# Recent Developments in the Depletion Reactivity Uncertainty

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# Outline

- Depletion Reactivity Uncertainty History
- ORNL Approach
- EPRI Depletion Reactivity Benchmarks
  - The Final Benchmarks
  - Results of Typical Analysis
- Current Status of Depletion Reactivity Uncertainty
- Summary

# Depletion Reactivity Uncertainty Important to Criticality

- For a typical SFP the Depletion Reactivity Uncertainty is about 2% in k.

- This is the largest uncertainty. The total of all uncertainties is about 3% in k.

- 2% in k is about 3 GWd/T burnup in reactivity.

- Pools are full so 3 GWd/T means early discharge to dry storage or purchase of absorber inserts - Real Money!

# Depletion Reactivity Uncertainty History

- Most PWRs use burnup credit and about 500 ppm of soluble boron credit for their spent fuel pools.

- In 1998 Larry Kopp issued an internal NRC memo giving burnup credit guidance for Spent Fuel Pools.

- This guidance allowed the use of 5% of the delta k of depletion to be used for the depletion reactivity uncertainty.

- There is no documentation on the origin of this 5%. (But from conversations with Larry it is based on power reactor experience.)

# Can We Predict Reactivity With Burnup?
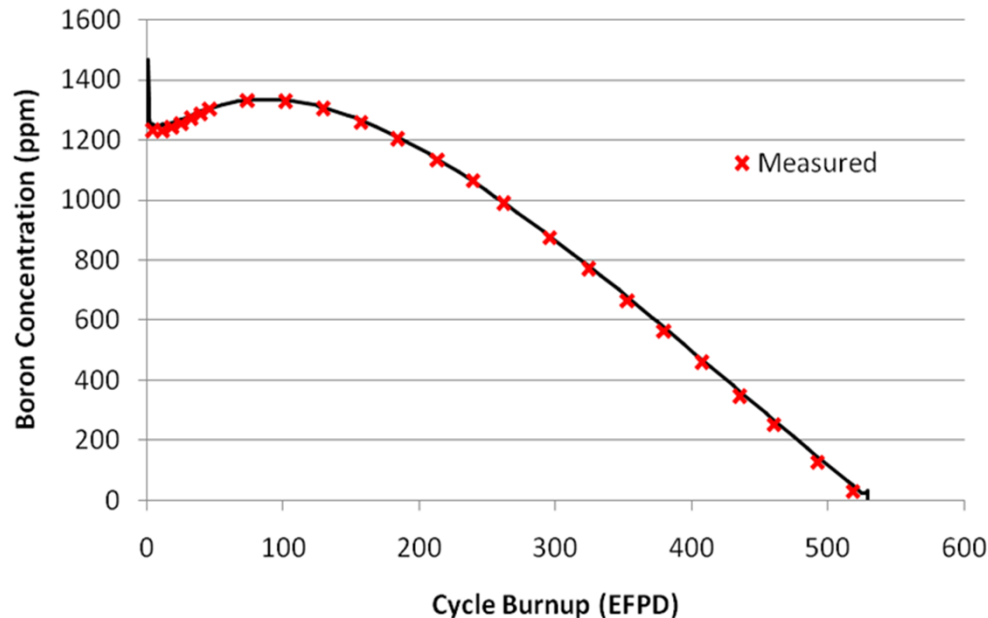


Smith, et al., *Benchmarks for Quantifying Fuel Reactivity Depletion Uncertainty*, EPRI Technical Report 1022909 (2011)

**Excellent agreement between predicted (line) and measured data!**

However, critical data from power plants are <u>global core</u> values where the average burnup reaches about 35 GWd/T by end of cycle. We want to credit <u>assembly burnup</u> at 45 GWd/T and beyond

# More History

- The Kopp approach was viewed as acceptable since there is considerable safety margin (only 500 out of 2000 ppm soluble boron credit is taken).

- Casks are licensed assuming flooding with pure (0 ppm) water; so it was presumed that there was little margin.

- Casks used a more conservative approach (ORNL approach in future slides)

# Spent Fuel Pool Regulation Change

- In February 2009, the NRC raised concern over the Kopp 5% depletion uncertainty.
- In August 2010, the NRC issued a draft ISG for spent fuel pool criticality analysis that re-interpreted the Kopp memo and started the process to stop using the 5% from the Kopp memo.
- In May 2010, ORNL (funded by the NRC) and EPRI started to work on alternatives.
- To date the 5% still shows up on all license applications.
- First post-Kopp application will be Dominion's Millstone Spent Fuel Pool. This application is using a combination of ORNL and EPRI methods.

# ORNL Approach

- Over the past decade, ORNL has been working on transport cask burnup credit mostly for PWR applications

- Funding for ORNL work is primarily from the NRC transport cask criticality.

- NRC has a burnup credit task force combining efforts for casks and pools.

- For casks depletion validation is done in two steps: (1) Validate the isotopic content; then (2) validate the reactivity worth of the credited isotopes (cross section validation).

# ORNL Approach

- Chemical Assays of fuel specimens cut through fuel rods are used to determine the isotopic content of spent fuel.

- Historically only actinide isotopes were determined in the chemical assays, so transport burnup credit only credited actinides.

- Now there are 100 ORNL qualified chemical assays from PWR rods, which include fission products.

# ORNL Approach

- In April 2012 ORNL produced a Technical Report on how to use chemical assays for isotopic validation (NUREG/CR-7108)

- With the isotopic content validated, ORNL proposes propagating the cross section measurement uncertainty to determine the uncertainty in the isotopic reactivity worth. (NUREG/CR-7109)

# ORNL Approach

- NRC Transport Criticality team issued ISG-8 Rev 3 (September 2012)

- This ISG implements the ORNL approach.

- The ORNL approach is technically sound.

- This is a <u>major step forward</u> for **cask criticality** that historically only credited actinides.

# ORNL Approach For Pools

- Pools have been using all isotopes. The ORNL approach only uses 28 isotopes.

- The <u>chemical assays have a high uncertainty</u>.

- This high uncertainty results in a large depletion uncertainty.

- The Kopp memo was conservative so the large chemical assay uncertainty is only 20 to 40% larger than the Kopp 5%. (e.g., 6% to 7%)

# ORNL Approach For Pools

- Reactivity <u>worth uncertainty</u> proposed by ORNL is small.  Only concern is the approach to generate the uncertainty requires complicated analysis.  If a new cross section library is used, this could be a problem.

- Compared to Kopp's guidance, an estimated cost of implementing the ORNL Approach is about **$1.5 Million** per pool (additional absorber plates or earlier cask loading).  [EPRI Report **1026483** (Nov. 2012)]

# EPRI Approach

- From measured reactor power distributions, it is possible determine the change in reactivity as a function of burnup.

- The EPRI approach validates the <u>change in reactivity</u> with burnup, not the change of isotopic content and uncertainty from the fission product cross sections.

- The uncertainty derived from relying on reactor measurements include uncertainties associated not only with isotopic contents and cross sections, but also with irradiation effects such as pellet cracking/relocation, pellet stack swelling, cladding creepdown, etc.

# EPRI Burnup Credit Validation

- Use flux maps from 44 cycles of operation of the McGuire and Catawba plants to infer the reactivity distribution.

- Compare the inferred reactivity distribution to the predicted reactivity distribution and determine a bias as a function of burnup.

- Use the bias to establish benchmarks of the delta k of depletion to be calculated with the criticality analysis tools.

# Modeling for Benchmark #3 of 11
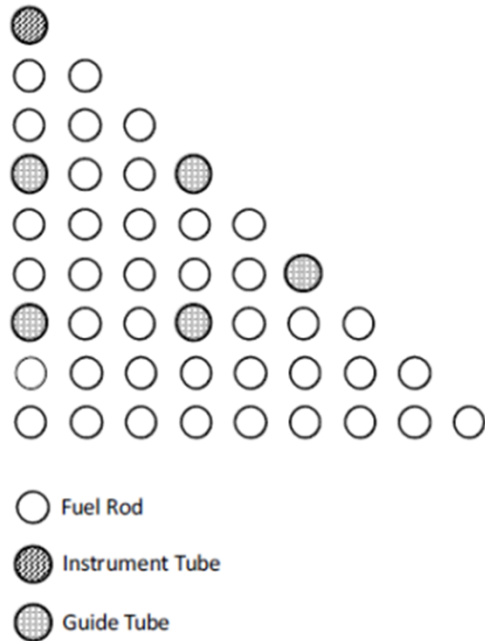


*Physical Description*

| | |
|---|---|
| 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 | $0.12 \cdot T_{fuel} + 0.88 \cdot T_{coolant}$ |

| 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 |

# EPRI Benchmark Depletion Reactivities

*Measured Depletion Reactivity*

| 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 | -0.1 | | | | | |
| 4 | -0.1 | | | | | |
| 5 | -0.2 | | | | | |
| 6 | -0.1 | | | | | |
| 7 | -0.2 | | | | | |
| 8 | -0.1 | | | | | |
| 9 | -0.1 | | | | | |
| 10 | -0.1 | | | | | |
| 11 | -0.1 | | | | | |

15 years 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 | | | | | | |
| 5 | | | | | | |
| 6 | | | | | | |
| 7 | | | | | | |
| 8 | | | | | | |
| 9 | | | | | | |
| 10 | | | | | | |
| 11 | | | | | | |

5 years 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 |

100 hours Cooling

*Benchmark Uncertainty (same for all cooling)*

| 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 |

Higher Uncertainty due to Higher Temperature

# Determination of $\Delta k_d$ for SCALE 6.1 238 Group ENDF/B-VII

- SCALE 6.1 TRITON with the 238-Group ENDF/B-VII for the depletion analysis

| Burnup GWD/MTU | Calculated k | Monte Carlo σ | Calculated Decrement | EPRI Benchmark Decrement | Bias Calc–EPRI Decrement |
|---|---|---|---|---|---|
| 0 | 1.4712 | 0.0001 | | | |
| 10 | 1.3484 | 0.0002 | 0.1228 | 0.1223 | 0.0005 |
| 20 | 1.2553 | 0.0002 | 0.2159 | 0.2157 | 0.0002 |
| 30 | 1.1721 | 0.0001 | 0.2991 | 0.2990 | 0.0001 |
| 40 | 1.0958 | 0.0001 | 0.3754 | 0.3758 | -0.0004 |
| 50 | 1.0267 | 0.0001 | 0.4445 | 0.4445 | 0.0000 |
| 60 | 0.9688 | 0.0001 | 0.5024 | 0.5029 | -0.0005 |

Negative Bias is conservative and will be ignored

Results in the above table are for Case 3 (4.25 wt%)

# Comparison of Methods

| Burnup (GWd/T) | Kopp Uncertainty (delta k) | ORNL (ISG8 Rev 3) Uncertainty (delta k) | EPRI Method Uncertainty and bias (delta k) |
|---|---|---|---|
| 10 | 0.006 | 0.016 | 0.008 |
| 20 | 0.011 | 0.015 | 0.008 |
| 30 | 0.015 | 0.016 | 0.008 |
| 40 | 0.019 | 0.021 | 0.008 |
| 50 | 0.022 | 0.030 | 0.008 |
| 60 | 0.025 | 0.030 | 0.008 |

# Status of Depletion Reactivity Uncertainty

- Millstone, Comanche Peak , and South Texas are planning to submit an application in 2013.  Exact implementation is -under consideration.

- NRC's Division of Safety Systems is expected to make recommendations in 2013.

- EPRI submitted the reactor-based benchmarks for inclusion in the OECD/NEA's International Handbook of Evaluated Reactor Physics Benchmarks.  The benchmarks have been approved as a draft for the 2013 edition.  The acceptance process has involved significant international reviews.

# Summary

- Depletion Reactivity Uncertainty is changing.
- Two new approaches that use measured data.
- Difference ORNL uses Chemical Assays, EPRI uses Power Reactor Measurements.
- The changes may cost about $1.5 million per pool, assuming that the Kopp guidance cannot be defended.  (Or savings of that magnitude if EPRI approach accepted)
- 2013 will be the year that the approach gets settled.

# Reports

- The details on the ORNL and EPRI approaches are beyond the scope of this presentation, but are available in the following public domain reports:

EPRI REPORTS:
The benchmarks:
http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001022909
The utilization of the benchmarks:
http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001025203
The cost of ORNL approach:
http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001026483
(That is 11 leading 0's)
ORNL Reports:  (NUREG/CR-7108 and NUREG/CR-7109)
http://pbadupws.nrc.gov/docs/ML1211/ML12116A124.pdf
http://pbadupws.nrc.gov/docs/ML1211/ML12116A128.pdf

# Questions?

# ENDF/B-VII Results

| Case | Lattice Description | Bias (Calculated Reactivity Decrement – Measured Reactivity Decrement) For 100-Hour Cooling | | | | | |
|------|---------------------|------|------|------|------|------|------|
| | | Burnup (GWd/T) | | | | | |
| | | 10 | 20 | 30 | 40 | 50 | 60 |
| 1 | 3.25% enrichment depletion | -0.0004 | -0.0008 | -0.0010 | -0.0015 | -0.0014 | -0.0022 |
| 2 | 5.00% enrichment depletion | 0.0004 | 0.0005 | 0.0003 | 0.0006 | 0.0005 | 0.0008 |
| 3 | 4.25% enrichment depletion | 0.0005 | 0.0002 | 0.0001 | -0.0004 | 0.0000 | -0.0005 |
| 4 | off-nominal pin depletion | 0.0002 | -0.0002 | -0.0004 | -0.0010 | -0.0011 | -0.0016 |
| 5 | 20 WABA depletion | 0.0005 | 0.0009 | 0.0007 | 0.0002 | -0.0002 | 0.0001 |
| 6 | 104 IFBA depletion | 0.0016 | 0.0010 | 0.0008 | -0.0002 | -0.0008 | -0.0014 |
| 7 | 104 IFBA, 20 WABA depletion | 0.0015 | 0.0016 | 0.0010 | 0.0002 | -0.0001 | -0.0011 |
| 8 | high boron depletion = 1500 ppm | 0.0003 | 0.0004 | 0.0001 | -0.0001 | -0.0001 | -0.0004 |
| 9 | branch to hot rack = 338.7K | -0.0003 | -0.0002 | -0.0005 | -0.0004 | -0.0004 | -0.0004 |
| 10 | branch to rack boron = 1500 ppm | -0.0005 | -0.0010 | -0.0016 | -0.0019 | -0.0023 | -0.0026 |
| 11 | high power density depletion | 0.0001 | 0.0002 | -0.0002 | -0.0002 | -0.0003 | -0.0003 |

# Gd Credit for BWRs

- Since BWRs do not have soluble boron in their pools they do not use "burnup credit"

- However, BWR fuel designs use a large amount of Gd in the fuel as a burnable absorber.

- BWRs get some credit for Gd, called "Gd credit"

- The reactivity of fuel with a large amount of burnable absorbers increases with burnup.

# Gd Credit
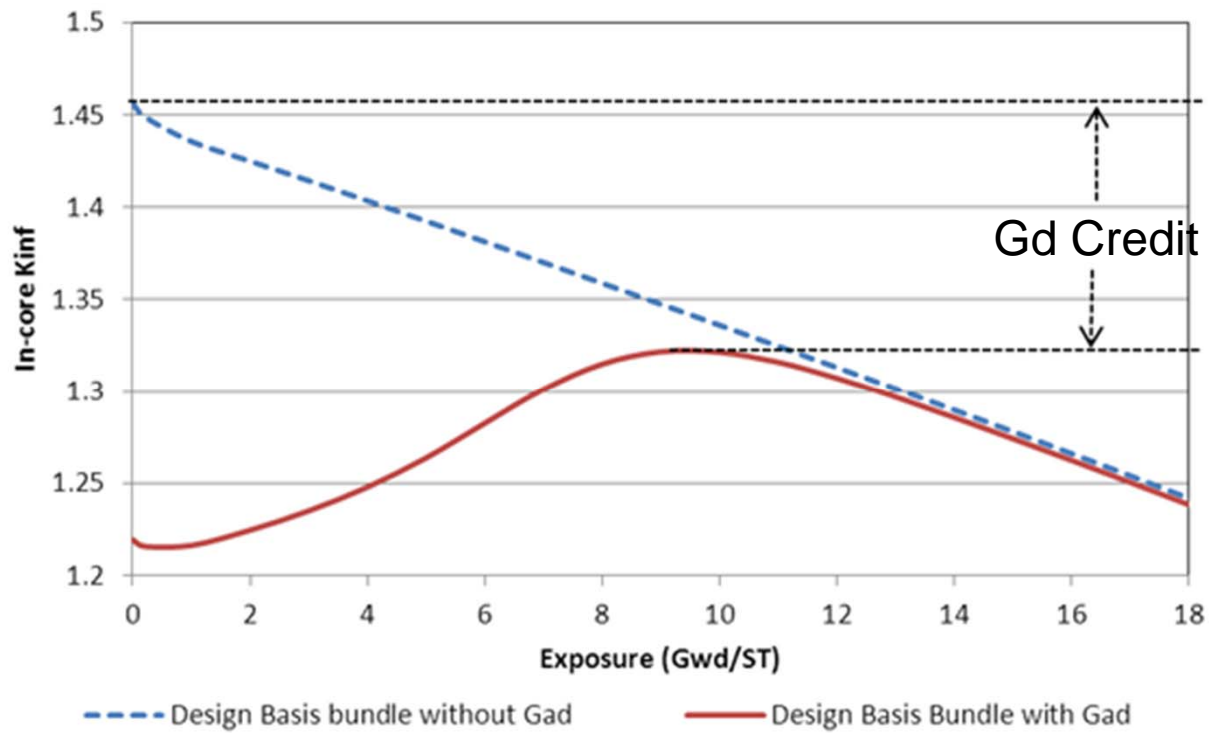


- Gd credit is also called peak reactivity credit.
- Gd credit requires depletion analysis so it is considered a subset of burnup credit.

# Flux Maps: Individual Assembly Reaction Rates

Each cell shows three stacked values:
Reaction Rate — SIMULATE-3 (top) / MEASURED (middle) / S3-MEAS (bottom)

| | R | P | N | M | L | K | J | H | G | F | E | D | C | B | A |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | 0.499 / 0.491 / 0.008 | | 0.483 / 0.483 / 0.000 | | | | | | |
| 2 | | | 0.369 / 0.389 / -0.020 | | | 0.998 / 1.008 / -0.006 | | 0.996 / 0.991 / 0.004 | | | | | | | |
| 3 | | | | | | | 1.195 / 1.175 / 0.020 | | 1.081 / 1.069 / 0.012 | | | 0.998 / 0.985 / 0.012 | | 0.370 / 0.382 / -0.012 | |
| 4 | | 0.610 / 0.627 / -0.017 | 0.997 / 0.994 / 0.003 | | | | | 1.315 / 1.323 / -0.008 | | | | | | | |
| 5 | | | | | 1.309 / 1.298 / 0.010 | | | | 1.330 / 1.331 / -0.001 | | 1.309 / 1.304 / 0.005 | | 1.177 / 1.170 / 0.007 | | |
| 6 | 0.484 / 0.479 / 0.004 | | 1.082 / 1.071 / 0.011 | | | 1.331 / 1.332 / -0.001 | | | | | | | | | |
| 7 | | | | 1.191 / 1.179 / 0.011 | | | 1.276 / 1.287 / -0.011 | | 1.236 / 1.224 / 0.011 | | | 1.270 / 1.274 / -0.004 | | | |
| 8 | 0.475 / 0.478 / -0.003 | | 1.196 / 1.183 / 0.013 | | 1.232 / 1.224 / 0.008 | | 1.209 / 1.206 / 0.003 | | | | 1.317 / 1.319 / -0.002 | | 1.195 / 1.178 / 0.017 | 0.996 / 0.995 / 0.001 | |
| 9 | | 0.958 / 0.951 / 0.007 | | | | | | | 1.278 / 1.272 / 0.006 | | 1.332 / 1.317 / 0.014 | | | | 0.497 / 0.501 / -0.004 |
| 10 | | | | | | | | | | | | 1.296 / 1.298 / -0.002 | | | |
| 11 | 0.355 / 0.372 / -0.018 | | | | 1.306 / 1.323 / -0.017 | | 1.233 / 1.212 / 0.020 | | | | 1.308 / 1.305 / 0.004 | | | | 0.354 / 0.370 / -0.015 |
| 12 | | | | | | 1.294 / 1.305 / -0.011 | | | 1.192 / 1.182 / 0.009 | | | 1.170 / 1.173 / -0.003 | | | |
| 13 | | | 0.876 / 0.876 / 0.000 | | 1.170 / 1.188 / -0.018 | | 1.196 / 1.183 / 0.013 | | | | | | | 0.369 / 0.383 / -0.014 | |
| 14 | | 0.369 / 0.395 / -0.026 | | | | | 0.956 / 0.938 / 0.018 | | | 1.000 / 0.996 / 0.003 | | 0.611 / 0.642 / -0.032 | | | |
| 15 | | | | | 0.354 / 0.366 / -0.012 | | 0.475 / 0.476 / -0.001 | | | | | | | | |

Legend (bottom-right, highlighted): Reaction Rate — SIMULATE-3 — MEASURED — S3-MEAS

# Sensitivity of Flux Maps To Reactivity of Sets of Assemblies

Each cell lists three stacked values (top / middle / bottom).

| | R | P | N | M | L | K | J | H | G | F | E | D | C | B | A |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | -0.005 / 0.008 / 0.020 | | | | -0.023 / 0.000 / 0.022 | | | | | |
| 2 | | | -0.046 / -0.020 / 0.006 | | | -0.045 / -0.006 / 0.032 | | 0.012 / 0.004 / -0.003 | | | | | | | |
| 3 | | | | | | | | 0.032 / 0.020 / 0.007 | | -0.017 / 0.012 / 0.039 | | -0.042 / 0.012 / 0.064 | | -0.039 / -0.012 / 0.013 | |
| 4 | | -0.056 / -0.017 / 0.020 | -0.051 / 0.003 / 0.055 | | | | | 0.061 / -0.008 / -0.062 | | | | | | | |
| 5 | | | | | 0.032 / 0.010 / -0.010 | | | | 0.069 / -0.001 / -0.066 | | 0.027 / 0.005 / -0.015 | -0.042 / 0.007 / 0.055 | | | |
| 6 | -0.013 / 0.004 / 0.026 | | -0.018 / 0.011 / 0.038 | | | 0.038 / -0.001 / -0.040 | | | | | | | | | |
| 7 | | | | 0.039 / 0.011 / -0.014 | | | 0.031 / -0.011 / -0.053 | | 0.064 / 0.011 / -0.039 | | | -0.011 / -0.004 / 0.002 | | | |
| 8 | -0.008 / -0.003 / 0.001 | | 0.025 / 0.013 / 0.001 | | 0.080 / 0.008 / -0.059 | | 0.042 / 0.002 / -0.037 | | | | | 0.057 / -0.002 / -0.056 | 0.029 / 0.017 / 0.005 | 0.009 / 0.001 / -0.007 | |
| 9 | | -0.009 / 0.007 / 0.022 | | | | | | | 0.048 / 0.006 / -0.036 | | 0.084 / 0.014 / -0.051 | | | | -0.017 / -0.004 / 0.009 |
| 10 | | | | | | | | | | | | -0.005 / -0.002 / 0.001 | | | |
| 11 | -0.039 / -0.018 / 0.003 | | | | 0.005 / -0.017 / -0.037 | | 0.092 / 0.020 / -0.047 | | | | 0.026 / 0.004 / -0.016 | | | | -0.036 / -0.015 / 0.005 |
| 12 | | | | | | -0.015 / -0.012 / -0.009 | | | 0.037 / 0.009 / -0.016 | | | -0.048 / -0.003 / 0.040 | | | |
| 13 | | | -0.057 / 0.000 / 0.054 | | -0.068 / -0.018 / 0.029 | | 0.025 / 0.013 / 0.001 | | | | | | | -0.041 / -0.014 / 0.011 | |
| 14 | | | -0.052 / -0.026 / 0.000 | | | | 0.002 / 0.018 / 0.033 | | -0.036 / 0.003 / 0.041 | | | -0.070 / -0.031 / 0.006 | | | |
| 15 | | | | | -0.033 / -0.012 / 0.008 | | -0.005 / -0.001 / 0.003 | | | | | | | | |

**r.m.s. diff**

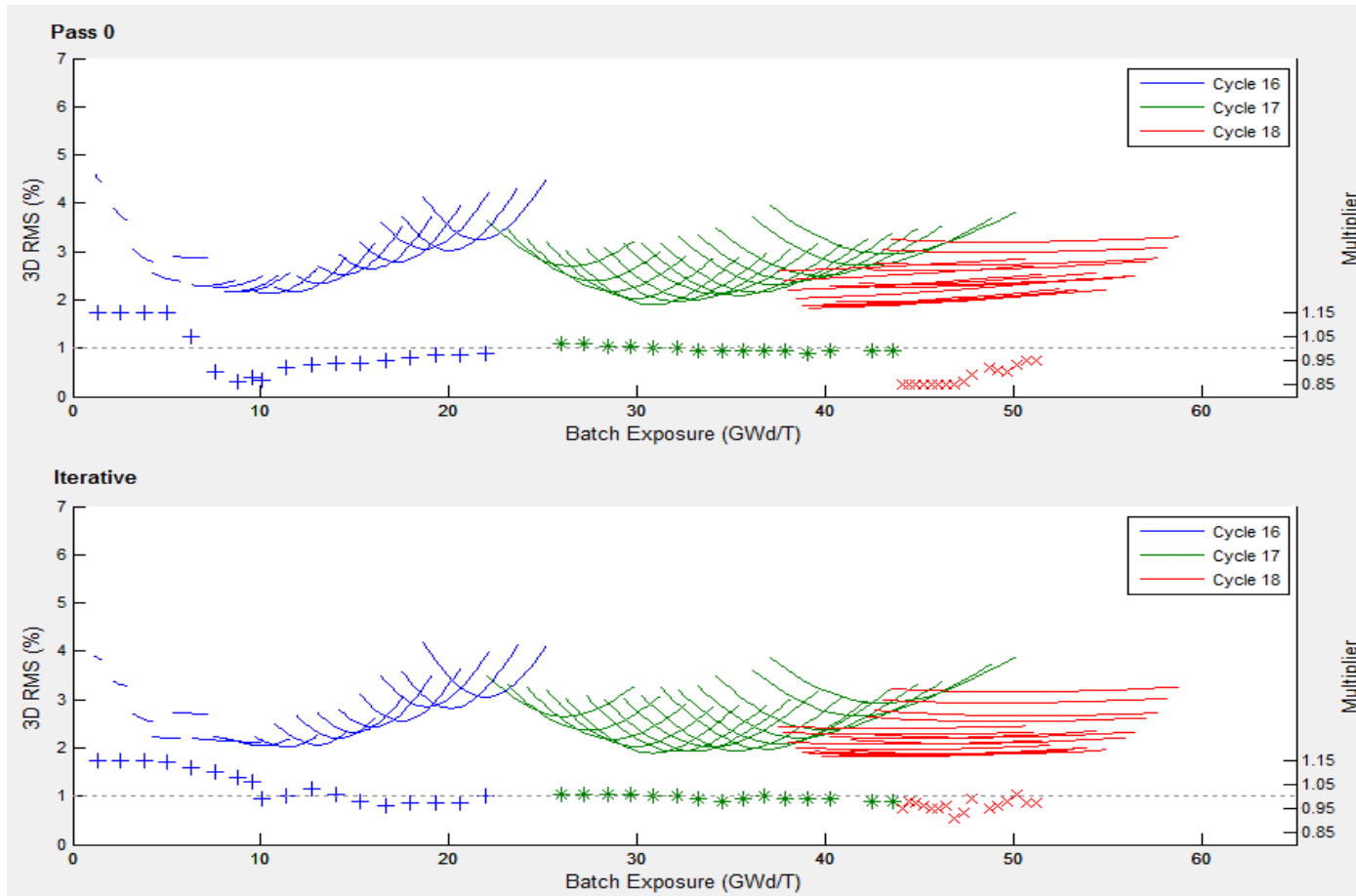| | |
|---|---|
| $M_B = 0.9$ | 4.2% |
| $M_B = 1.0$ | 1.2% |
| $M_B = 1.1$ | 3.3% |

# EPRI Method

- Assembly reactivity is modified by evaluating nodal parameters (e.g., group cross-sections) at burnups perturbed by a multiplication factor, $M_B$
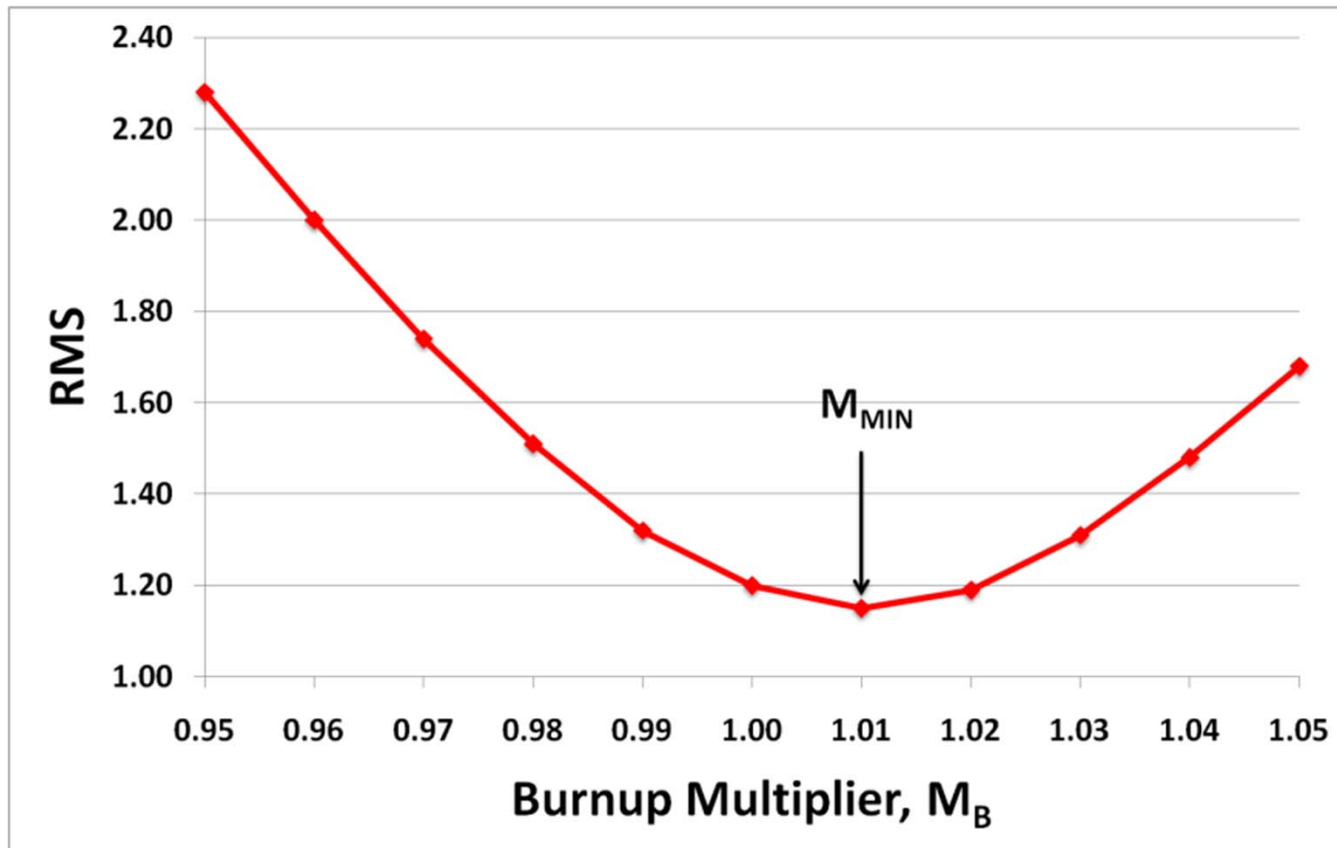
# The Depletion Reactivity Biases for CASMO5
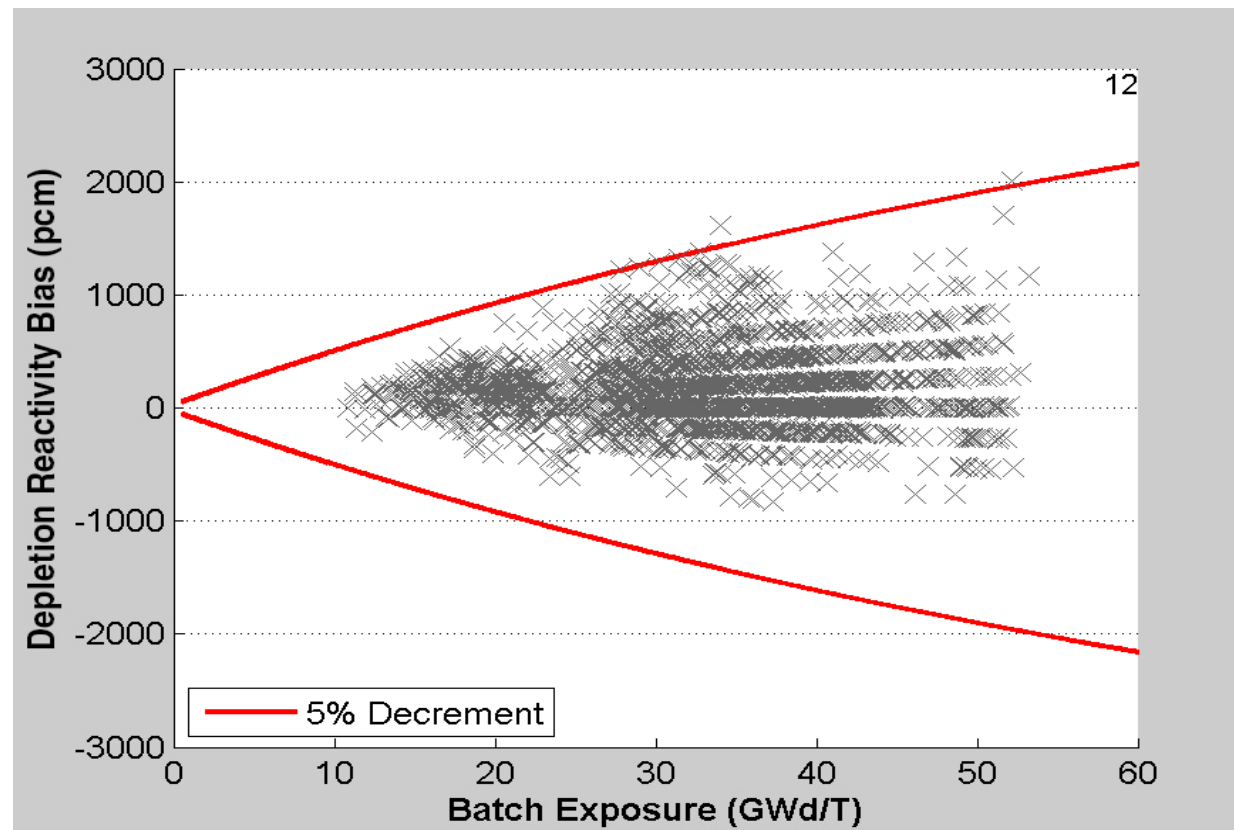
# Iterative Determination of Multipliers

# Computer Code Sensitivity



Inferred Depletion Reactivity Using All Models