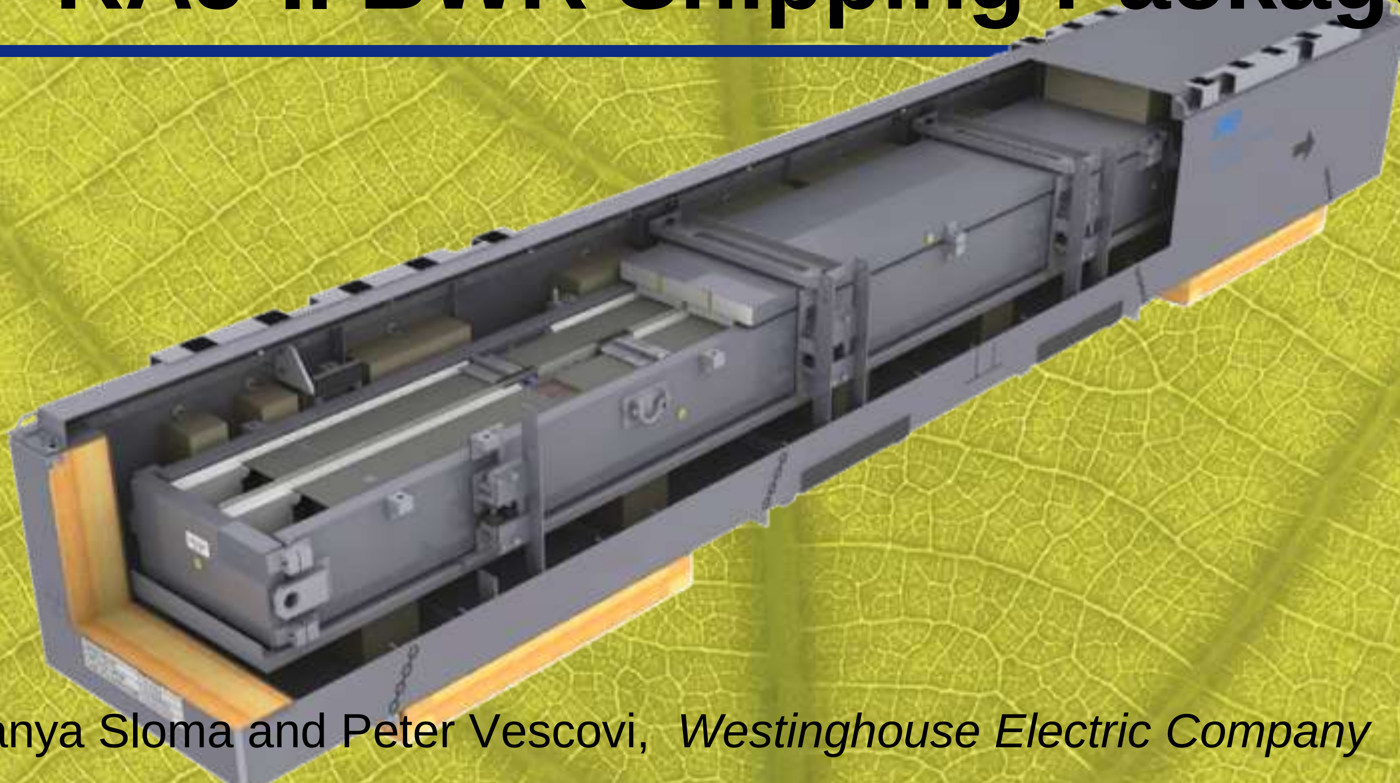
Gad Rod Worth Evaluation for Criticality Safety Analysis of the RAJ-II BWR Shipping Package



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Background: RAJ-II Transport Package

- Type B, Fissile material package (Type B(U)F)
- Currently approved to transport
  - AREVA and GNF BWR fuel bundles
- Revision of Safety Analysis Report
  - WEC entered agreement with GNF to allow shipping of WEC BWR fuel
  - Approval in Europe required additional response to questions regarding current licensed criticality safety evaluation

European Requested Information

- Extent of fuel rearrangement during accident condition
- Use of uniform enrichment to bound actual average lattice enrichment
- Distribution for Gadolinia Oxide neutron absorber

Background: Criticality Safety Evaluations

- Fissile package assessments are performed assuming contents specification provides the maximum k_{eff} , consistent with
  - Fuel bundle design and
  - Transport conditions
- Assumes presence of burnable neutron absorber rods
  - Composed of Urania Oxide-Gadolinia Oxide (Gad)
  - Used to achieve desired core performance
    - By quantity, arrangement, and Gd content variation

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Application of Uniform Enrichment

- Simplify contents specification for RAJ-II
  - Revise package assessment to
    - Specify single minimum number of Gad rods
    - Minimize rules for distribution of Gad rods
    - Eliminate dependence on ^{235}U enrichment

Current
Certificate of Compliance

Parameter	Units	Type	Type	Type	Type
Gadolinia Requirements					
Lattice Average Enrichment[b]	#				
≤ 5.0 wt % U-235	@ wt%	7 @ 2 wt %	10 @ 2 wt %	12 @ 2 wt %	12 @ 2 wt %
≤ 4.7 wt % U-235	Gd_2O_3	6 @ 2 wt %	8 @ 2 wt %	12 @ 2 wt %	12 @ 2 wt %
≤ 4.6 wt % U-235		6 @ 2 wt %	8 @ 2 wt %	10 @ 2 wt %	10 @ 2 wt %
≤ 4.3 wt % U-235		6 @ 2 wt %	8 @ 2 wt %	9 @ 2 wt %	9 @ 2 wt %
≤ 4.2 wt % U-235		6 @ 2 wt %	6 @ 2 wt %	8 @ 2 wt %	8 @ 2 wt %
≤ 4.1 wt % U-235		4 @ 2 wt %	6 @ 2 wt %	8 @ 2 wt %	8 @ 2 wt %
≤ 3.9 wt % U-235		4 @ 2 wt %	6 @ 2 wt %	6 @ 2 wt %	6 @ 2 wt %
≤ 3.8 wt % U-235		4 @ 2 wt %	4 @ 2 wt %	6 @ 2 wt %	6 @ 2 wt %
≤ 3.7 wt % U-235		2 @ 2 wt %	4 @ 2 wt %	6 @ 2 wt %	6 @ 2 wt %
≤ 3.6 wt % U-235		2 @ 2 wt %	4 @ 2 wt %	4 @ 2 wt %	4 @ 2 wt %
≤ 3.5 wt % U-235		2 @ 2 wt %	2 @ 2 wt %	4 @ 2 wt %	4 @ 2 wt %
≤ 3.3 wt % U-235		2 @ 2 wt %	2 @ 2 wt %	2 @ 2 wt %	2 @ 2 wt %
≤ 3.1 wt % U-235		None	2 @ 2 wt %	2 @ 2 wt %	2 @ 2 wt %
≤ 3.0 wt % U-235		None	None	2 @ 2 wt %	2 @ 2 wt %
≤ 2.9 wt % U-235		None	None	None	None

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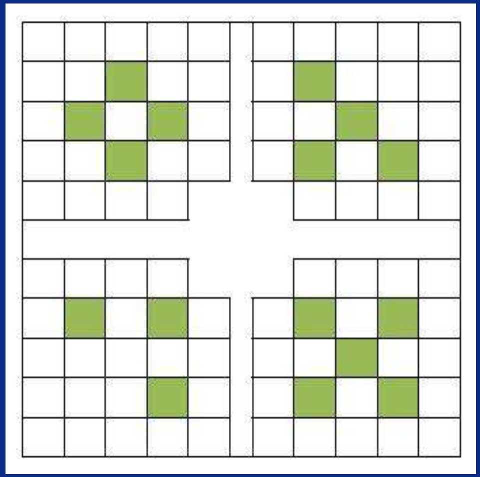
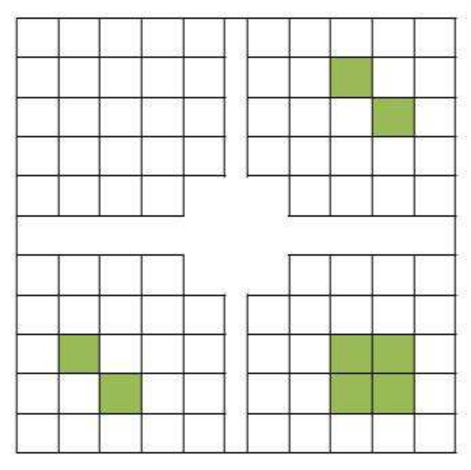
Distribution of Neutron Absorbers

- Simplify contents specification for RAJ-II
  - By evaluating burnable absorber contents
  - Relying on current BWR fuel design criteria

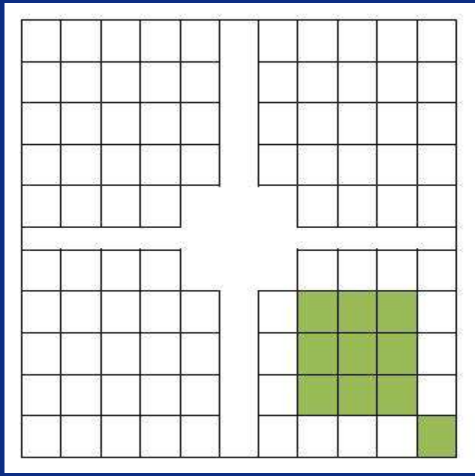
Actual



Revised Model



Licensed Model



k_{eff} increasing →

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Application of Perturbation Theory

- Perturbation theory is useful in studying the relative worth of burnable absorber rod positions
- Absorption characterizing a burnable absorber rod is too strong to allow meaningful estimates of absolute burnable absorber rod worth
- Burnable absorber rods are characterized by relatively weak absorption by using a small quantity of Gadolinia Oxide

Gad Worth Evaluation Methodology

- Sensitivity analysis of burnable absorber contents
  - Determine relative effectiveness of Gad rod as a neutron absorber in BWR lattice
    - Quantified by ^{157}Gd total reaction
- Implemented by TSUNAMI-3D module in SCALE
  - Executes method for sensitivity and uncertainty analysis based on perturbation theory
- Results in selection of least effective reactivity locations for Gad rods in the BWR lattice
  - Ensuring demonstration of most reactive and realistic contents specification

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Gad Rod Worth Evaluation

- Gad rod, or other burnable absorbers, utilized to extend fuel bundle life during power generation
- Neutron absorber location in bundle is significant to reactivity of RAJ-II transport package
- Evaluation process

1. Assessment of each location
2. Evaluate selected Gad rod pattern
3. Ensure most reactive and realistic model

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Calculation Tool: TSUNAMI-3D

- Control module of SCALE code package
- Calculates adjoint-based first-order linear perturbation theory sensitivity coefficients with multi-group Monte Carlo methods [3]
- General processing sequence

NITAWLST – Computes implicit portion of sensitivity coefficient data from cross-section library

TSUNAMI-3D-K5 – Performs Monte Carlo KENO-V.a forward and adjoint criticality calculation

SAMS – Executes linear perturbation theory sensitivity and uncertainty calculations

Source: [3] B. T. Rearden

SAMS Sensitivity Coefficients

- Indicates sensitivity of calculated k_{eff} value [2]
  - To changes in cross-sections
  - To uncertainty in basic nuclear data
- Coefficient calculations include
  - Implicit effect of resonance self-shielding calculations
  - Explicit effect, k_{eff} sensitivity to a particular groupwise cross-section data component
- Gad worth determined by sensitivity coefficient and Monte Carlo uncertainty integrated over energy and region for ^{157}Gd

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Source: [2] SCALE, NUREG/CR-0200

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Gad Worth Evaluation Model Inputs

- Single BWR fuel assembly
  – Exact rod patterns modeled (i.e., part length rods)
- Materials
  – All rods enriched with 5wt% ^{235}U at theoretical density
  – Doped with 0.1% Gd_2O_3
    - To allow calculation of relative sensitivity coefficient without large perturbation of the flux in the fuel lattice
- Excluded Gad rod locations
  – Part length rods, periphery rods, and corner rods

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Gad Worth Evaluation Models

- Transport condition representative models
  - Single Package represented by single fuel bundle
    - One BWR fuel bundle flooded, reflected by 20 cm of full density water
  - Multiple RAJ-II packages represented by single fuel bundle with mirrored boundaries
    - One BWR fuel bundle flooded surrounded by 0.1 cm of stainless steel, in an infinite array
- Each vendor's BWR fuel designs independently evaluated, hence specific optimized Gad rod patterns

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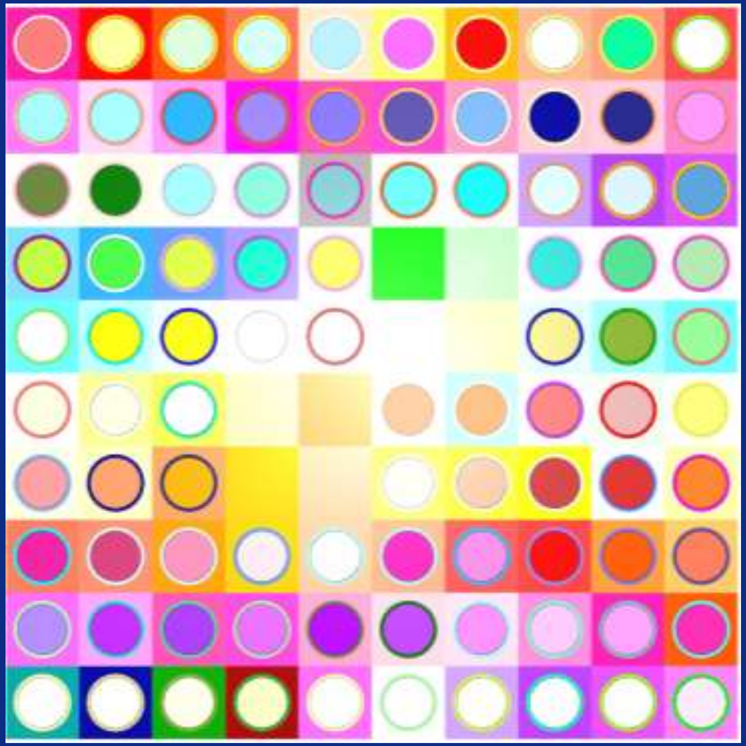
SCALE Model Input Specifications

- Cross-section Parameters
  - Library: 238 group ENDF/B-V
  - Processor: NITAWLST
- Individual unit cells modeled for each fuel pin cell
  - Each rods contribution individually evaluated



Gad Rod Relative Worth Results

^{157}Gd sensitivity coefficients mapped in bundle configurations

Red represents least worth

Yellow represents most worth

20	19	18	17	16	15	14	13	12	11
30	29 -2.29E-03	28 -1.94E-03	27 -2.02E-03	26 -2.58E-03	25 -2.64E-03	24 -1.96E-03	23 -1.92E-03	22 -2.24E-03	21
40	39 -1.89E-03	38 **-1.66E-03**	37 -1.85E-03	36 -2.80E-03	35 -2.77E-03	34 -1.89E-03	33 **-1.61E-03**	32 -1.94E-03	31
50	49 -1.95E-03	48 **-1.84E-03**	47 -2.73E-03	46	45	44 -2.78E-03	43 **-1.82E-03**	42 -1.97E-03	41
60	59 -2.50E-03	58 -2.71E-03	57	56	55	54	53 -2.73E-03	52 -2.64E-03	51
70	69 -2.53E-03	68 -2.69E-03	67	66	65	64	63 -2.78E-03	62 -2.62E-03	61
80	79 -1.96E-03	78 **-1.83E-03**	77 -2.71E-03	76	75	74 -2.72E-03	73 **-1.77E-03**	72 -1.94E-03	71
90	89 -1.88E-03	88 **-1.60E-03**	87 **-1.84E-03**	86 -2.70E-03	85 -2.83E-03	84 **-1.80E-03**	83 **-1.60E-03**	82 -1.89E-03	81
100	99 -2.30E-03	98 -1.86E-03	97 -1.93E-03	96 -2.51E-03	95 -2.57E-03	94 -1.98E-03	93 -1.92E-03	92 -2.23E-03	91
110	109	108	107	106	105	104	103	102	101

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20	19	18	17	16	15	14	13	12	11
30	29 -1.99E-03	28 **-1.71E-03**	27 -1.74E-03	26 -1.80E-03	25 -1.90E-03	24 -1.86E-03	23 -1.84E-03	22 -2.03E-03	21
40	39 -1.73E-03	38 **-1.46E-03**	37 **-1.57E-03**	36 -2.07E-03	35 -2.74E-03	34 -2.54E-03	33 -1.79E-03	32 -1.81E-03	31
50	49 **-1.72E-03**	48 **-1.62E-03**	47 -2.34E-03	46	45	44	43 -2.52E-03	42 -1.85E-03	41
60	59 -1.80E-03	58 -2.17E-03	57	56	55	54	53 -2.70E-03	52 -1.87E-03	51
70	69 -1.88E-03	68 -2.80E-03	67	66	65	64	63 -2.17E-03	62 -1.87E-03	61
80	79 -1.86E-03	78 -2.58E-03	77	76	75	74 -2.37E-03	73 **-1.64E-03**	72 -1.74E-03	71
90	89 -1.78E-03	88 -1.80E-03	87 -2.54E-03	86 -2.67E-03	85 -2.19E-03	84 **-1.62E-03**	83 **-1.49E-03**	82 **-1.71E-03**	81
100	99 -2.01E-03	98 -1.74E-03	97 -1.83E-03	96 -1.93E-03	95 -1.82E-03	94 **-1.70E-03**	93 -1.74E-03	92 -1.97E-03	91
110	109	108	107	106	105	104	103	102	101

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Gad Rod Pattern Selection Criteria

- Guidance to simplify contents specification for RAJ-II BWR package
  1. Minimum eight (8) Gad rods
  2. Symmetric about the major diagonal
     - Off-diagonal “pairs” selected by least worth average between pairs
  3. At least three (3) quadrants contain Gad rods
     - Varies selection of worth locations

Gad Rod Pattern Selection Example

- Identify least worth locations (including pairs)
- Calculate average worth among pairs
- Select pattern

20	19	18	17	16	15	14	13	12	11
30	29 -2.29E-03	28 -1.94E-03	27 -2.02E-03	26 -2.58E-03	25 -2.64E-03	24 -1.96E-03	23 -1.92E-03	22 -2.24E-03	21
40	39 -1.89E-0	38 -1.66E-03	37 -1.85E-03	36 -2.80E-03	35 -2.77E-0	34 -1.89E-0	33 -1.61E-03	32 -1.94E-03	31
50	49 -1.95E-0	48 -1.84E-03	47 -2.73E-03	46	45	44 -2.78E-0	43 -1.82E-03	42 -1.97E-03	41
60	59 -2.50E-03	58 -2.71E-03	57	56	55	54	53 -2.73E-03	52 -2.64E-03	51
70	69 -2.53E-03	68 -2.69E-03	67	66	65	64	63 -2.78E-03	62 -2.62E-03	61
80	79 -1.96E-0	78 -1.83E-03	77 -2.71E-03	76	75	74 -2.72E-0	73 -1.77E-03	72 -1.94E-03	71
90	89 -1.88E-0	88 -1.60E-03	87 -1.84E-03	86 -2.70E-03	85 -2.83E-0	84 -1.80E-03	83 -1.60E-03	82 -1.89E-03	81
100	99 -2.30E-03	98 -1.86E-03	97 -1.93E-03	96 -2.51E-03	95 -2.57E-03	94 -1.98E-03	93 -1.92E-03	92 -2.23E-03	91
110	109	108	107	106	105	104	103	102	101

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Final Resolution

- Validation of code method by direct perturbation of ^{157}Gd atom density and hand calculation of sensitivity coefficient
- Verification of selected Gad rod arrangement through k_{eff} comparison of varied pattern choices
- Resultant Gad rod arrangements utilized in next level fuel contents and package analyses

Final Resolution: Benefits

- Gad rod worth evaluation per fuel assembly lends a more realistic analysis that leads to
  - Less restrictive contents specification for RAJ-II
  - Minimization of any potential, unnecessary restrictions imposed on the fuel bundle design
  - Increased safety margin for NCS analyses
- TSUNAMI-3D facilitates more thorough understanding of lattice physics and more efficient evaluation of contents

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Supplemental Information

- Supplement A: References
- Supplement B: Validation
- Supplement C: Verification

Supplement A: References

1. "Safety Analysis Report for the Model Number RAJII Package," SA/9309/B(U)F-96, Docket Number 71-9309, Rev. 6, Global Nuclear Fuel-Americas, Wilmington, (2006).

2. "SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation," NUREG/CR-0200, ORNL/TM-2005/39, Version 5.1, Vols. I–III, CCC-732, Radiation Safety Information Computational Center (2006).

3. B. T. REARDEN, "Perturbation Theory Eigenvalue Sensitivity Analysis with Monte Carlo Techniques," Nuclear Science and Engineering, 146, 367-382 (2004).

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Supplement B: Validation

- Direct perturbation
  - Vary ^{157}Gd atom density ±10%
    - Scaled to linear comparison to avoid asymmetric result
  - Calculate sensitivity coefficient

$$S_{k,\alpha} = \frac{k_{\alpha^{+x\%}} - k_{\alpha^{-x\%}}}{k_{nominal}} \times \frac{100(\%)}{2x(\%)}$$

  - Compare to TSUNAMI-3D results

Method	^{157}Gd Sensitivity Coefficient
TSUNAMI-3D	-0.18828
Hand Calculation	-0.18815

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Supplement C: Verification

- Direct perturbation of varying Gad rod patterns
  - Patterns based on single and multi-assembly models
  - Validation of pattern selection criteria

Pattern 1	Pattern 2	Pattern 3	Pattern 4
k_{eff} = 0.61133	k_{eff} = 0.61362	k_{eff} = 0.62131	k_{eff} = 0.62182