Recent Developments in the Depletion Reactivity Uncertainty

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NuclearConsultants.com
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?

Excellent agreement between predicted (line) and measured data!

However, critical data from power plants are global core values where the average burnup reaches about 35 GWd/T by end of cycle. We want to credit assembly burnup 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 major step forward 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 chemical assays have a high uncertainty.
• 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 worth uncertainty 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 to determine the change in reactivity as a function of burnup.

• The EPRI approach validates the change in reactivity with burnup, not the change of isotopic content and uncertainty from the fission product cross sections.

• The uncertainty derived from relying on reactor measurements includes 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

Fuel Material Description
- Material Density: 10.340 (g/cm^3)
- Fuel Temperature: 900 K
- Nuclide
  - U-235: 9.92536E+20
  - U-234: 7.97571E+18
  - U-238: 2.20709E+22
  - O: 4.61429E+22

Structural Material Description
- Material (Zr-4) Density: 6.55 (g/cm^3)
- Temp., unheated: 580 K
- Temp., heated: 0.12*T_{fuel}+0.88*T_{coolant}
- Nuclide: Number Density
  - Zr-4: 4.32444E+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

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## EPRI Benchmark Depletion Reactivities

### Measured Depletion Reactivity

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<th>40</th>
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### Benchmark Uncertainty (same for all cooling)

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<td>-0.1076</td>
<td>-0.2176</td>
<td>-0.3075</td>
<td>-0.3931</td>
<td>-0.4715</td>
<td>-0.5385</td>
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### 15 years Cooling

- Case 1: 0.00576
- Case 2: 0.00576
- Case 3: 0.00576
- Case 4: 0.00576
- Case 5: 0.00576
- Case 6: 0.00576
- Case 7: 0.00576
- Case 8: 0.00576
- Case 9: 0.00576
- Case 10: 0.00576
- Case 11: 0.00576

### 5 years Cooling

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

Higher Uncertainty due to Higher Temperature

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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

<table>
<thead>
<tr>
<th>Burnup GWD/MTU</th>
<th>Calculated $k$</th>
<th>Monte Carlo $\sigma$</th>
<th>Calculated Decrement</th>
<th>EPRI Benchmark Decrement</th>
<th>Bias Calc–EPRI Decrement</th>
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<tr>
<td>0</td>
<td>1.4712</td>
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Negative Bias is conservative and will be ignored

Results in the above table are for Case 3 (4.25 wt%)
## Comparison of Methods

<table>
<thead>
<tr>
<th>Burnup (GWd/T)</th>
<th>Kopp Uncertainty (delta k)</th>
<th>ORNL (ISG8 Rev 3) Uncertainty (delta k)</th>
<th>EPRI Method Uncertainty and bias (delta k)</th>
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<tr>
<td>10</td>
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<td>0.016</td>
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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

### Bias (Calculated Reactivity Decrement – Measured Reactivity Decrement)

For 100-Hour Cooling

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<th>Lattice Description</th>
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<td>3.25% enrichment depletion</td>
<td>-0.0004</td>
<td>-0.0008</td>
<td>-0.0010</td>
<td>-0.0015</td>
<td>-0.0014</td>
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<td>2</td>
<td>5.00% enrichment depletion</td>
<td>0.0004</td>
<td>0.0005</td>
<td>0.0003</td>
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<td>3</td>
<td>4.25% enrichment depletion</td>
<td>0.0005</td>
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<td>-0.0004</td>
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<td>-0.0005</td>
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<td>4</td>
<td>off-nominal pin depletion</td>
<td>0.0002</td>
<td>-0.0002</td>
<td>-0.0004</td>
<td>-0.0010</td>
<td>-0.0011</td>
<td>-0.0016</td>
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<td>5</td>
<td>20 WABA depletion</td>
<td>0.0005</td>
<td>0.0009</td>
<td>0.0007</td>
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<td>104 IFBA depletion</td>
<td>0.0016</td>
<td>0.0010</td>
<td>0.0008</td>
<td>-0.0002</td>
<td>-0.0008</td>
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<td>7</td>
<td>104 IFBA, 20 WABA depletion</td>
<td>0.0015</td>
<td>0.0016</td>
<td>0.0010</td>
<td>0.0002</td>
<td>-0.0001</td>
<td>-0.0011</td>
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<td>high boron depletion = 1500 ppm</td>
<td>0.0003</td>
<td>0.0004</td>
<td>0.0001</td>
<td>-0.0001</td>
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<tr>
<td>9</td>
<td>branch to hot rack = 338.7K</td>
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<td>branch to rack boron = 1500 ppm</td>
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<td>-0.0010</td>
<td>-0.0016</td>
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<td>high power density depletion</td>
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<td>-0.0002</td>
<td>-0.0002</td>
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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 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

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**Reaction Rate**

**SIMULATE**

**MEASURED**

**S3-MEAS**
### Sensitivity of Flux Maps To Reactivity of Sets of Assemblies

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<th></th>
<th>R</th>
<th>P</th>
<th>N</th>
<th>M</th>
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**R.m.s. diff**

| Ms=0.9 | 4.2% |
| Ms=1.0 | 1.2% |
| Ms=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

![Graph showing depletion reactivity biases vs batch exposure]
Iterative Determination of Multipliers
Computer Code Sensitivity

Inferred Depletion Reactivity Using All Models

- Using CASMO-4 No LFP Model
- Using CASMO-4 Model
- Using CASMO-5 Model
- CASMO-5 Based Mean

Burnup (GWD/T) vs. Depletion Reactivity (delta k)