DPC-NE-1008-P
CASMO-5/SIMULATE-3 Physics Methods

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Non-Proprietary Version

Duke/NRC Pre-Meeting for DPC-NE-1008-P

April 14, 2015

Objective

- Obtain feedback from the NRC on technical approach
- Determine if any additional meetings should be held to facilitate the review process
- Obtain NRC feedback on proposed review schedule

Presentation Outline

- Background
- Update on Proposed Submittals
- Licensing Approach
- DPC-NE-1008-P
- CASMO-4 to CASMO-5 Model Differences
- CASMO-5/SIMULATE-3 Code Qualification
  - Power Reactor Benchmarks
  - Pin Power Benchmarks (Critical Experiments)
- Statistical Method
- Statistically Combined Uncertainty Factors
- Conclusion

Background

- Duke nuclear design methods implemented in 1982
- Methods have been used to design over 80 reloads
- Currently perform reload design analyses for McGuire, Catawba and Oconee Nuclear Stations (7 units)

Methods Reports

	MNS/CNS (Duke)	Proposed RNP/HNP (Duke)	Target Submittal Date
Physics Codes / Models	DPC-NE-1005 CASMO-4/SIMULATE-3	DPC-NE-1008 CASMO-5/SIMULATE-3	June 2015
Physics Applications Power Distribution Monitoring	DPC-NE-2011	DPC-NE-2011 revision	December 2015
Physics Applications Reload Design	DPC-NF-2010	DPC-NF-2010 revision	December 2015
NSSS Codes / Models	DPC-NE-3000 RETRAN-02	DPC-NE-3008 RETRAN-3D	July 2015
Subchannel T/H Methods	DPC-NE-3000 DPC-NE-2004 VIPRE-01	DPC-NE-3008 DPC-NE-2005 (Appendix) VIPRE-01	July 2015
SCD Methodology	DPC-NE-2005	DPC-NE-2005 revision	**March 5, 2015**
Transient Analysis	DPC-NE-3001 DPC-NE-3002 SIMULATE-3K (REA)	DPC-NE-3009 SIMULATE-3K (REA)	December 2015
Fuel Performance	DPC-NE-2008 (TACO-3) DPC-NE-2009 (PAD 4.0)	N/A - TS changes only COPERNIC-2	December 2015

Licensing Approach

- Goal is to extend nuclear analysis capability to Harris and Robinson
- Current nuclear analysis methodology uses the
  CASMO-4 /SIMULATE-3 computer codes described in:
  - DPC-NE-1005-PA C-4/S-3 method for McGuire and Catawba
  - DPC-NE-1006-PA C-4/S-3 method for Oconee
- Transition to CASMO-5 Adopted
  - State-of-the-art technology
  - Solution techniques are more robust and accurate
  - Implements modern cross section library (ENDF/B-VII.1)
  - Includes more nuclides allowing faithful representation of reactor materials and improved absorber depletion chains
  - Future vendor support for CASMO-4 is limited

Licensing Approach

- DPC-NE-1008-P includes benchmark of Harris, Robinson and McGuire fuel cycles
  - Harris and Robinson use soluble boron and gadolinia burnable absorbers for reactivity and peaking control
  - McGuire uses soluble boron, IFBA and WABA
- McGuire data added to qualify the CASMO-5/ SIMULATE-3 method for IFBA and WABA burnable absorbers
  - Allows for potential transition to other fuel vendor without resubmitting methods

Licensing Approach

- Long term, simplifies future transition of CASMO-5/ SIMULATE-3 methods to McGuire and Catawba
- Current submittal of DPC-NE-1008-P limited to the Harris and Robinson dockets
- Method applicable to all Duke Westinghouse PWRs

- Active CASMO-5/SIMULATE-3 Reviews
  - B&W mPower

Schedule

- Support the reload licensing analysis for Harris Cycle 22 and Robinson Cycle 32
  - H1EOC21 (4/18)
  - R2EOC31 (9/18)
- Reload Analyses Start:
  - HNP (December 2016)
  - RNP (Spring 2017)
- Review requested by end of 2016

DPC-NE-1008-P

- Describes the methodology for performing reload design calculations for Westinghouse PWRs using CASMO-5/SIMULATE-3
- Presents benchmark calculations against measured data from power operation and critical experiments
- Presents code-to-code comparisons for gadolinia and IFBA fuel
- Develops one-sided upper tolerance power distribution uncertainty factors

DPC-NE-1008-P

- Format and content will be similar to previously approved reports
- Major differences from the current licensed methodology
  - Replaces CASMO-4 with CASMO-5
  - Extends the CASMO/SIMULATE-3 design methodology to the Harris and Robinson PWRs
- Changes to CASMO-5 should improve model fidelity
  - Updated nuclear data library
  - Additional nuclides allow the more precise modeling of materials
  - Improved burnable absorber depletion chains

Summary

- DPC-NE-1008 seeks to builds upon Duke's experience with CASMO/SIMULATE-3
  - Over 50 McGuire/Catawba cycles designed
- Develop core modeling techniques that produce accurate and reliable results
- Methodology approach patterned after NRC-approved DPC-NE-1005-P and DPC-NE-1006-P methodology
- SIMULATE-3 methodology remains unchanged
- Extend nuclear analysis capability to the Harris and Robinson reactors
- Submittal targeting June 2015

CASMO-4/CASMO-5 Model Differences

Parameter	CASMO-4	CASMO-5
Data library evaluation	ENDF/B-IV	ENDF/B-VII.1
Data library energy groups	70	586
Resonance Groups	13	41
Fission product chains	Lumped Fission Product (LFP) (29 + 2 lumped)	Explicit fission product chains (490 fission products)
No. of nuclides/materials	103	1095
Burnable absorber chains	Limited	Extensive
PWR IFBA treatment	Homogenized	Explicit
Multi-assembly capabilities	2x2 Colorset	Generalized (up to full core)

CASMO-5/SIMULATE-3 Code Qualification

- Compare CASMO-5/SIMULATE-3 predicted results against measured and calculated data
- Reactivity comparisons performed against startup physics test and operating measurements
- Core power distribution comparisons performed against flux map measurements
- SIMULATE-3 pin power comparisons performed against critical experiments and CASMO-5 (colorset MxN comparisons)

CASMO-5/SIMULATE-3 Code Qualification

- Additional CASMO-5 code benchmarks performed by Studsvik Scandpower in the proprietary report:

  SSP-14-P01/012-R Rev. 0, "CASMO5 PWR Methods and Validation Report"

  - Includes CASMO-5 benchmarks against measured data and higher order calculations (MCNP)
  - Reactivity, reaction rate and pin power comparisons performed against KRITZ-3, B&W criticals (1810 and 1484), DIMPLE and others
  - Depletion models verified against Yankee Rowe and JAERI PWR Isotopic benchmarks

Power Reactor Benchmarks

- Benchmarks performed against most recent fuel cycles
- Fourteen Fuel Cycles Modeled
  - McGuire Unit 1 Cycles 20 through 23
  - Harris Unit 1 Cycles 14 through 18
  - Robinson Unit 2 Cycles 24 through 28
- Measured data available from
  - BOC startup physics testing at HZP
  - At power critical soluble boron concentration measurements
  - At power core power distribution measurements

Measurement of Core Power Distribution

- Performed approximately once per month (produces ~ 20 – 25 measurements per cycle)
- Based on electrical signals produced from moveable incore fission chambers
- Fission chambers traverse the core in a central instrument tube at a constant rate
- Measured signals are proportional to the flux level in the center of the fuel assembly
- The measured flux level measured in the center of the fuel assembly is related to the average assembly power

Core Characteristics

Parameter	Harris	Robinson	McGuire
Rated Thermal Power (RTP)	2948 MWth+	2339 MWth	3411 MWth
Number of Fuel Assemblies	157	157	193
Total Number of RCCAs	52	45	53
HFP Tave	588.8 °F	575.9 °F	585.1 °F
HZP Tave	557 °F	547.0 °F	557.0 °F
Number of Instrumented Locations	50	50	58

+ Uprated in Cycle 18

Fuel Characteristics

Parameter	Harris	Robinson	McGuire
Fuel Lattice	17x17	15x15	17x17
No. of Fuel Pins per Assembly	264	204	264
Number of GTs	24	20	24
Fuel Assembly Pitch	8.466 in	8.466 in	8.466 in
Fuel Pin Pitch	0.496 in	0.563 in	0.496 in
Fuel Rod OD	0.376 in	0.424 in	0.374 in
Fuel Clad Material	Zr-4 and M5	Zr-4 and M5	Zirlo
Structural Material (IT, GT and Grid)	Zr-4	Zr-4	Zirlo
Axial Blankets	3 in.	6 in.	6 in.

Fuel Management

Parameter	Harris	Robinson	McGuire
Loading Pattern Type	Low Leakage	Low Leakage	Low Leakage
Cycle Length	18 months	18 months	18 months
Number of Feed Assemblies	68 to 72	56 to 64	68 to 76
Burnable Absorber Type	Gadolinia	Gadolinia	IFBA and WABA
Burnable Absorber Loading	2.0 to 8.0 w/o gad	2.0 to 8.0 w/o gad	6816 to 7872 IFBA 32 to 528 WABA

Measured Minus Predicted Differences in BOC HZP ARO Critical Boron Concentrations

Measured Minus Predicted Deviation in BOC HZP Isothermal Temperature Coefficients

Measured Minus Predicted
Percent Deviation in Individual Bank Worths

Distribution of Measured Minus Predicted Bank Worth Errors

Harris Measured Minus Predicted Differences in HFP Critical Boron Concentrations

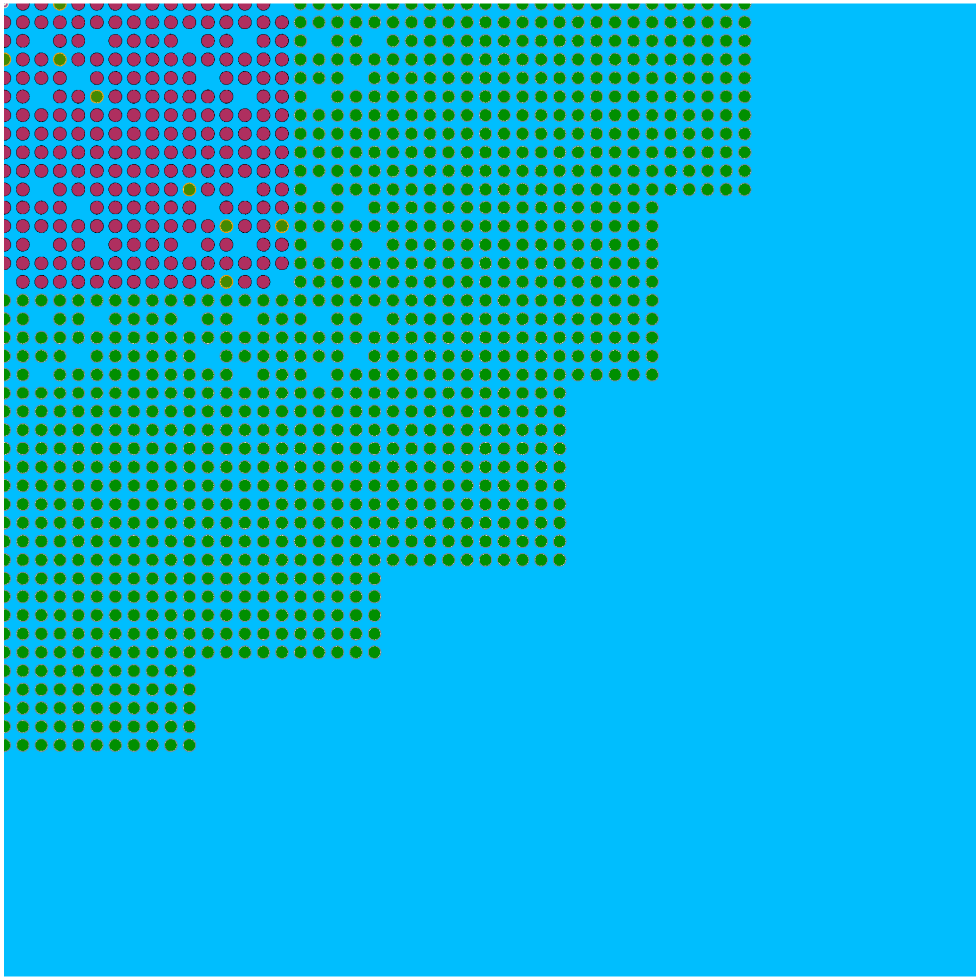
Robinson Measured Minus Predicted Differences in HFP Critical Boron Concentrations

McGuire Measured Minus Predicted Differences in HFP Critical Boron Concentrations

Distribution of HFP Critical Boron Concentration Deviations

Critical Experiment Benchmarks

- B&W Critical experiments evaluated to develop pin power uncertainties
- Cores consist of pin power measurements of LEU and gad fuel pins at clean cold conditions
- Pin power measurements performed in 6 cores
  - 3 contain gad fuel
- Small number of gad pins measured
  - Low power density inflates percent differences



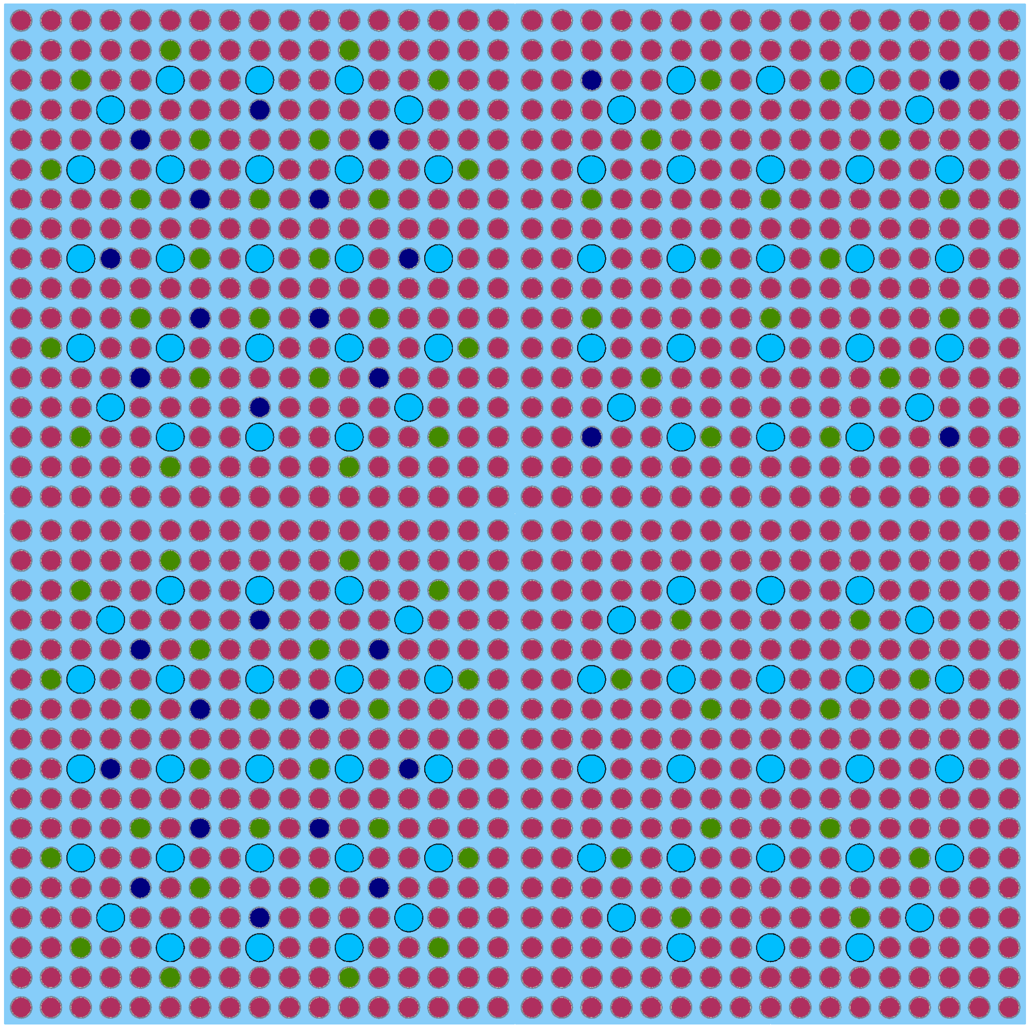
Critical Experiment Benchmarking

CASMO-5 Core 14 Results

SIMULATE-3 Core 14 Results

2x2 Theoretical Benchmarks

- 2x2 comparisons between CASMO-5 (MxN function) and SIMULATE-3
- 15x15 and 17x17 assemblies with varying enrichments, gadolinia/IFBA loadings, and assembly burnups
- Used to evaluate the ability of SIMULATE-3 to reconstruct CASMO-5 pin powers for gadolinia pins



2x2 Theoretical Benchmarks

Relative Comparisons (S3 – C5)/C5

Statistical Methodology

- One-sided upper tolerance limit uncertainties
- Uncertainty factor or ONRF = 1 – bias + Kσ
- K factor ensures with a 95% confidence level that 95% of the local power predictions are equal to or larger than the measured value
- The above definition is based on the assumption the data is normal
- If distribution is not normal, then non-parametric statistics are used

Comparison of Assembly Power Distribution Uncertainties

Statistically Combined Uncertainty Factors

- One-sided upper tolerance limit uncertainties
- Separate factors calculated for LEU and gad fuel
- Assembly and pin uncertainties combined

$$SCUF = 1 - Bias + \sqrt{(K_a\sigma_a)^2 + (K_p\sigma_p)^2}$$

- $K_a\sigma_a$ represents the statistical deviation in the comparison between measured and calculated inter-assembly power distributions and $K_p\sigma_p$ is the equivalent term for the intra-assembly pin power distribution deviation

Statistically Combined Uncertainty Factors

Conclusion

- CASMO-5/SIMULATE-3 core models are capable of accurately modeling reactor cores with boron and gadolinia based burnable absorbers
- Uncertainty factors are comparable (slightly better) than values generated using CASMO-4/SIMULATE-3