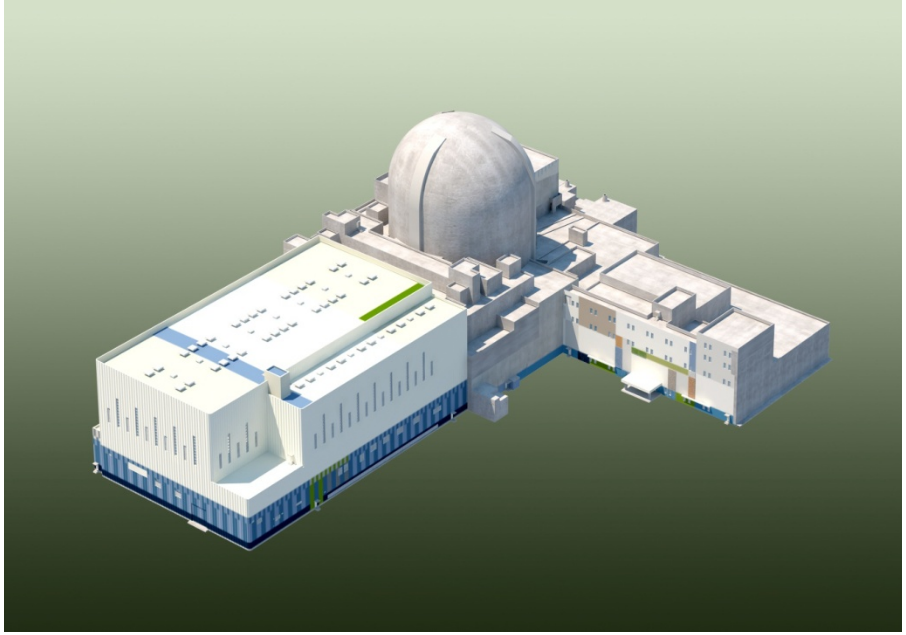
NON-PROPRIETARY

Burnup Credit Analysis Methodology



KEPCO/KHNP
APRIL 29, 2015

Public Meeting

Contents

- Introduction
- Burnup Credit Analysis Methodology
  - ✓ Computer code and Reactor parameters
  - ✓ Bias due to Axial burnup profile
  - ✓ Burnable Absorbers
  - ✓ Depletion Uncertainty
  - ✓ Bias due to Minor Actinide and Fission Product
  - ✓ Burnup Measurement Uncertainty
- Summary

Introduction

- **Spent Fuel Pool Acceptance Criteria (10CFR50.68)**
  - If credit is taken for soluble boron,
    - the k-eff of the spent fuel storage racks loaded with fuel of the maximum fuel assembly reactivity must not exceed 0.95, at a 95/95, if flooded with borated water, and
    - k-eff must remain below 1.0 (subcritical), at a 95/95, if flooded with unborated water.

Introduction

- **Major Guidance**
  - DSS-ISG-2010-01 : Staff Guidance Regarding the Nuclear Criticality Safety Analysis for SFPs
  - NEI 12-16, Rev. 1 : Guidance for Performing Criticality Analyses of Fuel Storage at Light Water Reactor Power Plants
  - Relevant NUREG's
  - NRC memorandum from L. Kopp to T. Collins (Kopp Memo)

NON-PROPRIETARY

Introduction

TS

Region I: 6 Racks (352 Cells)

5 Cells for Damaged Fuel Assembly

Region II: 23 Racks (1440 Cells)

Public Meeting

Introduction

- **Cell Configuration**

TS

Introduction

- **Biases and Uncertainties**

Description		Region I	Region II	
Code Validation	Bias	⊙	⊙	Bias
	Bias uncertainty (2σ)	⊙	⊙	Uncertainty
Monte Carlo uncertainty (2σ)		⊙	⊙	Uncertainty
Mechanical tolerance & design parameter		⊙	⊙	Bias/Uncertainty
Axial burnup distribution effect			⊙	Bias
Burnable poison effect			⊙	Bias
Depletion uncertainty			⊙	Uncertainty
Bias due to minor actinide and fission product			⊙	Bias
Burnup measurement uncertainty			⊙	Uncertainty

$$k_{eff} = k_{cal} + \sum \Delta k_{Bias} + \sqrt{\sum (\Delta k_{Unc})^2}$$

Introduction

- **Related Issues for the Burnup Credit Analysis**
  - Computer Code & Reactor Parameters
  - Axial Burnup Profile
  - Burnable Absorbers
  - Depletion Uncertainty
  - Bias due to Minor Actinide and Fission Product
  - Burnup Measurement Uncertainty

Computer Code and Reactor Parameters

- **Computer Code & Cross Section Library**
  - Depletion Calculation : ORIGEN-ARP (SCALE 6.1.2)
  - Cross Section Generation : TRITON/NEWT (SCALE 6.1.2)

    - Fuel : PLUS7
    - Assembly Lattice : 16x16
    - Enrichment Range: 1.5 ~ 6.0* wt% U-235
    - Burnup Range: 0 ~ 72* GWd/MTU
    - Burnup Step: 2.25 GWd/MTU (Total 33 steps)
    - Cross Section Library: ENDF/B-VII 238-group

* The maximum initial enrichment and burnup were 5.0 wt% U-235 and 62 GWd/MTU, respectively. However, enrichment and burnup beyond the maximum value were considered to generate cross section library for the purpose of sensitivity studies.

Computer Code and Reactor Parameters

- Parameters used in depletion calculation consist of composition data, cell data, moderator data and operation data.

- DSS-ISG-2010-01 states that "Bounding values should be used, and they should be traceable to other licensee documents."

[ ]TS

Computer Code and Reactor Parameters

- The most important parameters which impact on the reactivity of spent fuel in depletion calculations are fuel and moderator temperature, power level, fuel density and soluble boron concentration.
  - Maximum Fuel Temperature : Higher fuel temperature causes Doppler broadening and it results in increased plutonium production.
  - Maximum Moderator Temperature (Minimum moderator density) : Higher moderator temperature causes less moderation and it results in energy spectrum hardening.
  - Maximum Power Level: Maximum power level was considered in depletion calculation since higher power level results in higher moderator and fuel temperature.
  - Maximum Pellet Density : Maximizes fissile material.
  - Maximum Cycle Average Soluble Boron Concentration : Higher soluble boron concentration causes energy spectrum hardening.

Computer Code and Reactor Parameters

TS

Bias due to Axial Burnup Profile

- When modeling the fuel assembly in the criticality analysis, the reactivity is affected by the distribution of burnup along the axial length of the fuel assembly.
- Therefore, sensitivity analyses were performed with and without a bounding axial burnup profile, to assess the magnitude of the end effect which is applied as a bias.
- The end effect is the k_{eff} difference between fuel assembly considering explicit axial burnup distribution and fuel assembly considering flat axial burnup distribution.

Bias due to Axial Burnup Profile

- **Selection of Bounding Axial Burnup Profile**
  - Survey 304 axial burnup profiles over cycle 1 to 8.
  - Find the axial burnup profile that has a minimum of burnup summed over top 10 axial nodes (33% of active core length).

- **Modeling of Axial Burnup Distribution**
  - Original 26 axial nodes are modified into the 18 nodes by merging flat burnup regions in the middle of fuel assembly.
  - The local powers for each node are assumed by multiplying a normalized burnup distribution by the assembly-averaged power.

Bias due to Axial Burnup Profile

TS

Bias due to Axial Burnup Profile

- **End Effect of Non-Blanketed Fuel and Blanketed Fuel**
  - The PLUS7 16x16 fuel assembly has blankets (6 inches long 2 wt% U-235 pellets) at the top and bottom end of the fuel rod.
  - Sensitivity analyses were performed to assess the magnitude of the blanket effect.
  - By comparing the end effect without blanket and with blanket shows that the non-blanketed fuel is up to 3% Δk_{eff} more reactive.
  - Therefore, axial blankets in the fuel rod are not considered for conservatism.

[ ] TS

Bias due to Axial Burnup Profile

TS

Burnable Absorbers

- Burnable absorber effect to the reactivity should be evaluated because it hardens the energy spectrum during operation.
- As a result of evaluation, the k_{eff} for the fuel assembly without burnable absorber is greater than the k_{eff} for the fuel assembly with burnable absorber.
- The reason for this result is that Gadolinium always has a net negative reactivity worth.
- This result was consistent with NUREG/CR-6760.
- Therefore, burnable absorbers were not considered in criticality analysis.

Burnable Absorbers

- APR1400 Burnable Absorber (Gd_2O_3) – Equilibrium Core

TS

Burnable Absorbers

TS

Public Meeting

Depletion Uncertainty

- DSS-ISG-2010-01 states that "Depletion uncertainty as cited in the Kopp memorandum should only be construed as covering the uncertainty in the isotopic number densities generated during the depletion simulations."

- Therefore, the uncertainty due to isotopic number density generation is taken to be 5% of the reactivity difference between the reactivity at the fresh fuel condition and the reactivity at the burned fuel condition of interest.

- EPRI report* titled "Utilization of the EPRI Depletion Benchmarks for Burnup Credit Validation" shows that the use of 5% Δk as an uncertainty is conservative.

*The EPRI report is still under NRC review but is only being used to demonstrate the conservatism of the 5% decrement method from the Kopp Memo.

Depletion Uncertainty

TS

Bias due to Minor Actinide and Fission Product

- **Nuclides considered in the criticality analysis**
  - 12 actinides and 16 fission products recommend in ISG-8 were considered for the criticality analysis.

9 Major Actinides	U-234, U-235, U-238, Pu-238, Pu-239, Pu-240 Pu-241, Pu-242, Am-241
19 Minor Actinides and Fission Products	Mo-95, Tc-99, Ru-101, Rh-103, Ag-109, Cs-133, Sm-147, Sm-149, Sm-150, Sm-151, Sm-152, Nd-143, Nd-145, Eu-151, Eu-153, Gd-155, U-236, Am-243, Np-237

Bias due to Minor Actinide and Fission Product

- Bias and bias uncertainty due to actinide are evaluated by criticality code validation (Ref. 7 of TeR) including HTC experiments.

- NUREG/CR-7109 states that one point five percent (1.5 %) of the worth of the minor actinides and fission products conservatively covers the bias due to these isotopes under the following range of applicability:

  a. Low enriched fuel (< 5.0 wt% U-235) with ENDF/B-VII cross section library,

  b. Maximum burnup is 70 GWd/MTU, and

  c. Total minor actinide and fission product nuclide worth does not exceed 0.1 in k_{eff}.

- The sensitivity analysis is performed to assess the worth of the minor actinides and fission products and the analysis results show that the credited minor actinide and fission product worth is less than 0.1 in k_{eff}.

Bias due to Minor Actinide and Fission Product

TS

Public Meeting

Burnup Measurement Uncertainty

- The burnup measurement uncertainty is calculated by difference between the reactivity with a burnup and the reactivity with 5% less burnup.

- **Burnup Measurement Uncertainty =**

$$k_{95\%\ burnup} - k_{burnup} + 1.645\sqrt{\sigma_{95\%\ burnup}{}^2 + \sigma_{burnup}{}^2}$$

- 5% change in burnup was based on the NEI 12-16 Rev. 1.

Burnup Measurement Uncertainty

TS

Summary

- Burnup credit analysis methodology used in criticality analysis of spent fuel storage racks of APR1400 was based on DSS-ISG-2010-01.
- Bias due to axial burnup profile, burnable absorber effects, depletion uncertainty, bias due to minor actinide and fission product and burnup measurement uncertainty were evaluated.
- The burnup credit analysis overestimates the reactivity of discharge fuel and therefore the burnup requirements developed in technical report titled “Criticality Analysis of New and Spent Fuel Storage Rack” are conservative and ensure the safe storage of fuel in the spent fuel pool.

Thank you for your attention.