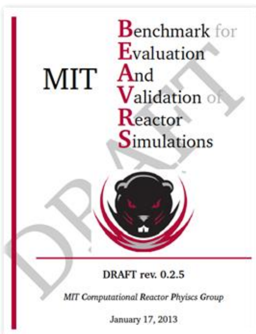
MIT's BEAVERS Project

- 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 <u>eliminate dependences on nodal models/codes</u>



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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)

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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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