Office of Civilian Radioactive Waste Management

Burnup Credit Approach in the Yucca Mountain License Application

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Outline

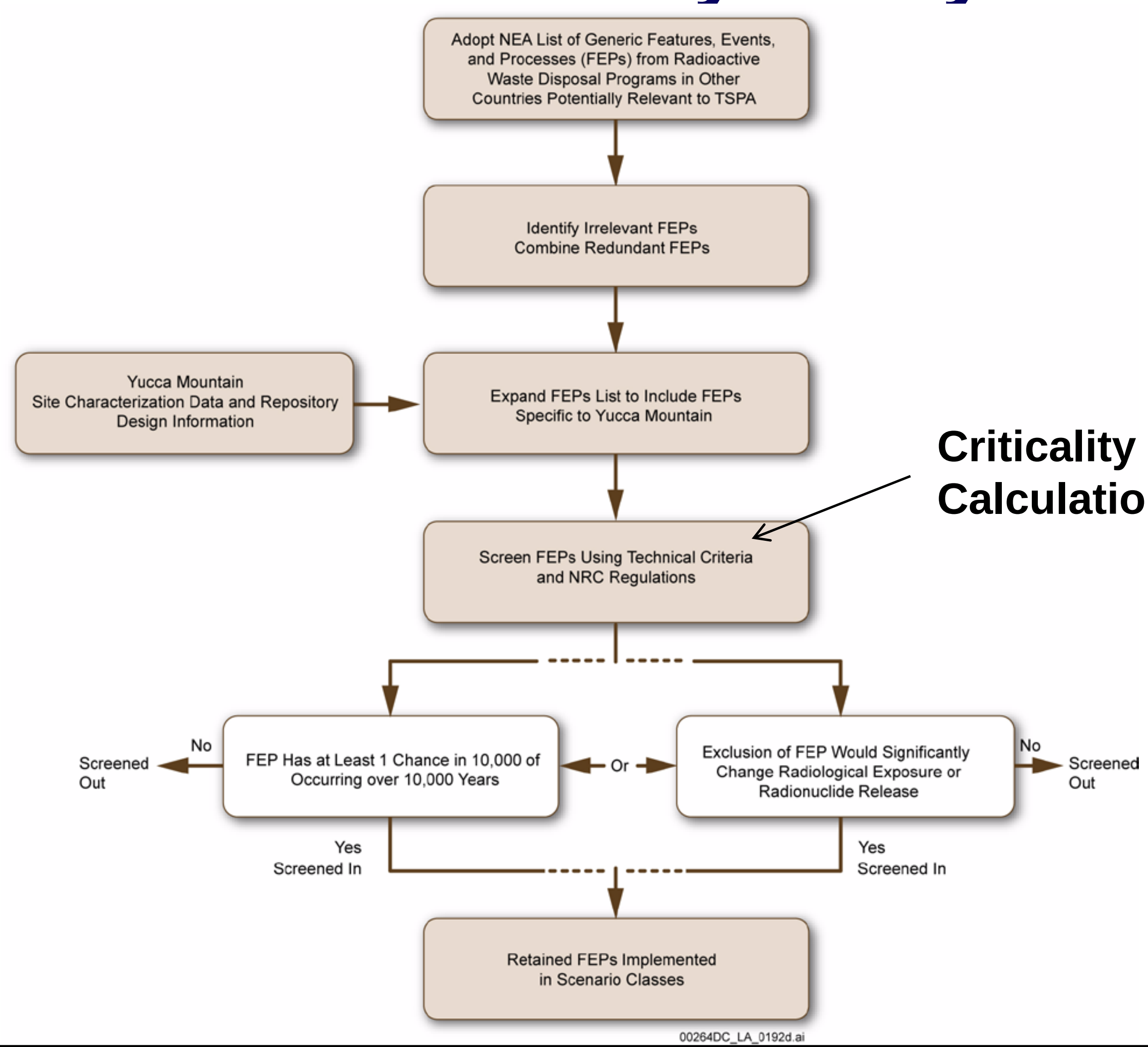
- License Application addressing of postclosure criticality
- Considerations for geologic disposal
- Isotopic modeling
- Criticality modeling
- Application discussion
- Loading curve
- Misload
- Sensitivity to number of credited isotopes

U.S. Regulatory Criterion

- **Proposed 10 CFR 63.342(a)* required "DOE's performance assessments conducted to show compliance with 63.311(a)(1), 63.321(b)(1), and 63.331 shall not include consideration of very unlikely features, events, and processes, i.e., those that are estimated to have less than one chance in 10,000 of occurrence within 10,000 years of disposal (less than one chance in 100,000,000 per year)" (70 FR 53313, pp. 53319 to 53320).**

*** NRC issued final rule on March 13, 2009 after initial license application submittal and does not contain any material differences from the proposed with respect to this presentation**

Role of Criticality Analyses

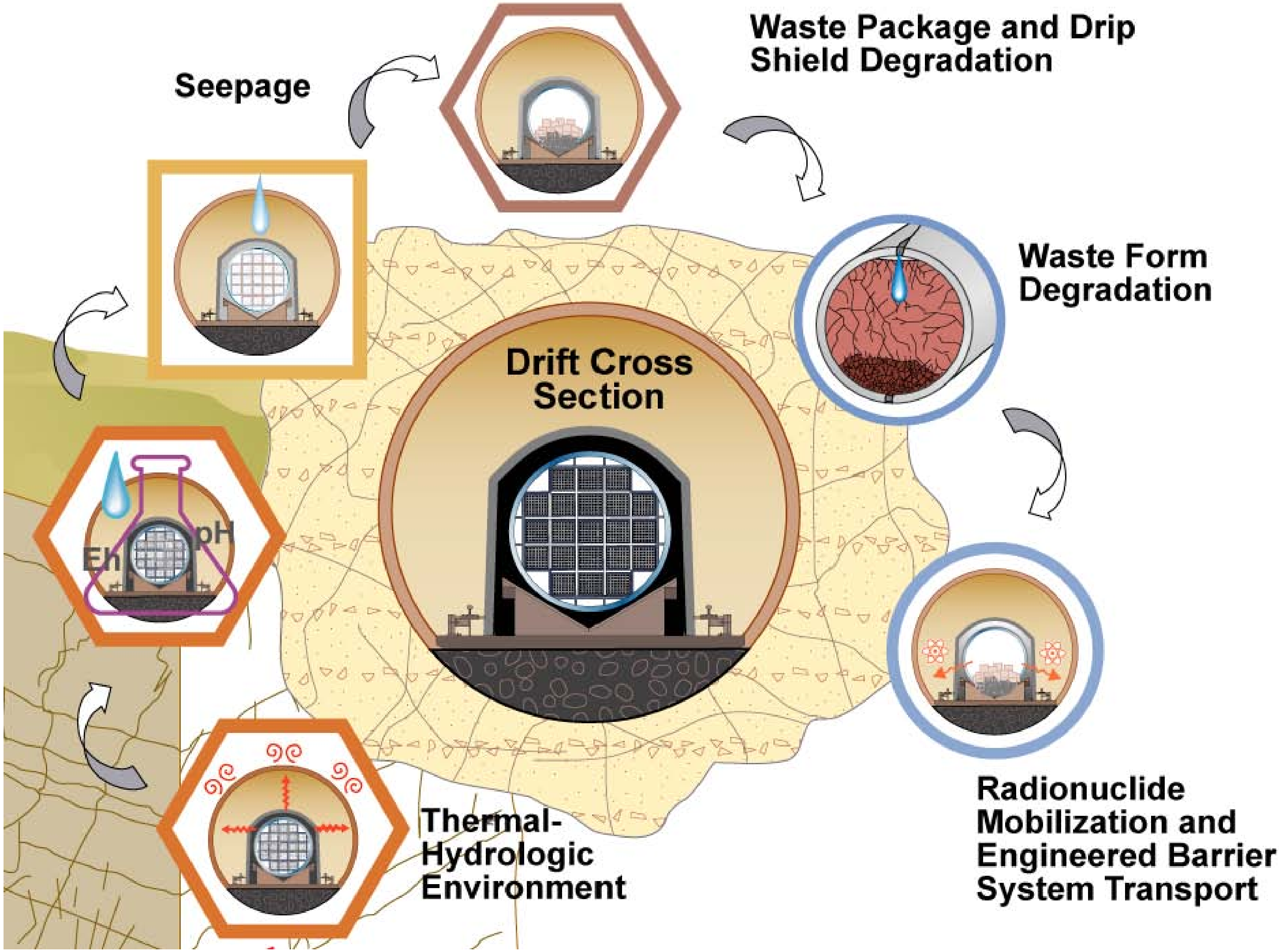


Criticality Calculations

Criticality Control in the License Application

- Rely on engineered systems, natural systems, and waste form properties to ensure the probability of criticality is less than the threshold for inclusion in the performance assessment as prescribed by the requirements of 10 CFR 63
- In-package criticality control uses neutron absorbers and burnup credit (for commercial spent nuclear fuel, CSNF)
  - Burnup credit loading curves are developed such that they preclude criticality for waste packages loaded in accordance to design specifications under fully flooded conditions

Considerations for SNF Geologic Disposal



Reactivity Credit from Burnup

- **Comprised of two primary calculations**
  - **Isotopic Calculation**
    - **Depletion of U-235**
    - **Buildup of higher actinides**
    - **Buildup of fission products**
  - **Criticality Calculation**
    - **Nuclear data**
    - **Geometry**
    - **Neutron spectrum**
- **Must work in conjunction with system application**

Critical Limit

$$CL < f(x) - \Delta k_{EROA} - \Delta k_{ISO} - \Delta k_m$$

x = a neutronic parameter used for trending

f(x) = the lower-bound tolerance limit function

Δk_{EROA} = penalty for extending the range of applicability

Δk_{ISO} = penalty for isotopic composition bias and uncertainty

Δk_m = traditional administrative margin turning the CL function into an upper subcritical limit function

Isotopic Calculation

- Used to quantify the bias and uncertainty for calculations of irradiated fuel isotopic compositions by direct difference method
  - $\Delta k_{eff} = k_{eff}[SAS2H] - k_{eff}[RCA]$
  - Aggregate effect of nuclide uncertainties on system k_{eff} directly
- Mathematically establish Δk_{ISO} penalty factor in critical limit equation from Δk_{eff} values

Principal Isotopes

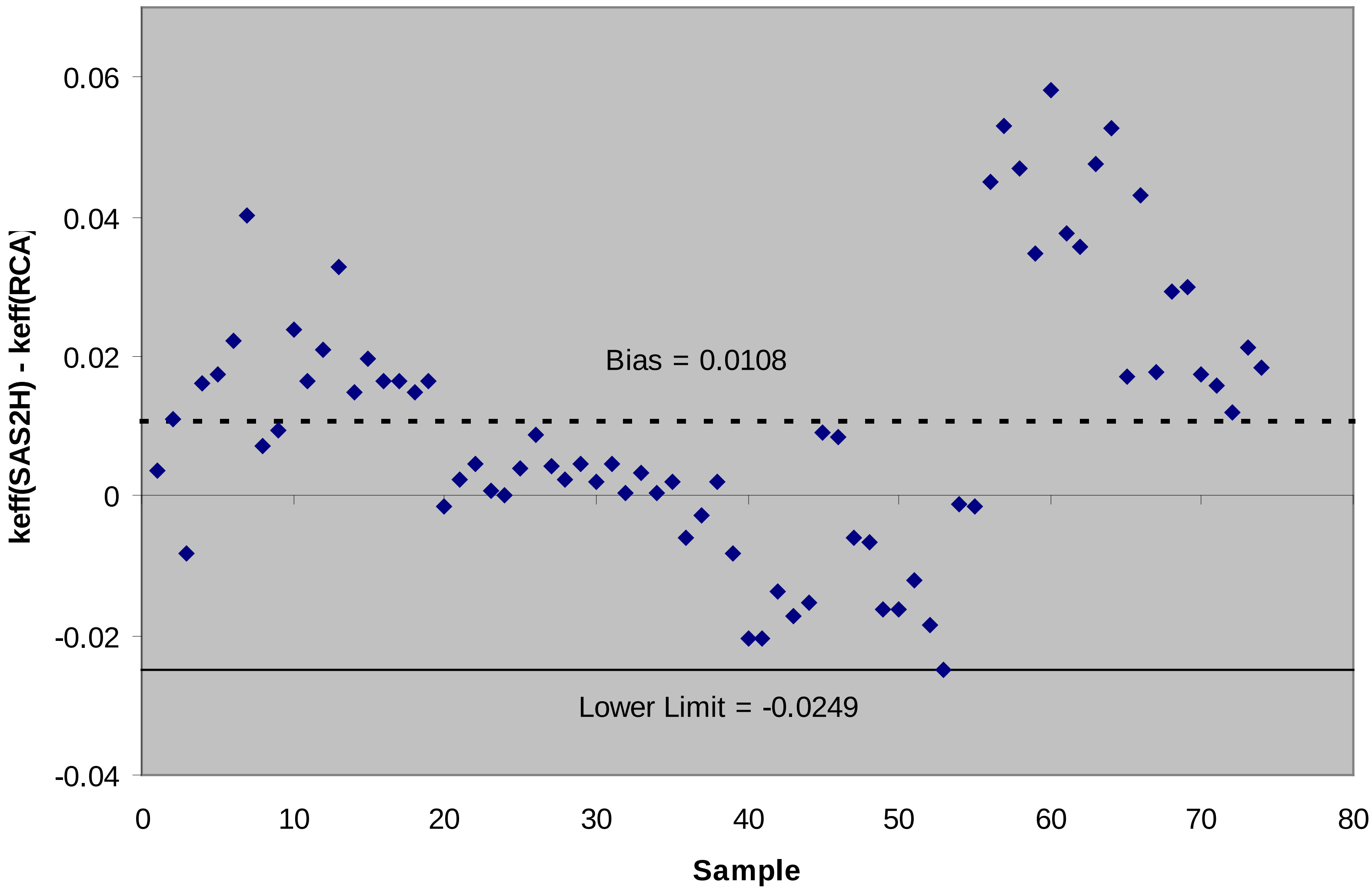
Fission Products				
^{95}Mo	^{99}Tc	^{101}Ru	^{103}Rh	^{109}Ag
^{143}Nd	^{145}Nd	^{147}Sm	^{149}Sm	^{150}Sm
^{151}Sm	^{152}Sm	^{151}Eu	^{153}Eu	^{155}Gd
Actinides				
^{233}U	^{234}U	^{235}U	^{236}U	^{238}U
^{237}Np	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu
^{242}Pu	^{241}Am	^{242m}Am	^{243}Am	--

RCA Sample Overview

Reactor	Assembly Design	# of Samples/ assemblies/rods	Sample Burnups (GWd/MTU)	Initial Enrichments (Wt% ^{235}U)
Trino Vercelles	Westinghouse (W), Irregular*	14/3/6	12.042 11.529-24.548	3.897 3.130
Yankee Rowe	W, Irregular	8/1/3	15.95-35.97	3.400
Turkey Point	W 15x15, 20 GT	5/2/5	30.72-31.56	2.556
Mihama	W 15x15, 20 GT	9/3/NA	6.92-8.3 14.66-21.29 29.5-34.32	3.208 3.203 3.210
H.B. Robinson	W 15x15, 20 GT, 12 BP	4/1/1	16.02-31.66	2.561
Obrigheim	Siemens 14x14	6/5/special**	25.93-29.52	3.130
Calvert Cliffs	Combustion Engineering 14x14 BP present	9/3/3	27.35-44.34 18.68-33.17 31.40-46.46	3.038 2.720 2.453
TMI	B&W 15x15, 16 GT	5/1/1 6/1/1 4/1/2 4/1/3	44.8-51.3 44.8-55.7 23.7-26.7 22.8-29.9	4.670 4.670 4.670 4.670

* Non-standard assembly design, ** Half assembly dissolved

RCA Δk_{eff} Results



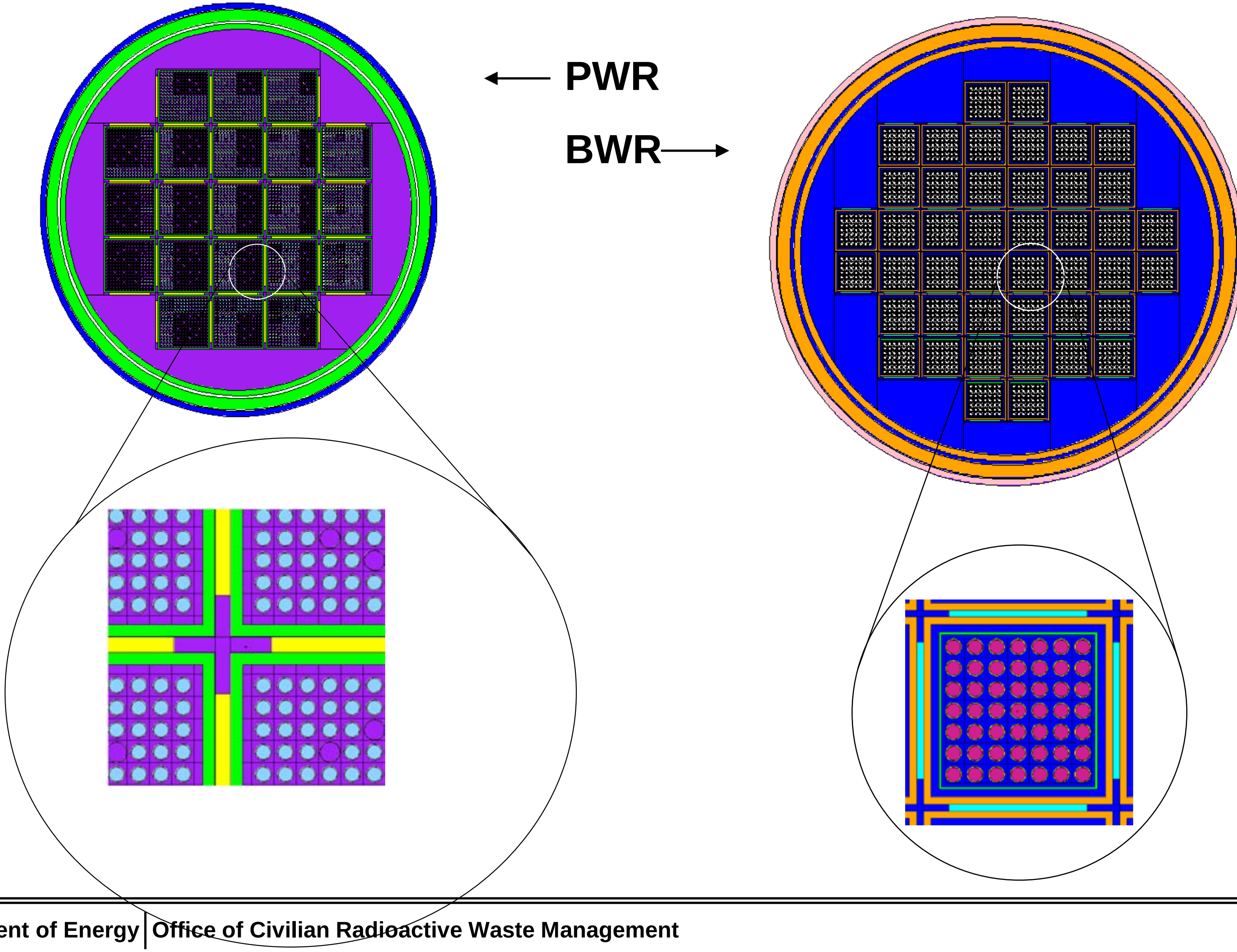
Criticality Calculation

- Requires detailed knowledge of the application system and modes for degradation/reconfiguration to select applicable benchmarks
  - Initiating events that can result in breached waste packages
- Design basis configurations were developed and used to bound, in terms of reactivity, possible relevant variations for each waste form
- Applicable benchmarks used for establishing lower bound tolerance limit function in CL equation (f(x))

Design Basis Geometry

- B-SS plate thickness accounts for >10,000 years of general corrosion to B-SS plates
  - Corroded B-SS would displace moderator and still contain B, but is completely removed from system for conservatism
- B-SS plate width reduced to allow assembly-to-assembly interaction at basket corners
- Tight-pack cylindrical geometry with assemblies in optimum cell position (non-physical)
- Most reactive assembly design (B&W 15x15, GE 7x7)

Design Basis Configurations



Critical Benchmarks

- LCEs
  - LEU and MOX
  - Haut Taux de Combustion
    - Mixture of U and Pu oxides
    - Pu:U ratio similar to 4.5wt% at 37.5 GWd/MTU
- CRCs
  - Irradiated fuel critical configurations
- Lower Bound Tolerance Limit = 0.9778

Summary of Applicable Critical Experiments (PWR)

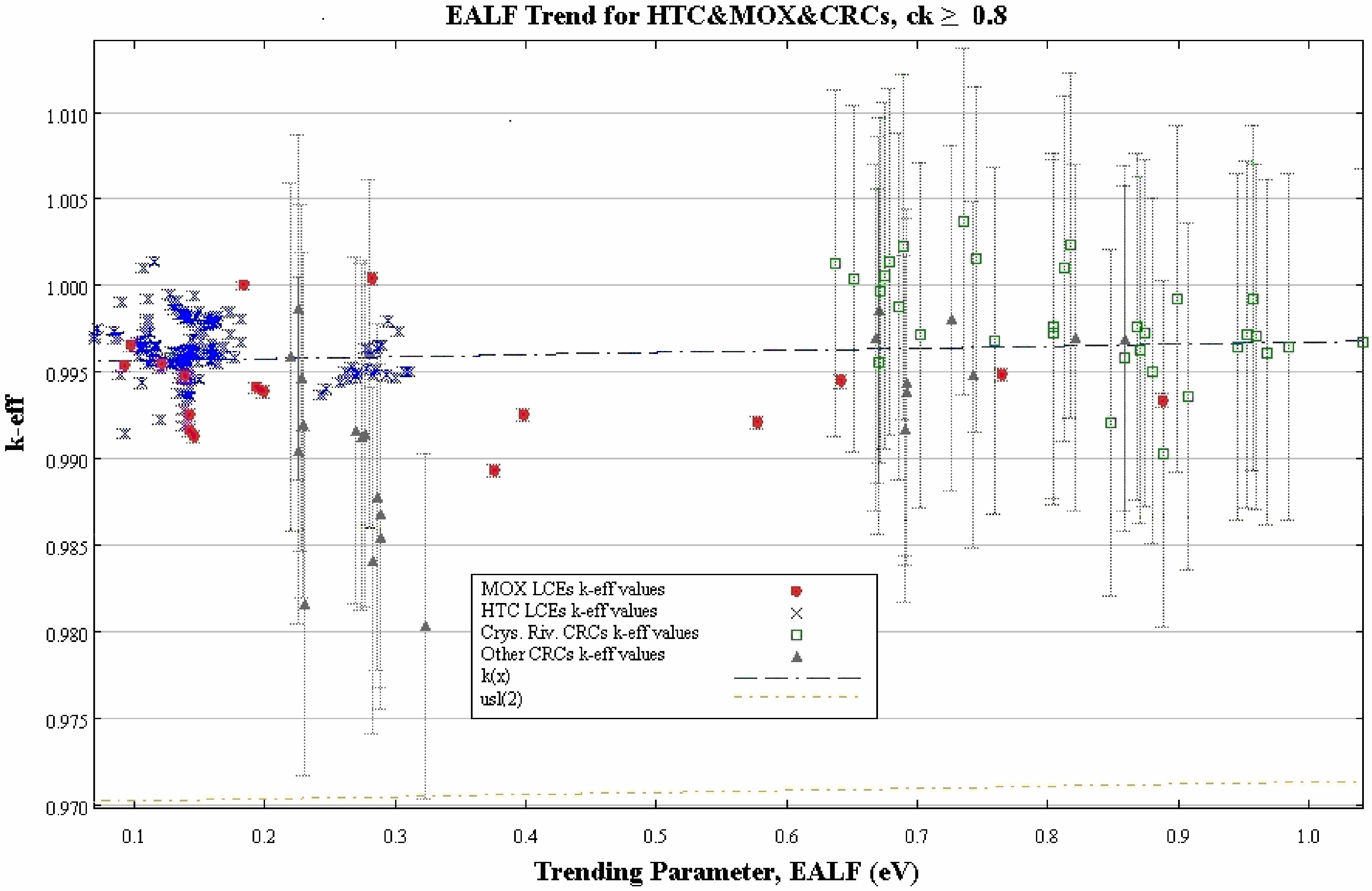
Application system		Number of applicable critical experiments					
Waste package	Enrichment / BU	MOX lattice	MOX solution	LEU	HTC	CRC	Total
21 PWR nominal configuration	2.0 / 0	0	0	37	0	4	41
	3.0 / 0	0	0	37	1	5	43
	3.0 / 15	17	0	0	145	56	218
	3.5 / 25	18	0	0	145	56	219
	4.0 / 30	18	1	0	145	56	220
	4.5 / 35	19	11	0	145	56	231
	5.0 / 40	18	1	0	145	56	220
21 PWR design-basis configuration	2.0 / 0	0	0	37	0	4	41
	3.0 / 0	0	0	37	1	5	43
	3.0 / 15	17	0	0	145	56	218
	3.5 / 25	18	0	0	145	56	219
	4.0 / 30	18	1	0	145	56	220
	4.5 / 35	19	11	0	145	56	231
	5.0 / 40	18	1	0	145	56	220

Summary of Applicable Critical Experiments (BWR)

Application system		Number of applicable critical experiments					
Waste package	Enrichment / BU	MOX lattice	MOX solution	LEU	HTC	CRC	Total
44 BWR nominal configuration	3.0 / 0	0	0	37	0	4	41
	3.0 / 10	20	9	0	145	56	230
	4.0 / 0	0	0	37	0	4	41
	4.0 / 20	21	17	0	145	51	234
	5.0 / 30	21	19	0	145	51	236
44 BWR design-basis configuration	3.0 / 0	0	0	37	0	4	41
	3.0 / 10	19	9	0	145	56	229
	4.0 / 0	0	0	37	0	4	41
	4.0 / 20	21	17	0	145	51	234
	5.0 / 30	21	21	0	145	51	238

Critical Experiment Applicability

Trending parameter



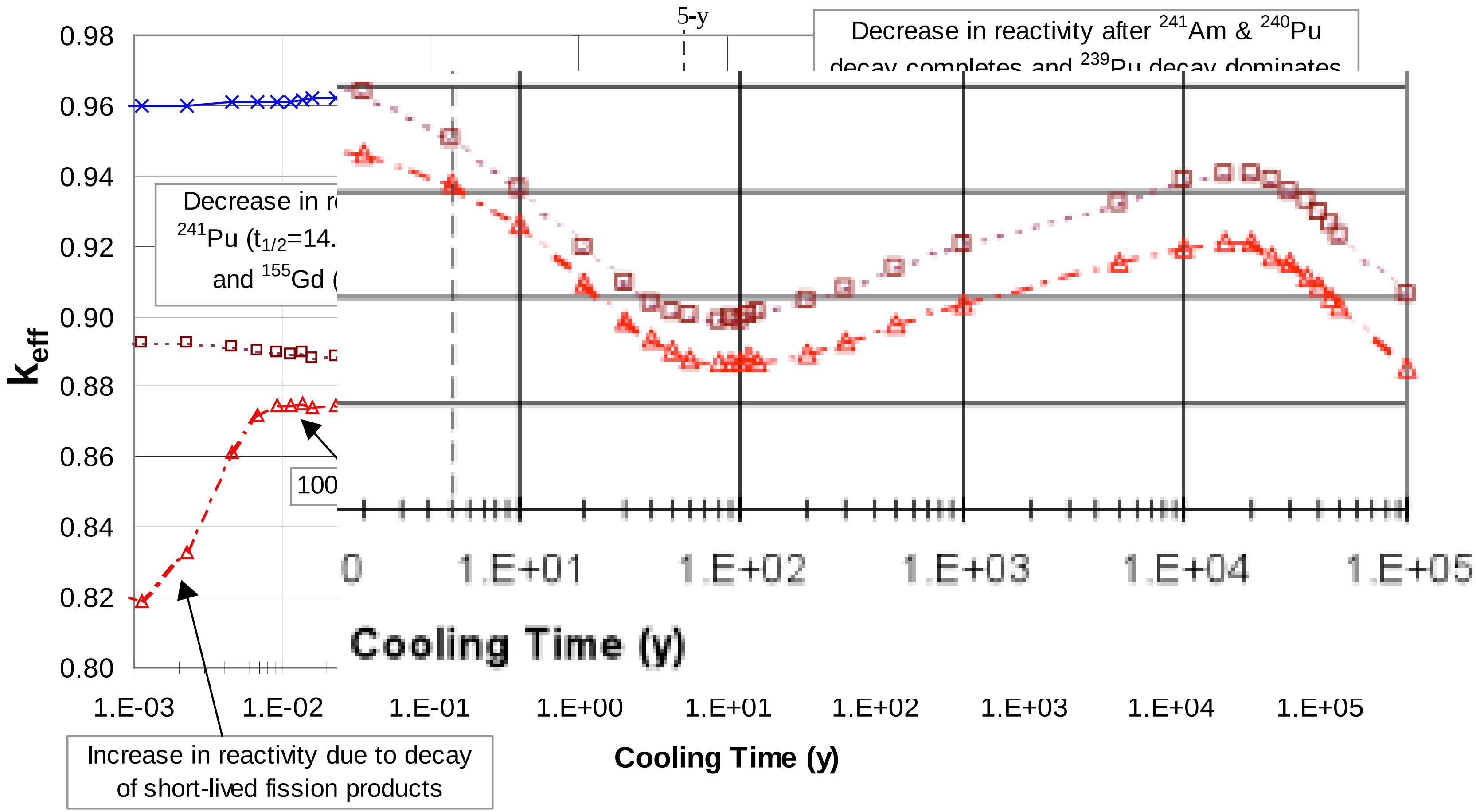
Application Model Parameters

- Uses Design Basis Geometry parameters
- Bounding isotopic compositions
  - Conservative depletion parameters to increase residual reactivity at discharge
  - 5-yr decayed isotopic compositions
  - Fuel density at 98% T.D.
- Conservative axial burnup profiles
- Maximum reflector effectiveness
- 75% Neutron absorber credit in plates
- Fully flooded with full density water (most reactive moderator)

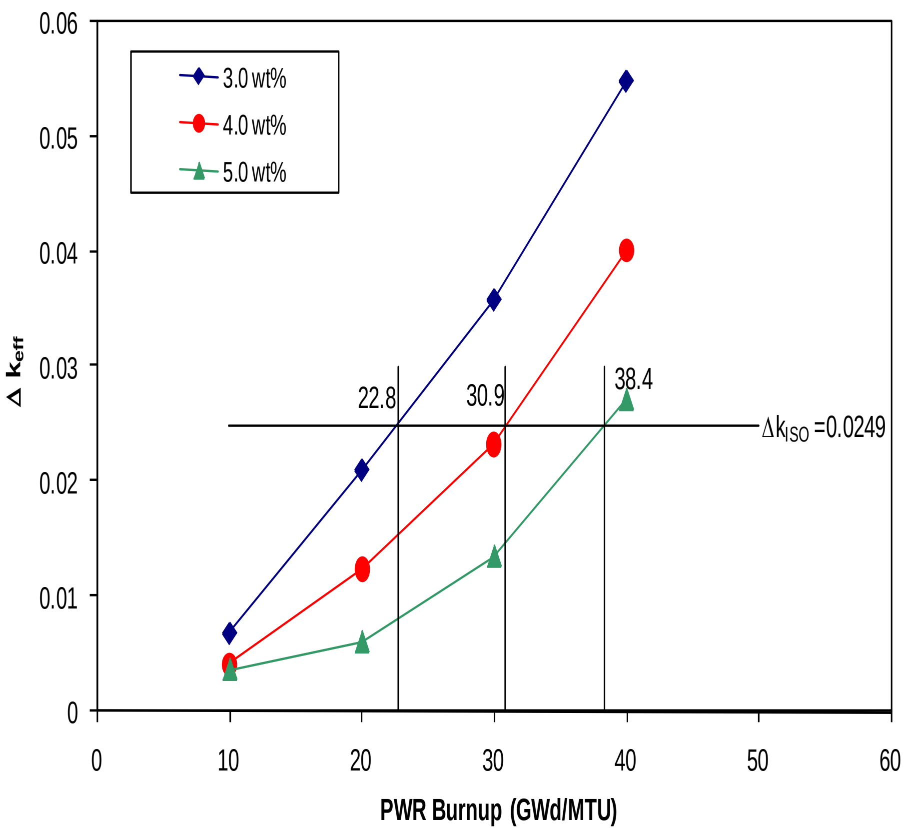
Conservative Depletion Parameters

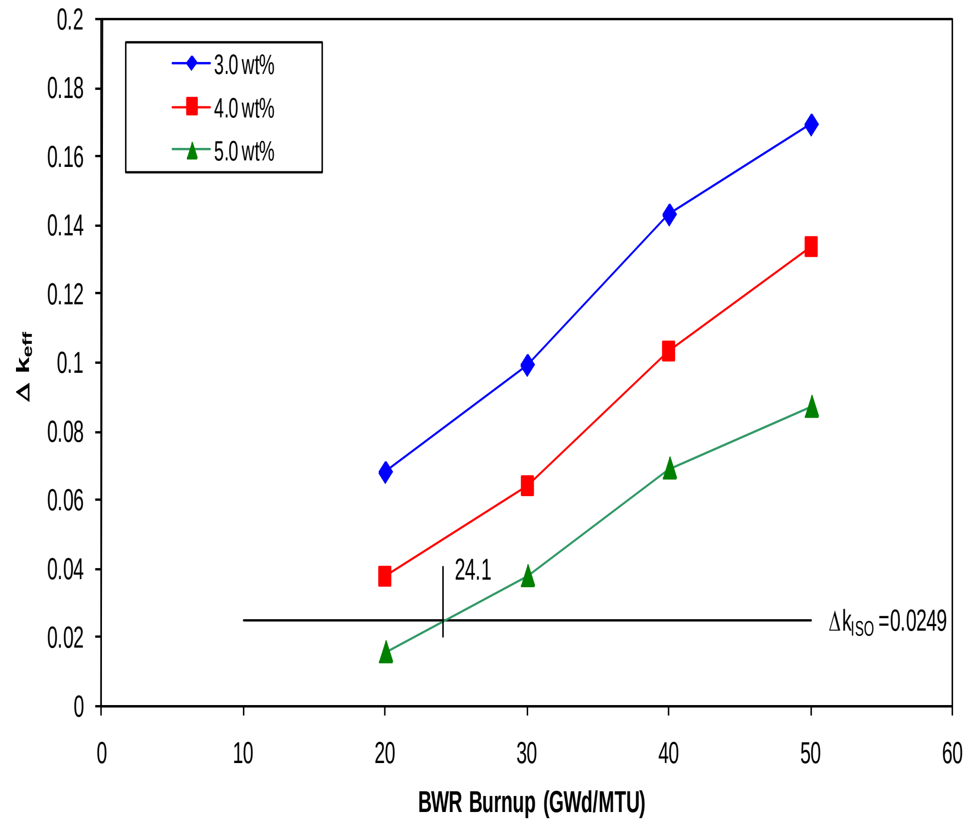
Parameter	PWR	BWR
Assembly design	B&W 15x15	GE 7x7
Fuel Temperature (K)	1144.1 [861.3]	1200 [1000]
Moderator Temperature (K)	588.7 [579.8]	560.7 [560.7]
Moderator density (g/cm^3)	0.6905 [0.7556]	0.3 [0.43 length avg.]
Soluble boron concentration (ppmB)	1000 (constant) [letdown curve per cycle]	N/A
Burnable poison rods (B_4C for PWRs) Gd_2O_3 fuel rods for BWRs	Inserted in all tubes for all cycles even if depleted (3.5 wt% B_4C) [inserted for 1st cycle then removed]	Not modeled [varies per assembly]
Control blades	N/A	Inserted full length for final 15 GWd/MTU of irradiation [Only fractionally inserted]
Fuel density (98% theoretical density) (g/cm^3)	10.741 [10.121 vol. avg., varies]	10.741 [≤10.4]
Specific power (MWt/mtU)	29.74 [43.0 varies]	22.38 [35.68 varies]

Reactivity of CSNF as a Function of Time

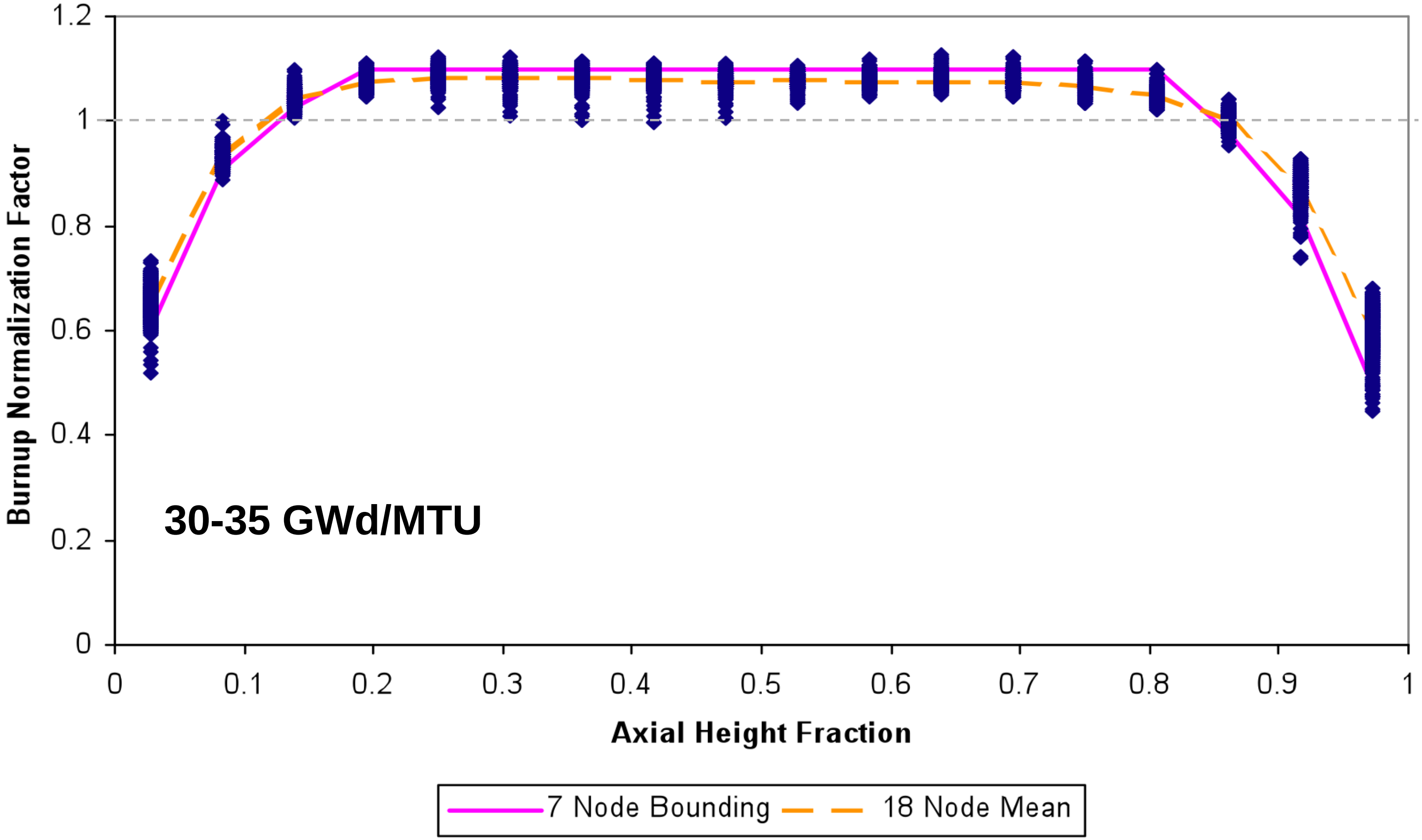


$k_{bounding} - k_{nominal}$

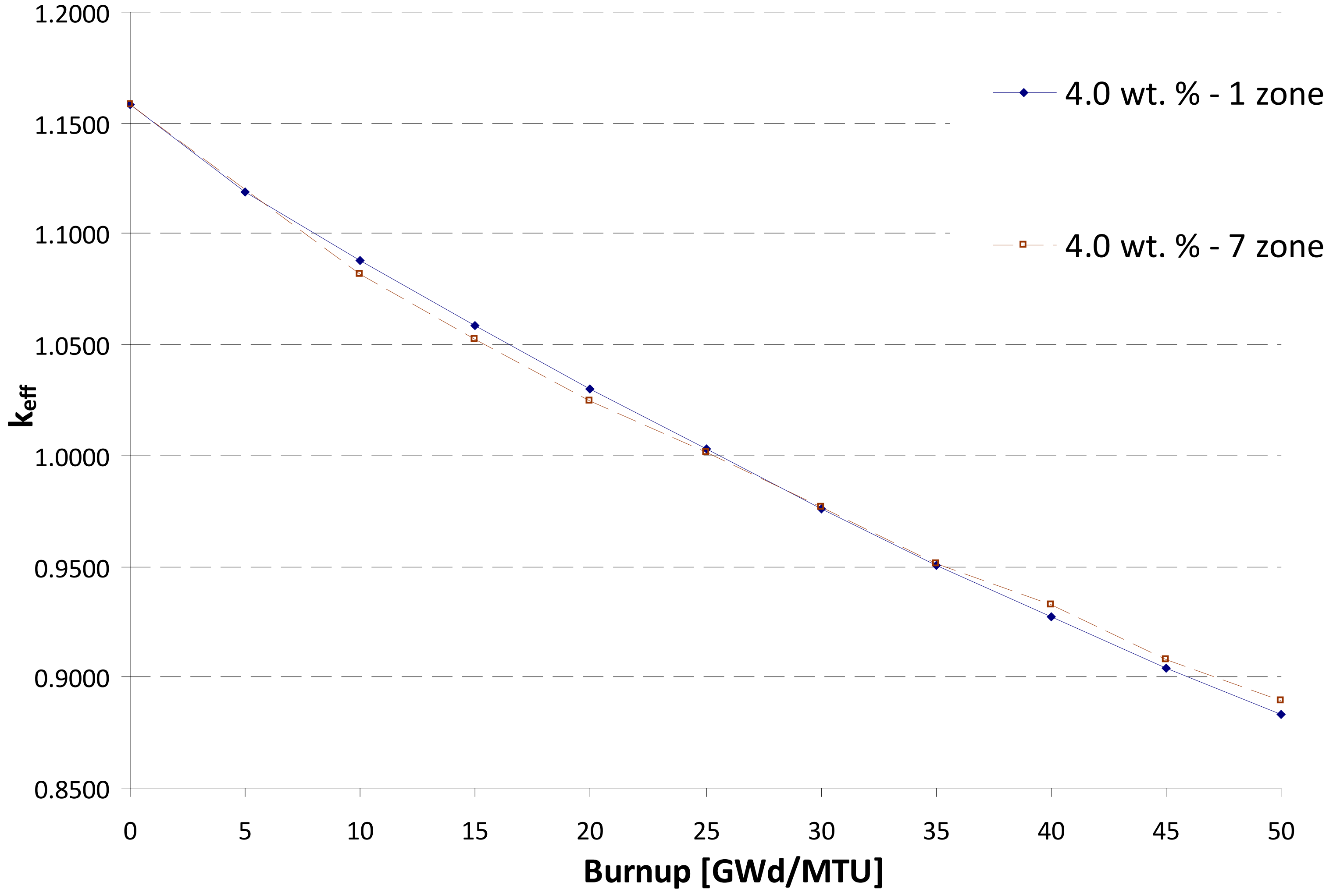




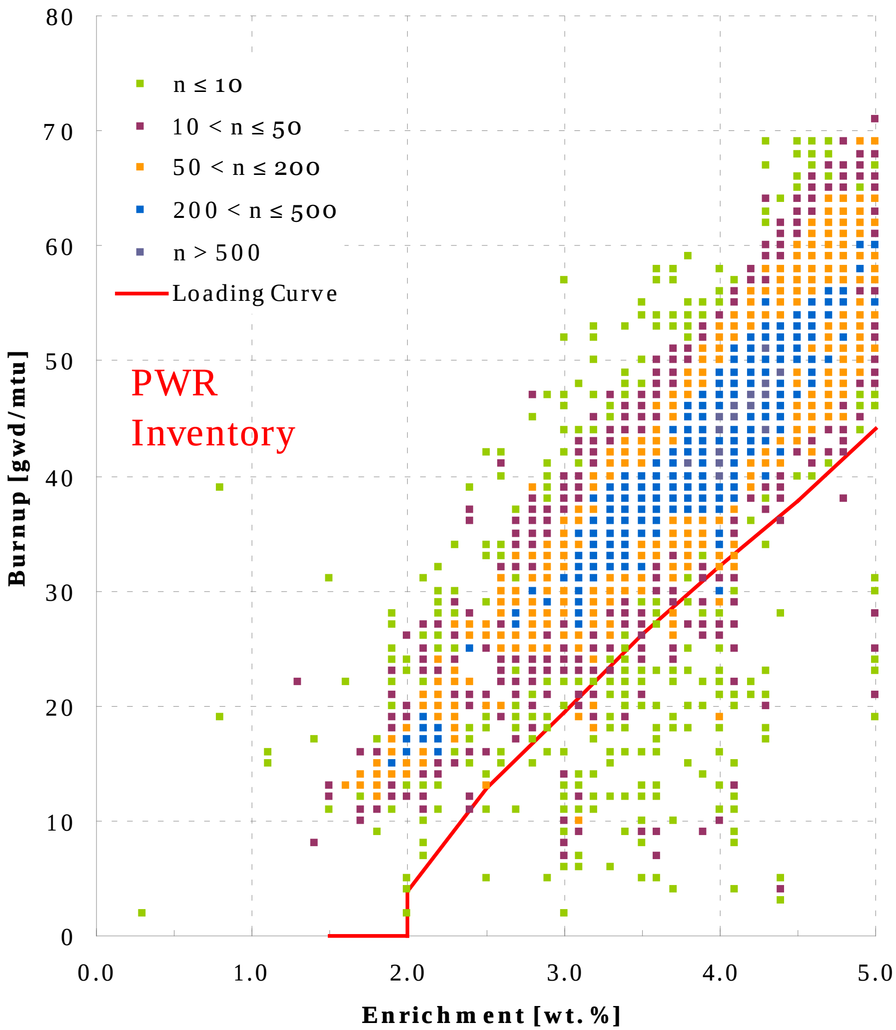
PWR Limiting Burnup Profile

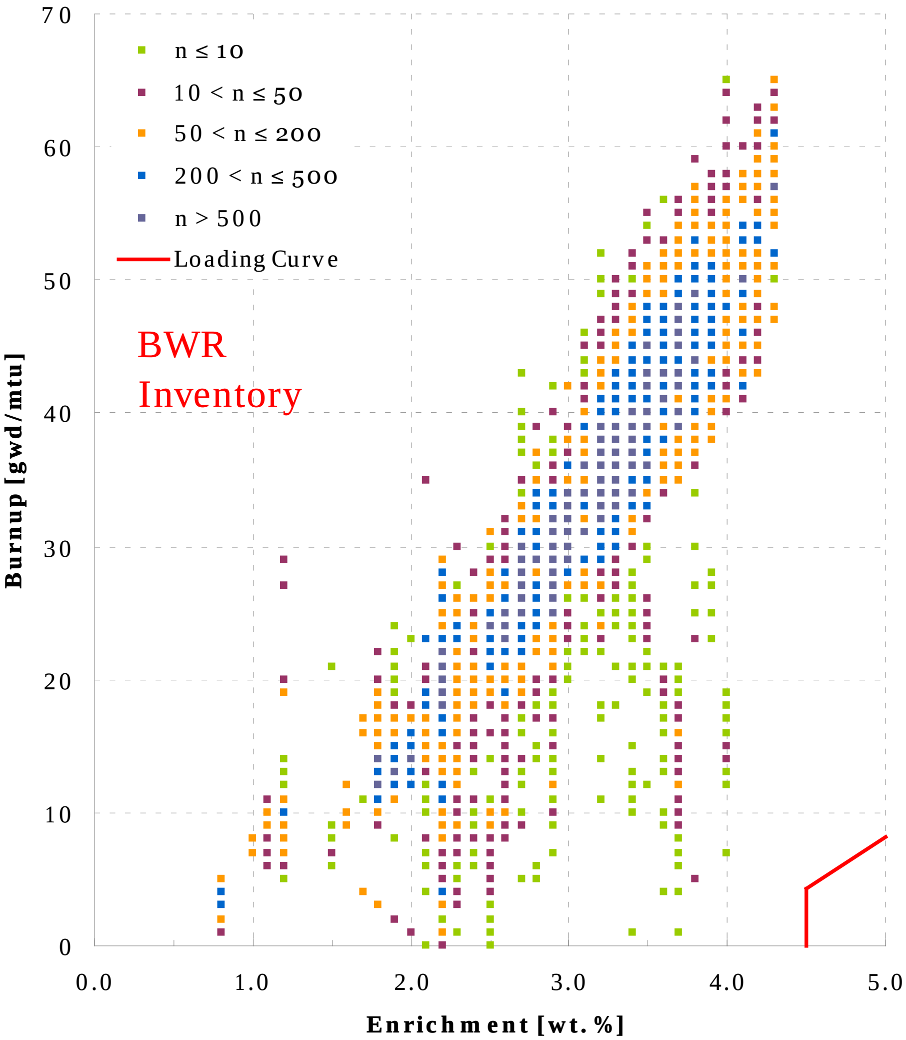


Axial Profile Effects



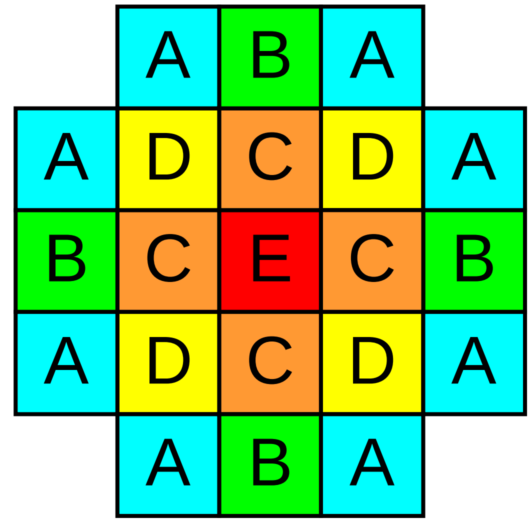
CSNF Loading Curves (CL = 0.9529)



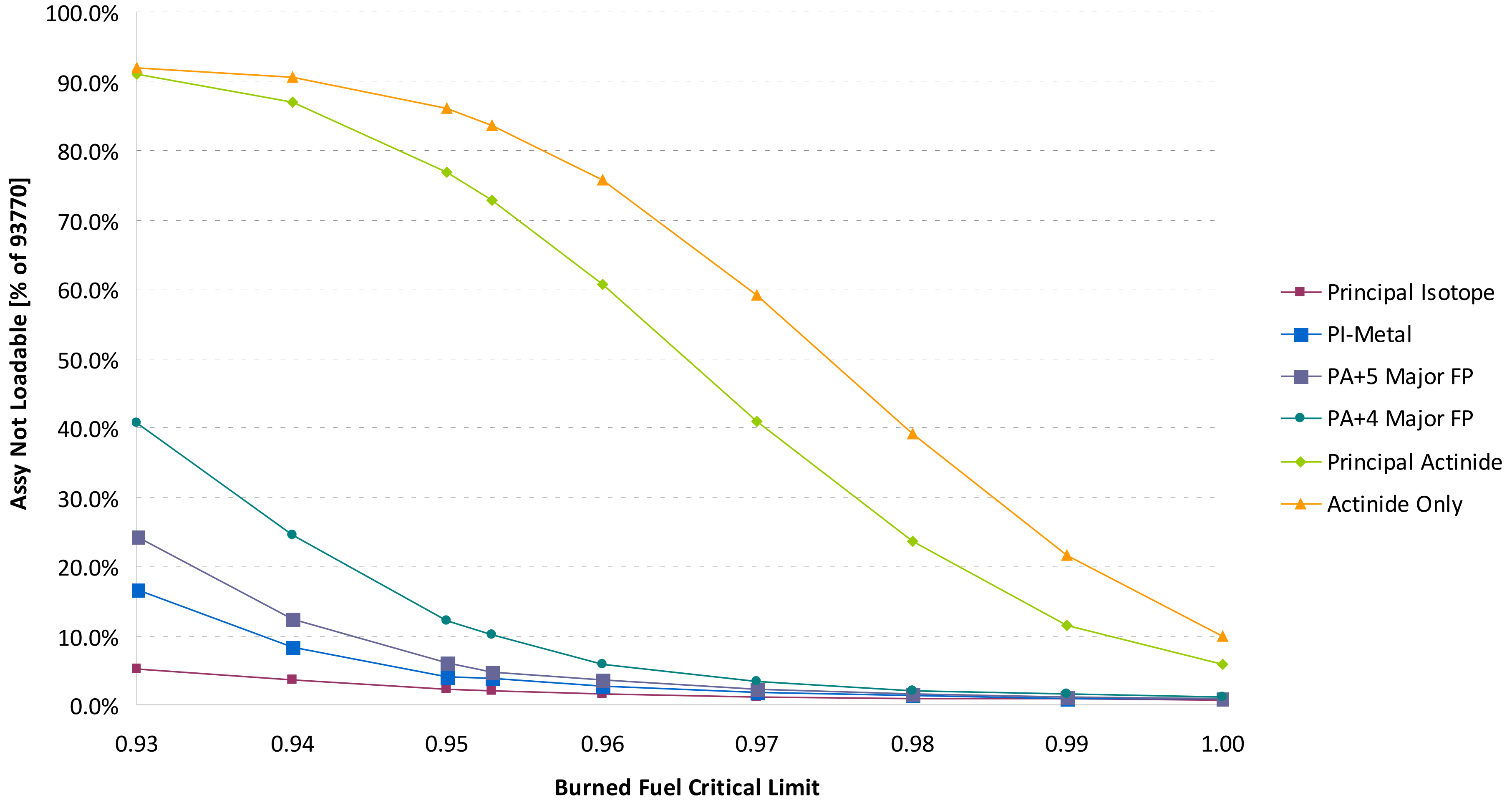


Misload Sensitivity

- Stochastic simulation inserting 1 misload and randomly filling remaining locations
- No credit for burnup in excess of 50 GWd/MTU
- Number of times k_{eff} exceeded CL tallied per location
- Combined failure probability was 0.2% (Assuming all in Position E is 1.4%)
- Misload in A or B location did not exceed CL
- 1990 potential misload assemblies (representative PWR SNF inventory 93770). Only 36 exceeded CL if misloaded (0.04% of inventory)



Loading Curve Sensitivity to Isotope Set

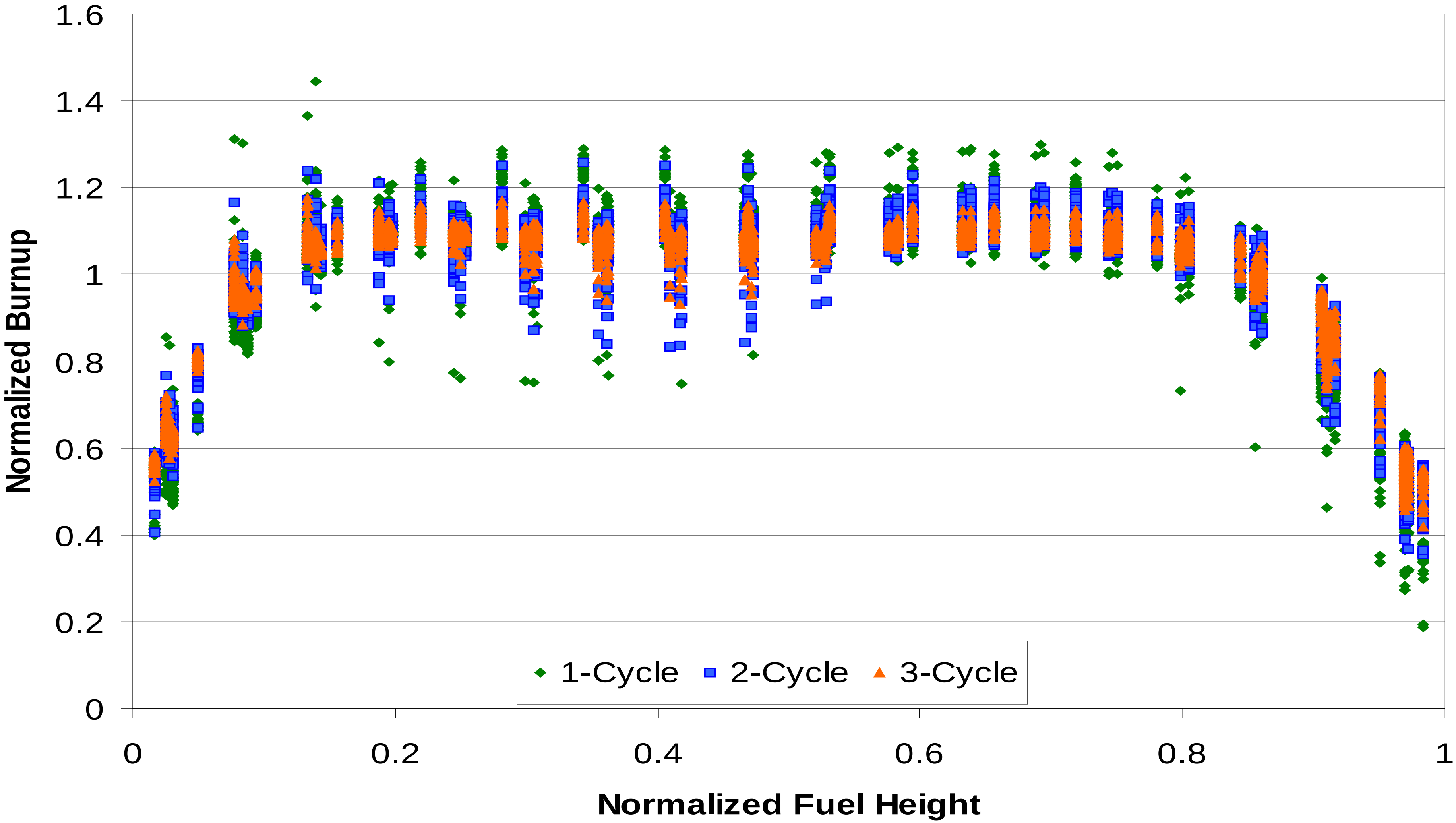


Summary

- Application model parameters selected to account for operational differences and geometry changes (realistic bound of k_{eff})
- Criticality calculations were used to identify conditions necessary for criticality in a geologic repository while taking reactivity credit for fuel burnup
- Conditions necessary for criticality were evaluated in a probabilistic assessment
- How and where the results of burnup credit criticality evaluations will be used must be factored into the regulator’s evaluation (risk-informed)
- Burnup credit is necessary for demonstrating criticality prevention over the post-closure time period

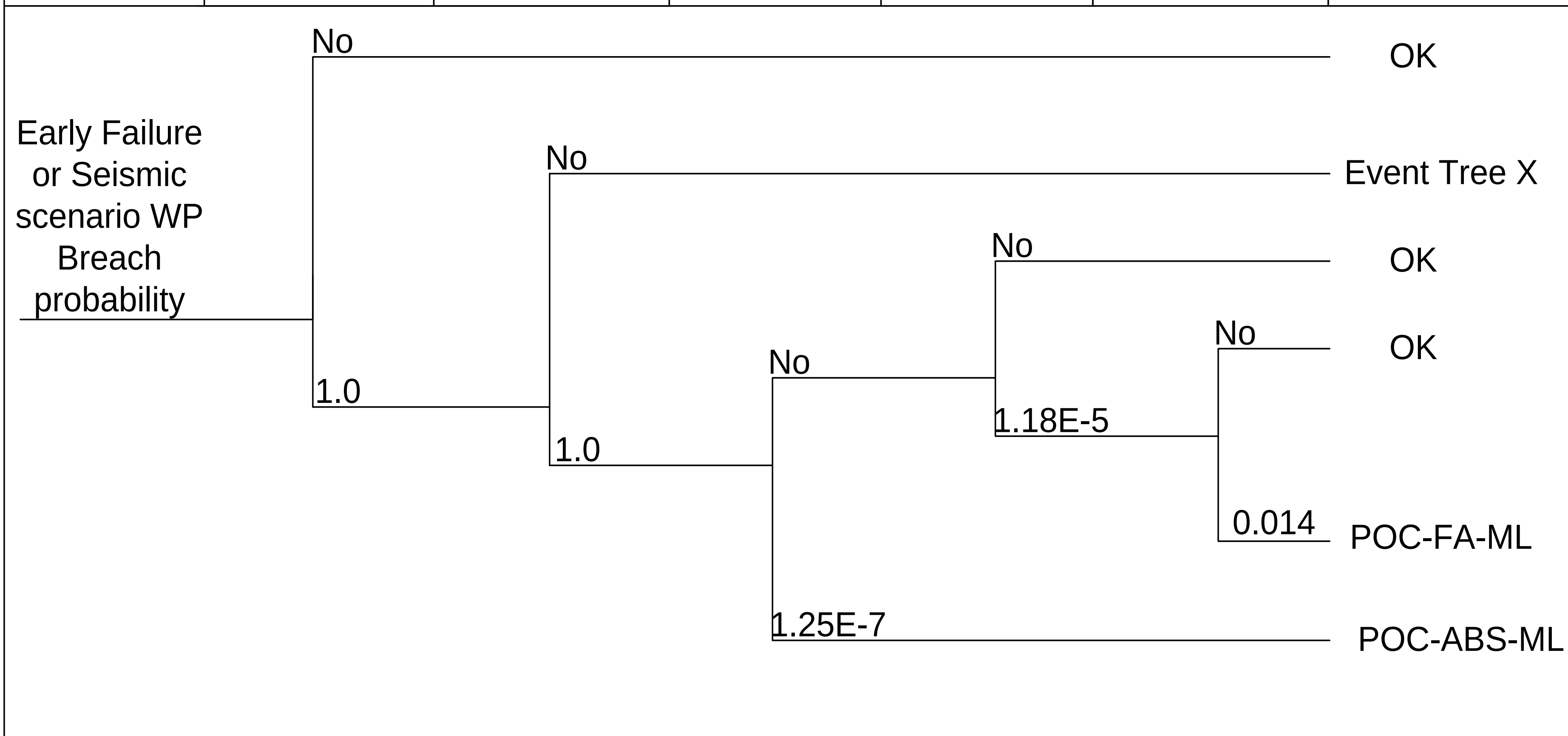
Backup

PWR Axial Burnup Profiles



Criticality Event Tree

Waste Package Outer Barrier Breach	Water Enters Waste Package	Design Basis Configuration	Neutron Absorber Misload	Waste Form Misload	Misloaded Assembly Exceeds CL	End-State



RCA Measured Isotopes

Isotope	# of Samples	Isotope	# of Samples	Isotope	# of Samples
U-234	44	Nd-145	31	Eu-155	14
U-235	74	Nd-146	20	Gd-155	22
U-236	74	Nd-148	44	Cm-242	31
U-238	49	Nd-150	20	Cm-243	11
Pu-238	60	Pm-147	3	Cm-244	32
Pu-239	74	Sm-147	22	Am-241	28
Pu-240	74	Sm-148	3	Am-242	6
Pu-241	74	Sm-149	22	Am-242m	27
Pu-242	70	Sm-150	22	Am-243	34
Np-237	31	Sm-151	22	U-232	9
Cs-133	3	Eu-151	22	Pu-236	3
Cs-134	11	Sm-152	22	Ag-109	11
Cs-135	3	Eu-153	22	Mo-95	11
Cs-137	22	Sm-154	3	Tc-99	11
Nd-143	31	Eu-154	3	Ru-101	11
Nd-144	12	Gd-154	3	Rh-103	11