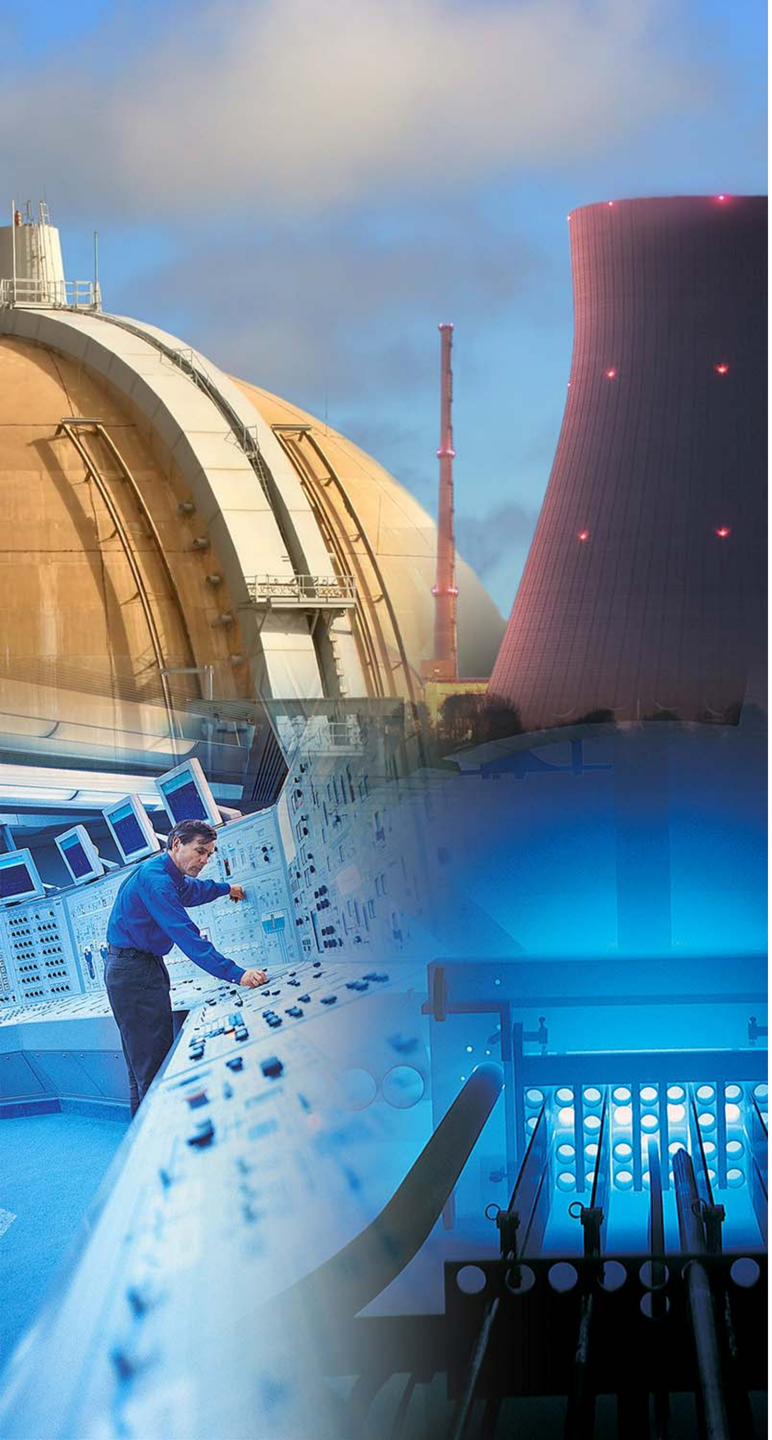

Direct Disposal of Dual-Purpose Canisters – *Options for Assuring Criticality Control*

Winter 2009 U.S. NWTRB Meeting
January 28, 2009

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Topics

1. Background
2. Criticality Evaluations
3. Results
   a) Burnup Credit Methodology
      i. Fission Products
      ii. Loading Pattern
      iii. Moderator Displacement
      iv. Surrogate Control Rods
   b) Biases and Uncertainties
4. Options for Criticality Control

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Background

- March '07: Information provided by TVA to US NWTRB Staff about HOLTEC Dual-Purpose MPC-32 canisters used at Sequoyah
- NWTRB Staff expressed interest to EPRI in a calculation of the potential of used (spent) fuel in two canisters to sustain a nuclear reaction (k_{eff}) assuming:
  - Fully flooded conditions
  - No neutron absorber
  - "Full" burnup credit (YMP approach)
  - As of December 31, 2017 if date was needed
- EPRI performed a number of calculations documented in EPRI Report 1016629 *"Feasibility of Direct Disposal of Dual-Purpose Canisters – Options for Assuring Criticality Control"*
  - http://mydocs.epri.com/docs/public/000000000001016629.pdf

Criticality Evaluation According to …

Reactor Operation	Fissile Material Transportation	System Performance Assessment
Operational purpose	Small number of scenarios	Potentially large number of scenarios
$k_{eff} \sim 1$	$k_{eff} < 1$	Probability of $k_{eff} = 1$
Approach to reactor criticality is monitored	No measurement of margin to criticality	No measurement of margin to criticality
CASMO/SIMULATE	SAS2H/KENO or MCNP	SAS2H/KENO or MCNP
Best-estimate approach	Highly conservative approach	Probabilistic approach
Use of actual fuel parameters	Use of a limited subset of "design basis fuel" parameters in a most conservative manner	Principal isotopes No arbitrary margin
Burnup is taken into account	From no to limited credit for burnup + arbitrary safety margin	

k_{eff} = effective neutron multiplication factor = ratio of the number of neutrons resulting from fission in each generation to the total number of neutrons lost by both absorption and leakage in the preceding generation

k_{∞} = infinite neutron multiplication factor (no leakage)

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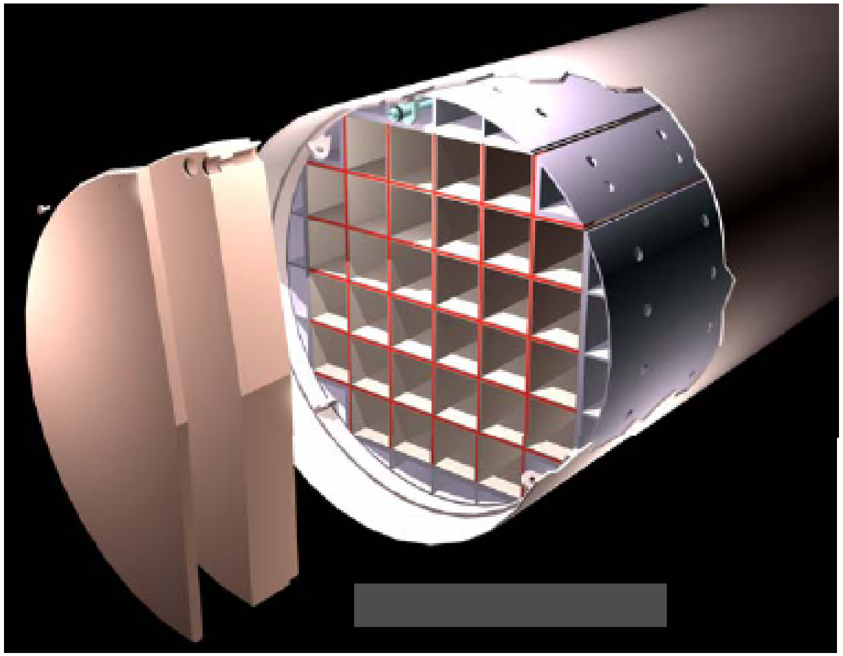
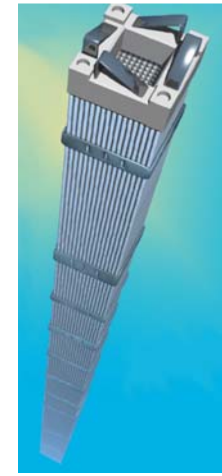
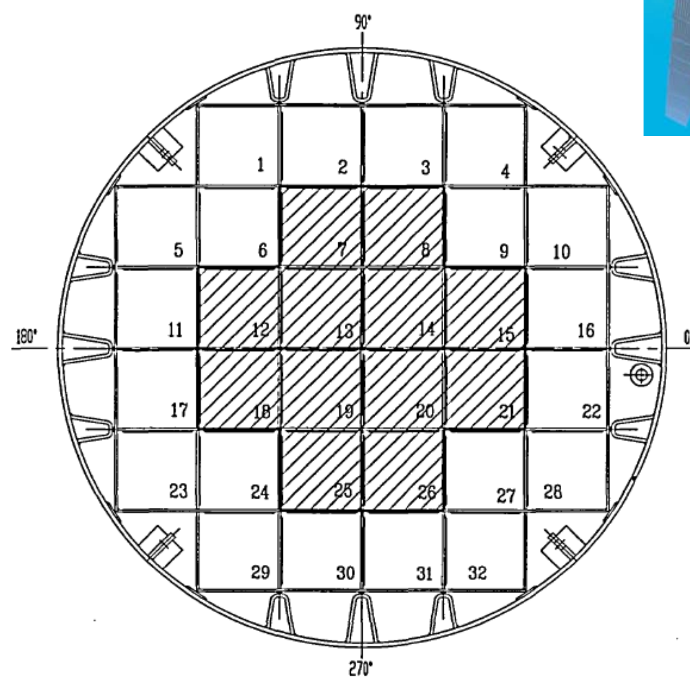
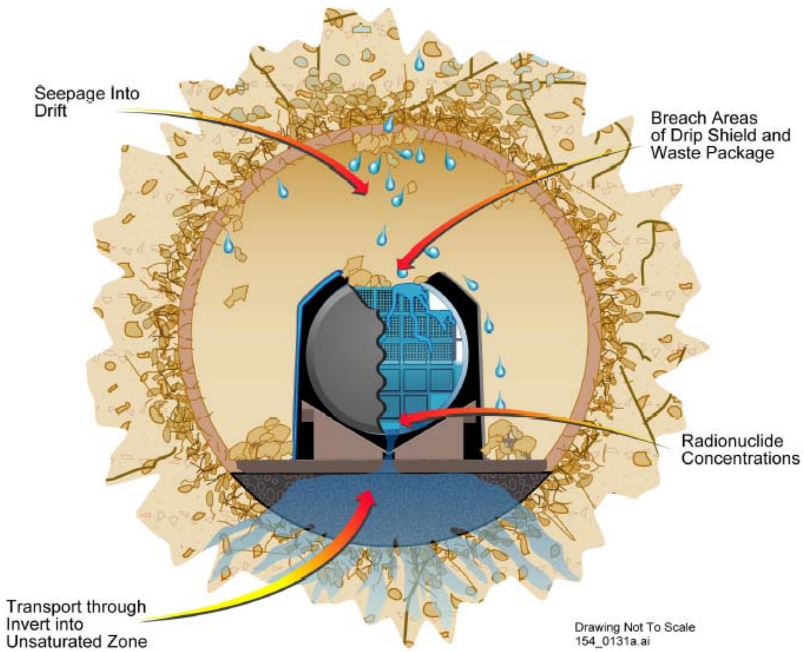
Dual-Purpose Canister for 32 PWR Assemblies

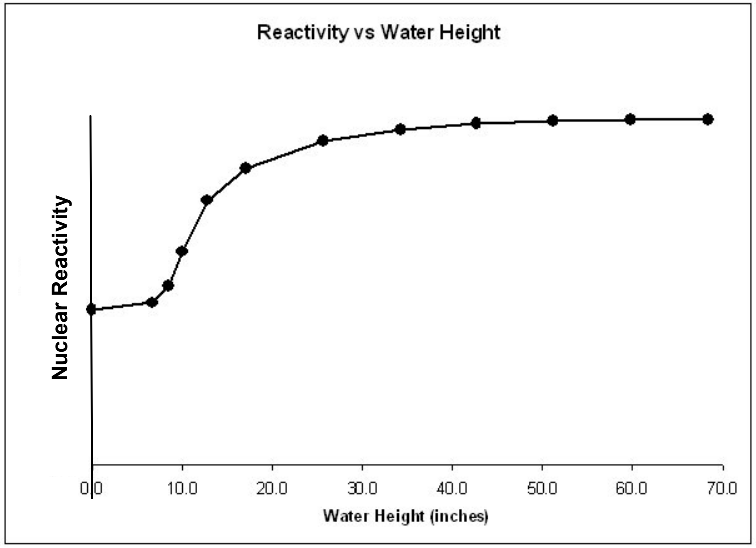


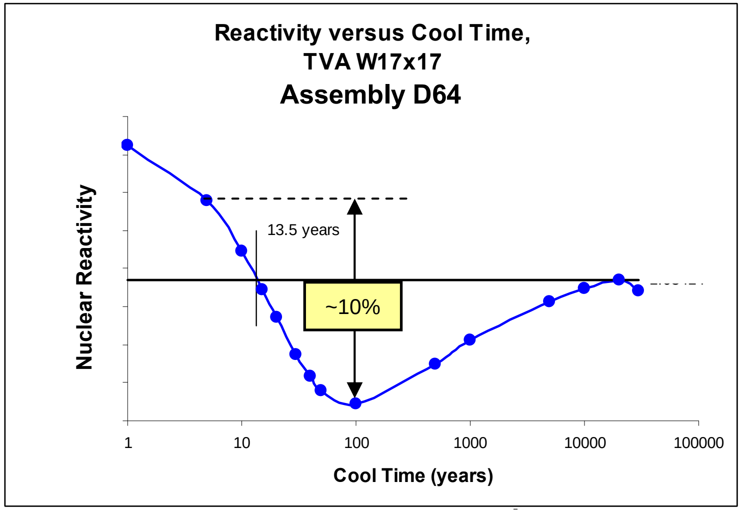




Probabilistic Approach Would Take Into Account ...







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Main Assumptions

- Assemblies: W 17x17 with Wet Annular Burnable Absorbers (WABAs) irradiated in TVA's Sequoyah reactors
- 32 assemblies stored in Holtec Dual-Purpose Canister (MPC-32)
- Neutron absorber material (METAMIC) in MPC basket
  - As-built: neutron absorber is assumed to be present
  - Disposal (degraded): neutron absorber is assumed to be completely dissolved away
- Canister, basket, and fuel assembly geometries remain unchanged
- Fully flooded with water (density = 1 g/cm^3)
  - Effect of partial flooding: significant for canister less than 5/8th full
  - Small effect of temperature in the temperature range between 4°C and 75°C
- Cooling time: 5 years
  - Effect of cooling time: significant
  - Assuming 10 years instead of 5 years result in a k_{eff} decrease of ~2%

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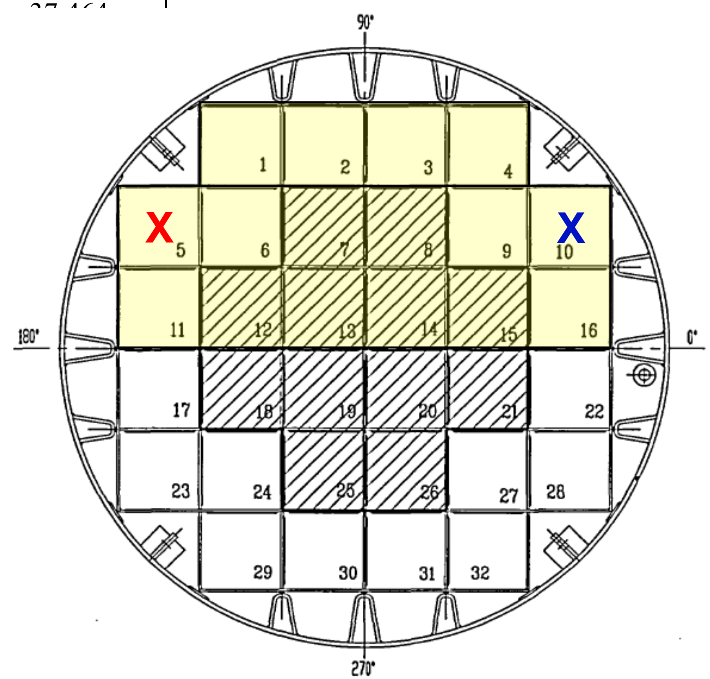
MPC-018 and -011 Loading (First 16 Cells)

MPC-018				MPC-011		
Assembly ID	Initial Enrichment (Wt% U-235)	Burnup (MWd/MTU)	Position	Asse mbly ID	Initial Enrichment (Wt% U-235)	Burnup (MWd/MTU)
F31	3.50	38,643	1	N29	3.10	[illegible]
E38	3.75	37,848	2	F55	3.80	[illegible]
E64	3.75	37,473	3	F41	3.80	[illegible]
R45	3.60	36,755	4	E18	3.75	[illegible]
➔ D64	3.65	42,743	5	P54	3.50	[illegible]
D04	3.65	42,084	6	P55	3.50	[illegible]
D25	3.65	37,920	7	D45	3.65	[illegible]
F12	3.50	42,081	8	D30	3.65	[illegible]
D44	3.65	40,167	9	P31	3.50	[illegible]
➔ N04	3.10	34,435	10	P61	3.50	[illegible]
N40	3.10	34,495	11	D68	3.65	[illegible]
F71	3.80	41,618	12	F66	3.80	[illegible]
F34	3.80	41,503	13	F36	3.80	[illegible]
F14	3.50	40,812	14	F10	3.50	40,982
F46	3.80	38,519	15	F24	3.50	40,735
N07	3.10	36,308	16	D10	3.65	42,374



Best-Estimate *Single Assembly* Reactivity (k_∞) Using CASMO Code

Assembly			Reactivity (k_∞)	
ID	**Enrichment (wt% U-235)**	**Burnup (MWd/MTU)**	**Reactor Conditions (600K/1000K)**	***Disposal* Conditions (300K)**
D64	3.65	42,743	0.946	0.993
N04	3.10	34,435	0.968	1.025

Reminder

"*Disposal*" = Neutron absorber material is assumed to be completely dissolved away

Cooling time = Five years

Comparison Between CASMO and SAS2H/MCNP Calculated Reactivity (Single Assembly k_∞)

Assembly	SAS2H/MCNP (16 Fission Products)		CASMO	
	Disposal Conditions	Reactor Conditions	Disposal Conditions	Reactor Conditions
D64	1.075	1.016	0.993	0.946
N04	1.080	1.024	1.025	0.968

From k_∞ (Single Assembly) to k_{eff} (MPC-32)

- 32 spent fuel assemblies with specific characteristics in specified positions (accounted for)
- Neutron absorption by structural and neutron absorber materials (accounted for)
- Neutron leakage (accounted for)
- Methodology to calculate k_{eff}

Burnup Credit Methodology

- 14 uranium and transuranic isotopes + oxygen
  - O-16; U-233, -234, -235, -236, -238; Np-237; Pu-238, -239, -240, -241, -242; Am-241, -242m, -243
- Options for fission products
  1. Actinide-only burnup credit
  2. **Five fission products**
     - **Rh-103; Nd-143; Sm-149 and -151; Gd-155**
  3. Six fission products
     - + Cs-133
  4. Sixteen fission products
     - + Mo-95; Tc-99; Ru-101; Ag-109; Nd-145; Sm-147, -150, -152; Eu-151 and -153

Effect of Fission Products

	k_{eff}	σ	FP Worth	
Actinide-Only Burnup Credit				
As-Built	0.88535	0.00022	0	
Disposal	1.06569	0.00020	0	
Actinides + 5 FPs				Worth of Rh^{103}, Nd^{143}, Sm^{149}, Sm^{151}, Gd^{155}
As-built	0.83555	0.00021	-0.050	
Disposal	1.00157	0.00019	-0.064	
Actinides + 16 FPs				+ Worth of Mo^{95}, Tc^{99}, Ru^{101}, Ag^{109}, Cs^{133}, Nd^{145}, Sm^{147}, Sm^{150}, Sm^{152}, Eu^{151}, Eu^{153}
As-built	0.80948	0.00021	-0.076	
Disposal	0.97029	0.00019	-0.095	
Best-Estimate (CASMO)				
As-built	~0.77		-0.12	Applied 5% correction based on comparison between calculated k_∞ using CASMO and (Actinides + 16 FPs)
Disposal	~0.92		-0.15	

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Results – Effect of Loading Pattern

Condition	k_{eff}	σ	Δk_{eff}
Disposal – As loaded	1.00157	0.00019	
Disposal – Rearranged 4 Center	0.99244	0.00019	-0.009
Disposal – Rearranged 4 Center + 8 Middle	0.98419	0.00019	-0.017
Disposal – Rearranged 4 Center + 12 Middle	0.98284	0.00019	-0.019
Disposal – Worst Case – Maximized Reactivity	1.00890	0.00019	+0.007

Δk_{eff} = 0.026

Simple Loading (4 Central Positions Minimized)

	1 1 6.69	2 2 7.59	3 3 7.65	4 4 7.36	
5 5 6.40	6 6 6.49	7 7 7.18	8 8 6.04	9 9 6.89	10 10 6.02
11 11 6.04	12 12 7.07	13 17 5.43	14 22 5.50	15 15 7.68	16 16 5.73
17 13 7.08	18 18 7.40	19 23 5.54	20 27 5.57	21 21 6.81	22 14 6.26
23 19 7.40	24 24 6.01	25 25 6.64	26 26 7.62	27 20 6.81	28 28 5.60
	29 29 5.82	30 30 5.69	31 31 5.70	32 32 5.72	

Optimized Loading (4 Central, 12 Middle Positions Minimized)

	1 1 6.69	2 2 7.59	3 3 7.65	4 4 7.36	
5 6 6.49	6 5 6.40	7 28 5.60	8 30 5.69	9 11 6.04	10 26 7.62
11 9 6.89	12 31 5.70	13 17 5.43	14 22 5.50	15 16 5.73	16 15 7.68
17 13 7.08	18 32 5.72	19 23 5.54	20 27 5.57	21 29 5.82	22 25 6.64
23 19 7.40	24 14 6.26	25 24 6.01	26 10 6.02	27 8 6.04	28 7 7.18
	29 21 6.81	30 20 6.81	31 12 7.07	32 18 7.40	

Results – Effect of Moderator Displacement

Condition	k_{eff}	σ	Δk_{eff}
Disposal	1.00157	0.00019	
Disposal - WABA Moderator Displacement	0.97862	0.00019	-0.023
Disposal - BAA Moderator Displacement	0.97319	0.00019	-0.028

WABA: Westinghouse Annular Burnable Absorber

BAA: Burnable Absorber Assembly (borated pyrex)

Results – Effect of Adding Surrogate Control Rods

Condition	$\mathbf{k_{eff}}$	$\boldsymbol{\sigma}$	$\mathbf{\Delta k_{eff}}$
Disposal	1.00157	0.00019	
Disposal – Spiked 4 Center Assembly	0.95493	0.00020	-0.047
Disposal – All 32 Assemblies Spiked	0.64817	0.00019	-0.353

Biases and Uncertainties

- *Fissile Material Transportation* applications presently require taking biases and uncertainties into account in a conservative manner
  - Uncertainties in cross sections
    - Actinides
    - Fission products
  - Uncertainties in isotopic concentrations
  - Methodological biases
  - **+** Arbitrary safety margin

  Bias + uncertainties can potentially negate a large share of the benefits provided by adding fission products
- *System Performance Assessment* should, in principle, be handled in a more rigorous manner

Feasibility of Direct Disposal of Dual-Purpose Casks – Options for Assuring Criticality

Canister Contents

1. Actual fuel inventory
2. Moderator displacement

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3. Loading optimization
4. Moderator displacement
5. Corrosion-resistant control element inserts

Analysis Method

1. Probabilistic approach
   a) Level of flooding
   b) Time-dependent reactivity
2. Sufficient credit for burnup with appropriate treatment of uncertainties associated with fuel composition and nuclide parameters

EPRI Reports

- Feasibility of Direct Disposal of Dual-Purpose Canisters – Options for Assuring Criticality Control. EPRI, Palo Alto, CA: 2008. 1016629 http://mydocs.epri.com/docs/public/000000000001016629.pdf
- Criticality Risks During Transportation of Spent Fuel – Revision 1. EPRI, Palo Alto, CA: 2008. 1016635

  http://mydocs.epri.com/docs/public/000000000001016635.pdf
- Fuel Relocation Effects for Transportation Packages – EPRI, Palo Alto, CA: 2007. 1015050

  http://mydocs.epri.com/docs/public/000000000001015050.pdf
- Feasibility of Direct Disposal of Dual-Purpose Canisters in a High-Level Waste Repository. EPRI, Palo Alto, CA: 2008. 1018051
- http://mydocs.epri.com/docs/public/000000000001018051.pdf

Backup Slide
Reactivity Calculations – Main Parameters

- Irradiation Parameters
  - Fuel temperature: 1000K
  - Moderator temperature: 600K
  - Moderator density: 0.670 g/cm^3
  - Boron concentration: 550 ppm average, constant
  - Specific power: calculated from Sequoyah unit power history, constant
  - Absorbers in guide tubes: assumed to be present for the full three cycles (later corrected)
- Main Software Tool
  - Isotopic calculation: SAS2H
  - Reactivity calculations: MCNP4B/MCNP5