PWR Fuel Reactivity Depletion Uncertainty Quantification - Methods Validation Tests

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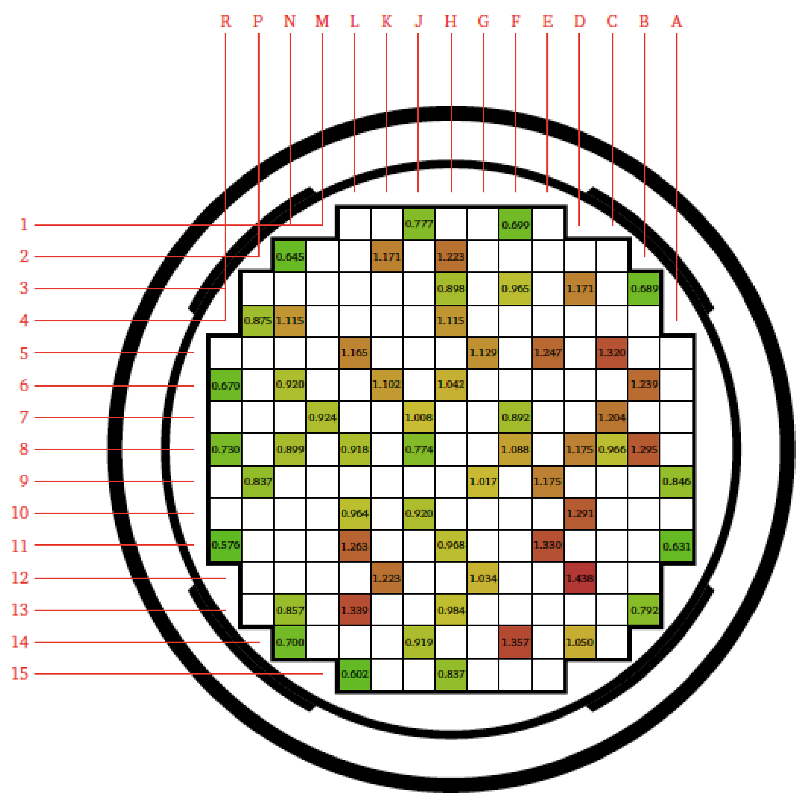


Using Commercial PWR Measured "Power Distribution" Data

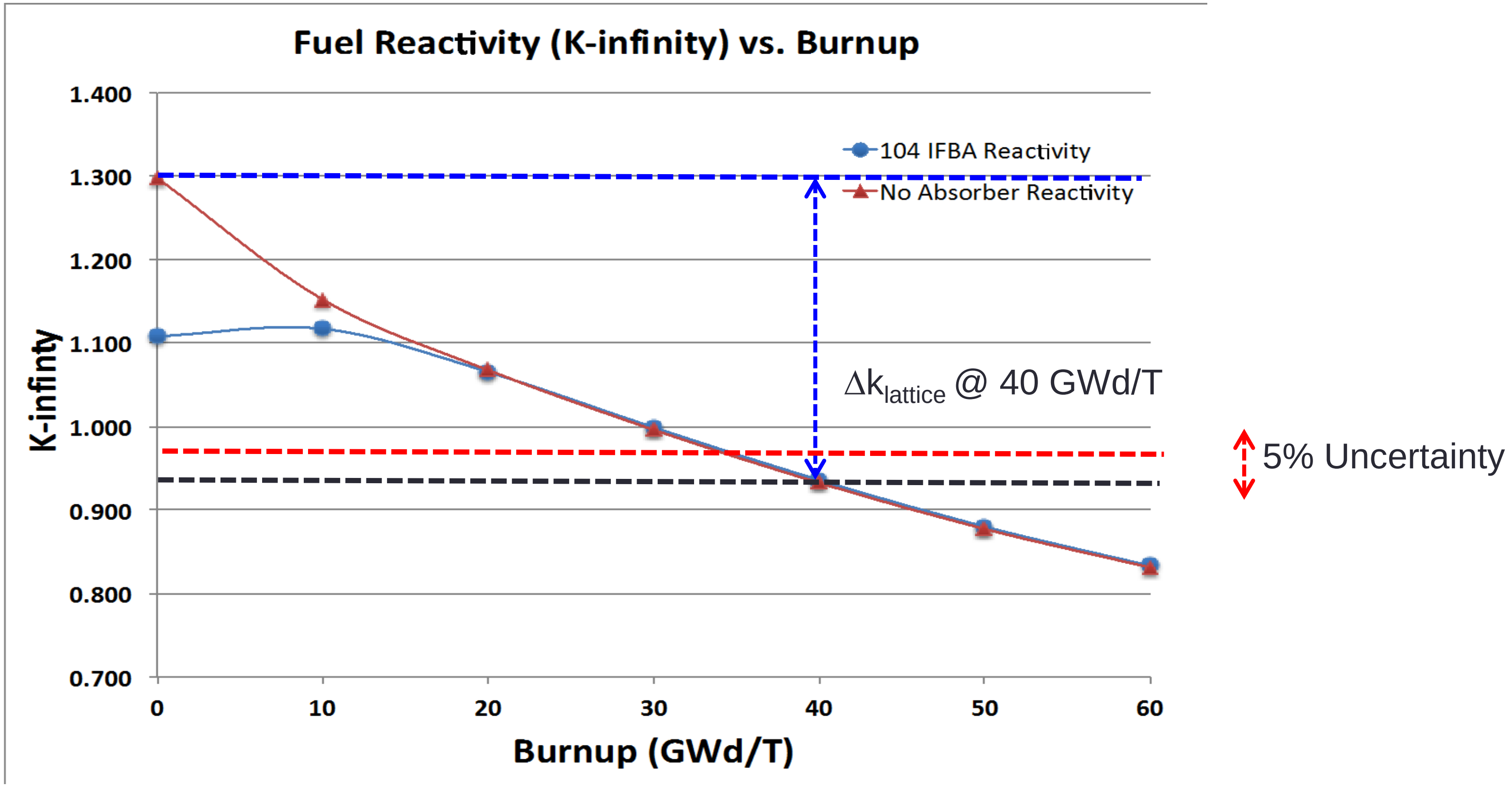
Background – The "Kopp Memo"

SFP burnup credit needs the reactivity of depleted fuel at cold rack conditions:

- **Reactivity of fresh fuel at rack conditions determined from cold criticals**

- **NRC's 1998 "Kopp Memo" allowed applicants to compute the depletion reactivity change and apply 5% of the decrement as the uncertainty**

NRC wants justification and/or quantification of depletion reactivity uncertainty



EPRI Project To Quantify Code Depletion Reactivity Bias and Uncertainty

1) Measure errors in lattice-computed fuel assembly reactivity at hot full power
2) Determine enrichment and burnable absorber trends in hot bias/uncertainty
3) Use regression analysis to determine burnup shape of hot bias/uncertainty
4) Use SCALE sensitivity/uncertainty to determine cold reactivity uncertainty
5) Evaluate "measured" lattice cold reactivity bias/uncertainty

6) Define 11 benchmark lattice's for applicants to develop lattice code's and SFP tool's depletion reactivity biases and uncertainties

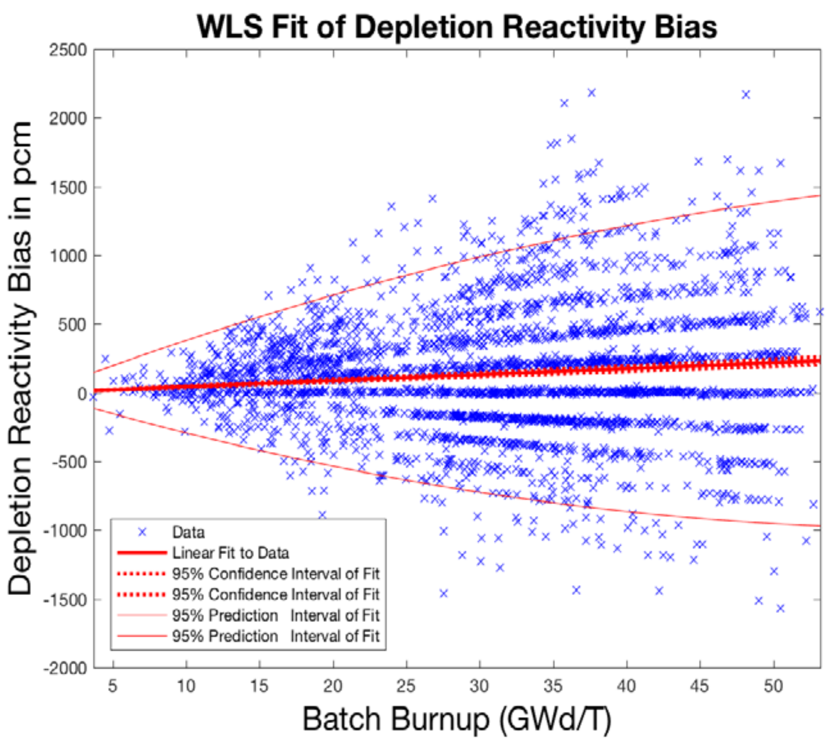


Table XIII. Benchmark Lattice Experimental Reactivity Decrements for 100 Hour Cooling

		Depletion Reactivity (delta k_{inf})					
		Burnup (GWd/T)					
Case	Lattice Description	10	20	30	40	50	60
1	3.25% enrichment depletion	-0.1329	-0.2339	-0.3211	-0.3956	-0.4554	-0.5002
2	5.00% enrichment depletion	-0.1146	-0.2021	-0.2806	-0.3545	-0.4238	-0.4867
3	4.25% enrichment depletion	-0.1223	-0.2157	-0.2990	-0.3758	-0.4445	-0.5029
4	off-nominal pin depletion	-0.1207	-0.2176	-0.3075	-0.3931	-0.4715	-0.5385
5	20 WABA depletion	-0.2045	-0.2335	-0.2998	-0.3717	-0.4372	-0.4932
6	104 IFBA depletion	-0.1736	-0.2215	-0.2968	-0.3726	-0.4418	-0.5009
7	104 IFBA, 20 WABA depletion	-0.2524	-0.2418	-0.2981	-0.3686	-0.4343	-0.4910
8	high boron depletion = 1500 ppm	-0.1216	-0.2129	-0.2932	-0.3662	-0.4310	-0.4860
9	branch to hot rack = 338.7K	-0.1237	-0.2171	-0.2998	-0.3756	-0.4432	-0.5005
10	branch to rack boron = 1500 ppm	-0.0967	-0.1784	-0.2530	-0.3217	-0.3826	-0.4335
11	high power density depletion	-0.1235	-0.2149	-0.2945	-0.3664	-0.4299	-0.4838

Step 1: Determining Reactivity Errors using PWR In-Core Detector Data

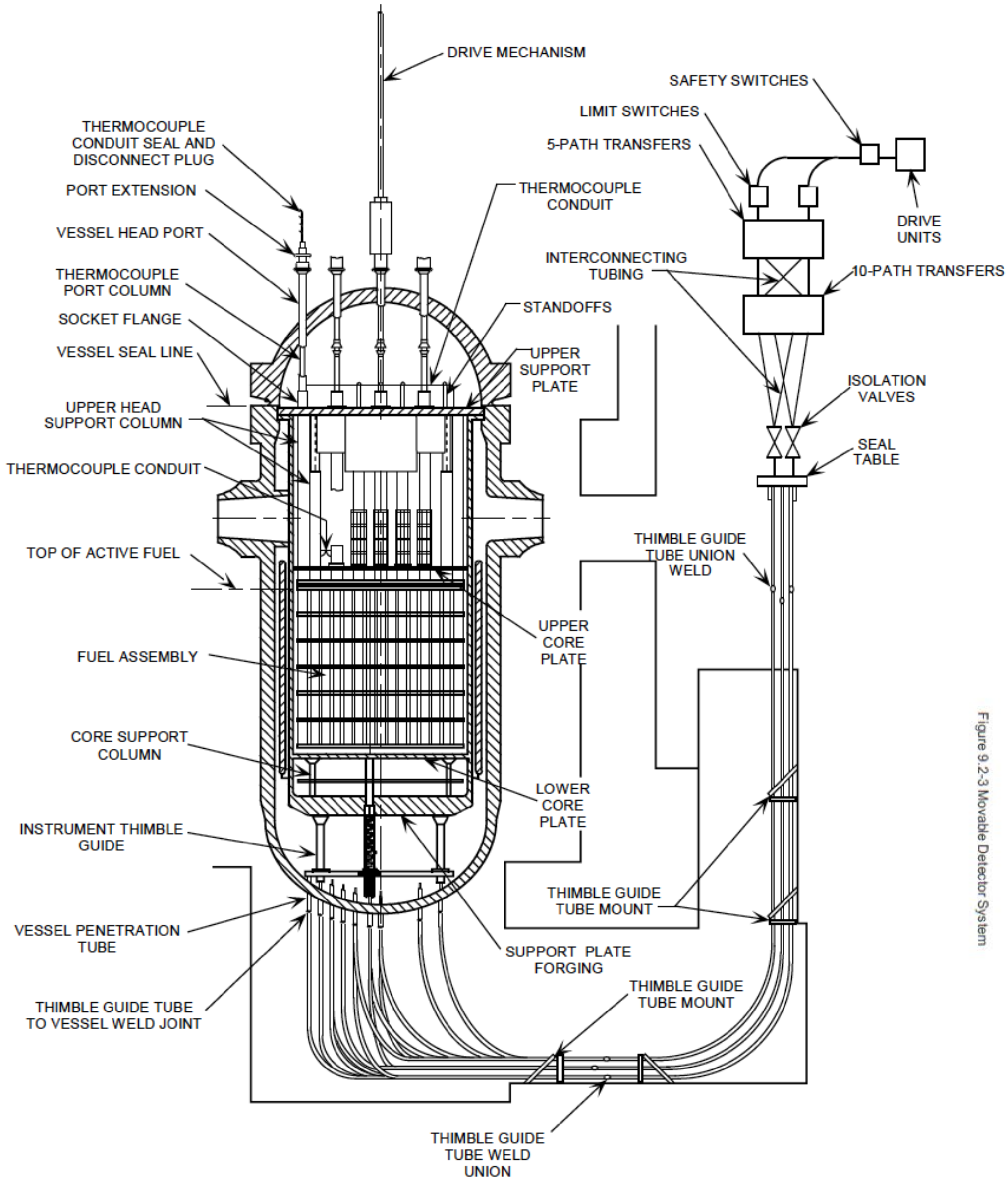
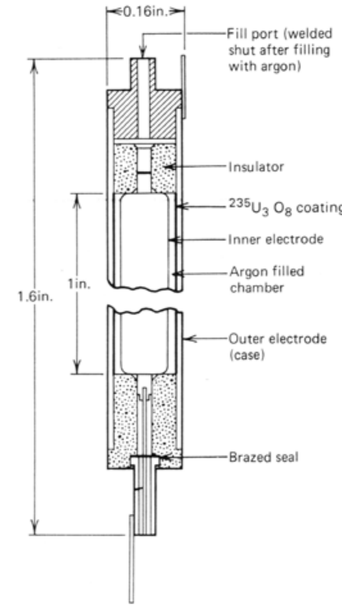
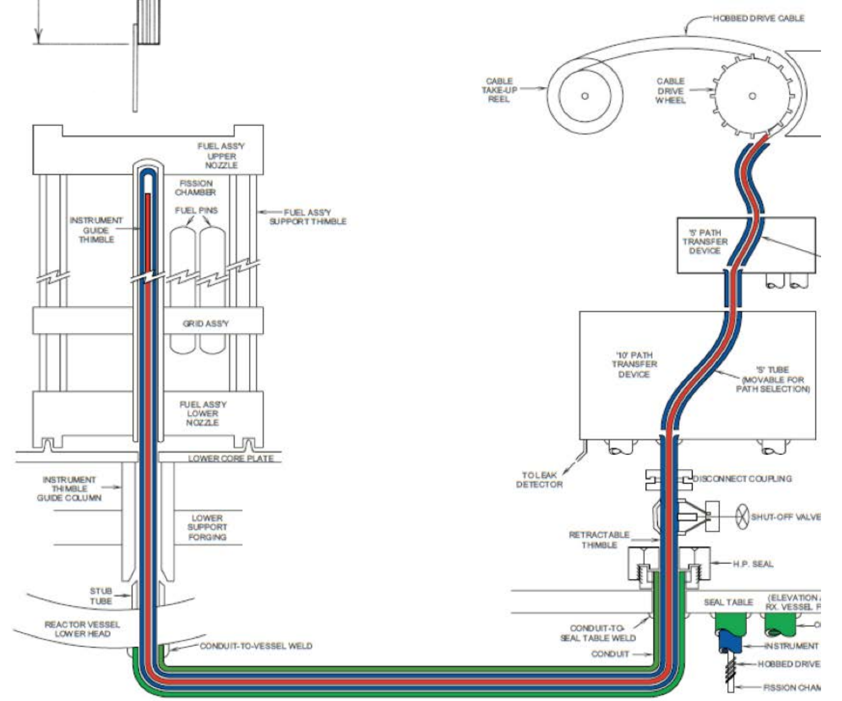
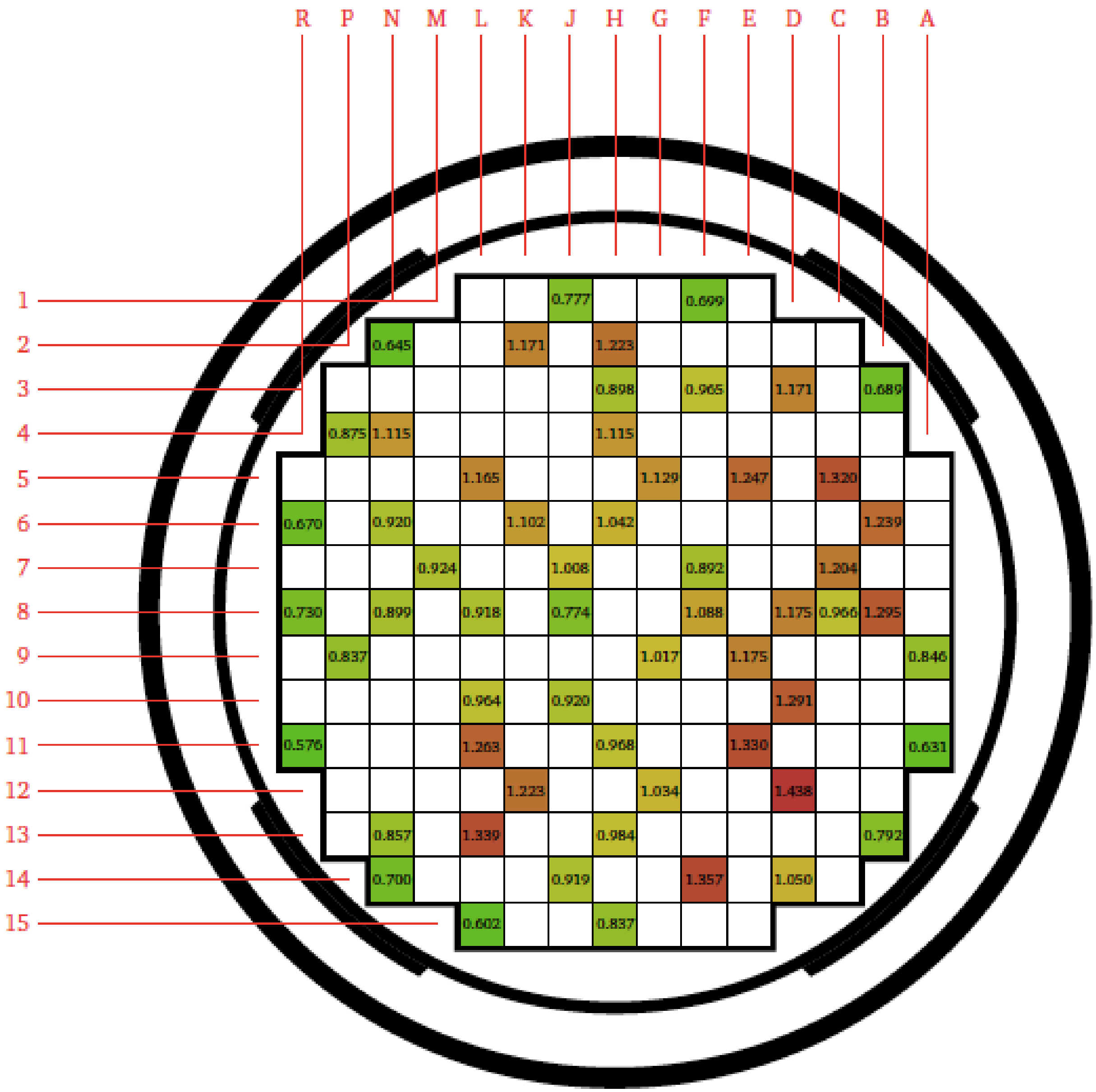


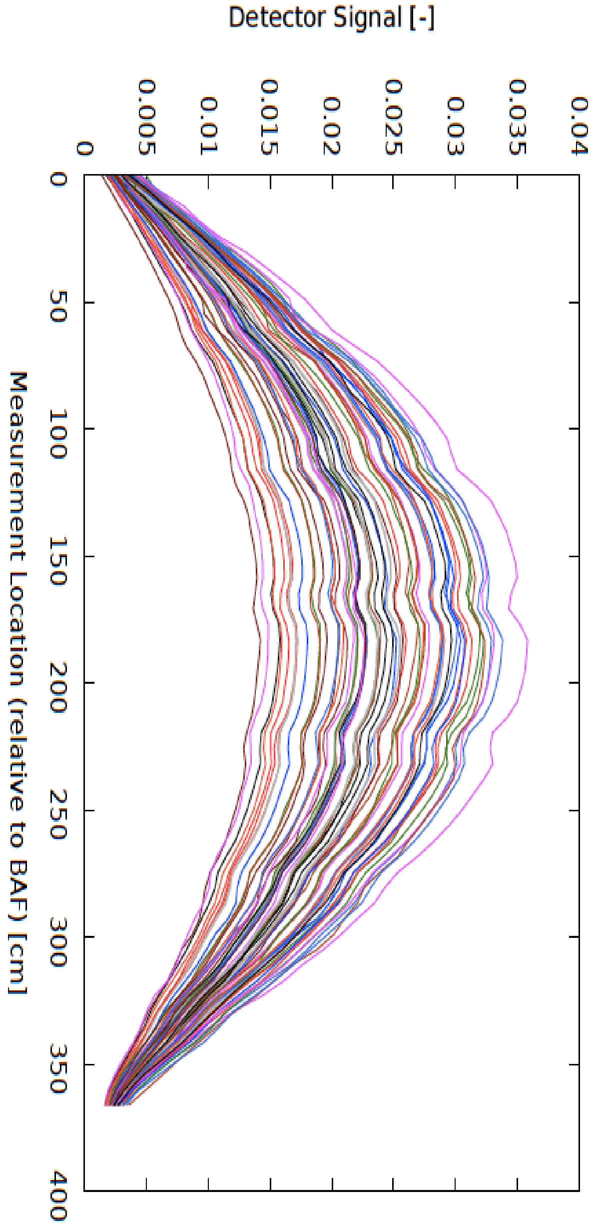
Figure 9.2-3 Movable Detector System





PWR: Monthly Measured ^{235}U Fission Rate Distributions

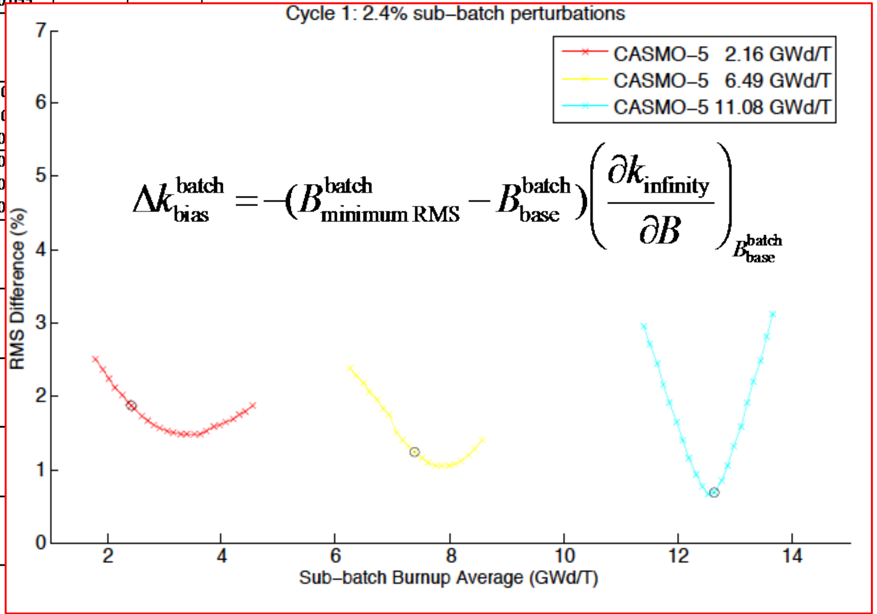




Perturbing Sub-batch Lattice Reactivity to Find Best Measurement Fit

1) Compute r.m.s. difference (Calculated-Measured)
2) Perturb lattice reactivity (k-infinity)
3) Re-compute r.m.s. differences
4) Search for perturbed lattice reactivity that provides best fit to measured data
5) Tabulate sub-batch lattice reactivity bias

	R	P	N	M	L	K	J	H	G	F	E	D	C
1							-0.005 0.008 0.020			-0.023 0.000 0.022			
2			-0.046 -0.020 0.006			-0.045 -0.006 0.032		0.012 0.004 -0.003					
3								0.032 0.020 0.007		-0.017 0.012 0.039			
4		-0.056 -0.017 0.020	-0.051 0.003 0.055					0.061 -0.008 -0.062					
5					0.032 0.010 -0.010				0.069 -0.001 -0.066		0.02 0.005 -0.015		0.007 0.055
6	-0.013 0.004 0.026		-0.018 0.011 0.038			0.038 -0.001 -0.040							
7				0.039 0.011 -0.014			0.031 -0.011 -0.053			0.064 0.011 -0.039			
8	-0.008 -0.003 0.001		0.025 0.013 0.001		0.080 0.008 -0.059		0.042 0.002 -0.037					0.057 -0.002 -0.056	
9		-0.009 0.007 0.022							0.048 0.006 -0.036		0.084 0.014 -0.051		
10												-0.005 -0.002 0.001	
11	-0.039 -0.018 0.003				0.005 -0.017 -0.037			0.092 0.020 -0.047			0.026 0.004 -0.016		
12						-0.015 -0.012 -0.009			0.037 0.009 -0.016			-0.048 -0.003 0.040	
13			-0.057 0.000 0.054		-0.068 -0.018 0.029			0.025 0.013 0.001					
14			-0.052 -0.026 0.000				0.002 0.018 0.033			-0.036 0.003 0.041		-0.070 -0.031 0.006	
15					-0.033 -0.012 0.008			-0.005 -0.001 0.003					

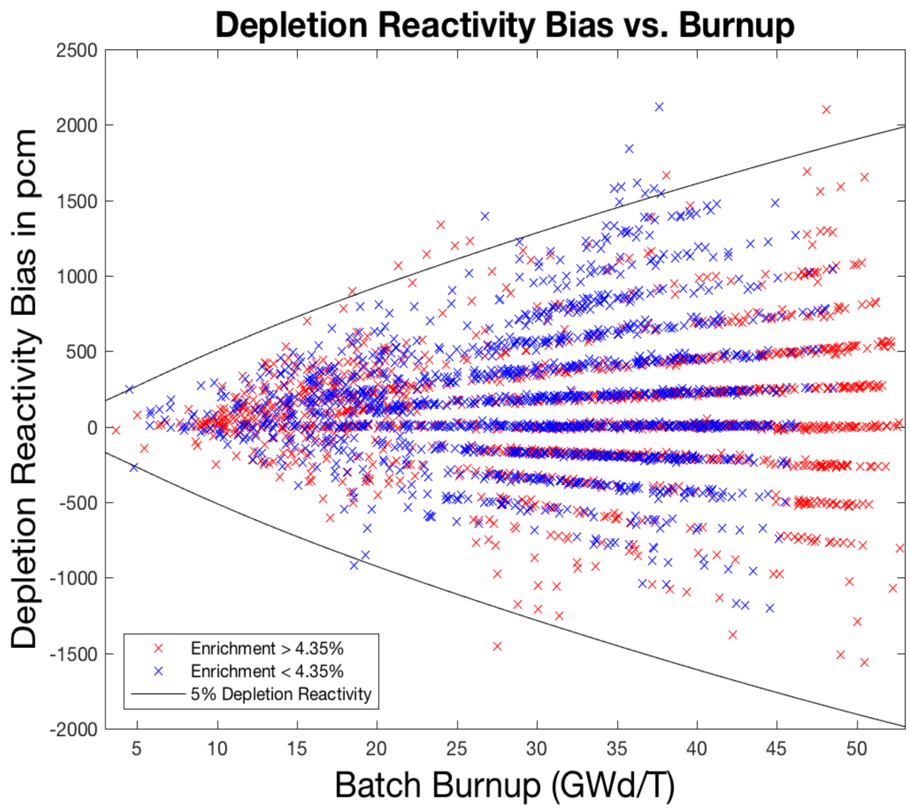


$$\Delta k_{\text{bias}}^{\text{batch}} = -\left(B_{\text{minimum RMS}}^{\text{batch}} - B_{\text{base}}^{\text{batch}}\right)\left(\frac{\partial k_{\text{infinity}}}{\partial B}\right)_{B_{\text{base}}^{\text{batch}}}$$

r.m.s. diff	
M_B=0.9	4.2%
M_B=1.0	1.2%
M_B=1.1	3.3%

Data Generation

- **4 Duke reactors over 44 cycles of operation**
- **> 600 flux maps and >8000 sub-batch reactivities**
- **> 10 million core calculations with CASMO-5 and SIMULATE-3 nodal codes**
- **No enrichment or burnable poison trends observed**

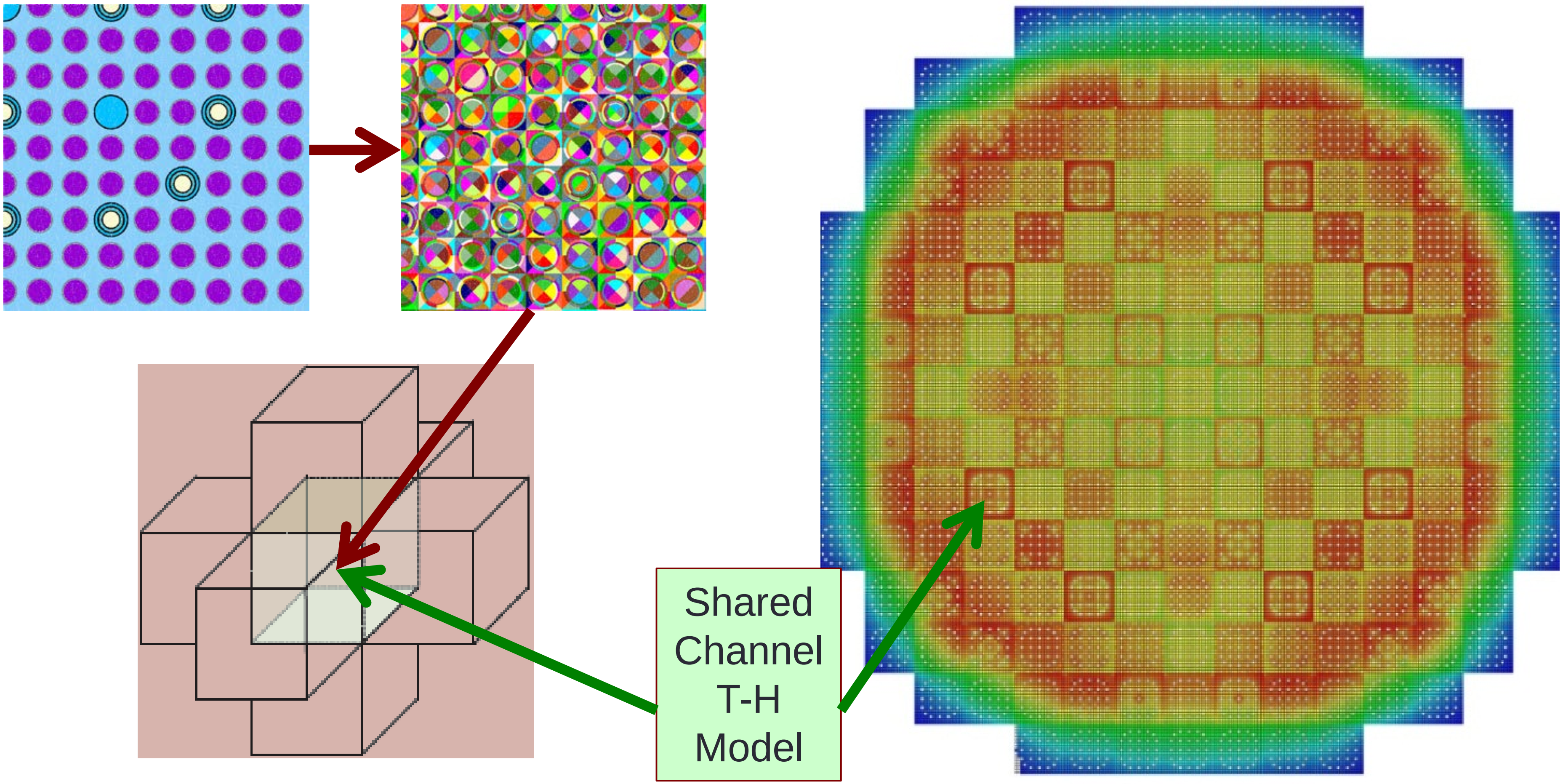


NRC Request: "Can you demonstrate that Step 1 inferred biases/uncertainties are not influenced by the nodal code and reactivity perturbation techniques?"

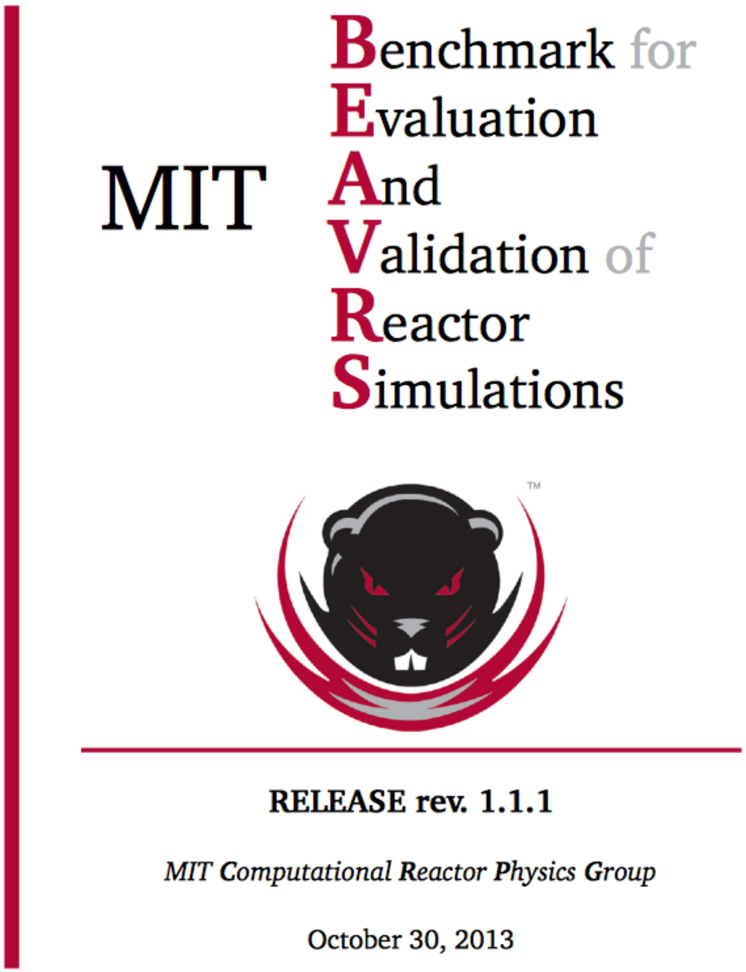
Homogenized Nodal Diffusion vs. Heterogeneous Discrete Transport

- 35-group fine-mesh lattice transport
- Assembly homogenized Data
- 2-Group nodal diffusion theory
- Assembly depletion of nuclides
- Pin-power and detector reconstruction

- No Lattice calculation needed
- Lattice-detail model for every pin
- 35-group fine-mesh transport
- Pin depletion of nuclides
- Explicit detector model



Analysis Used BEAVRS Two-Cycle PWR Open Benchmark
(Rather than the Duke 44 Cycle Data)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Benchmark for
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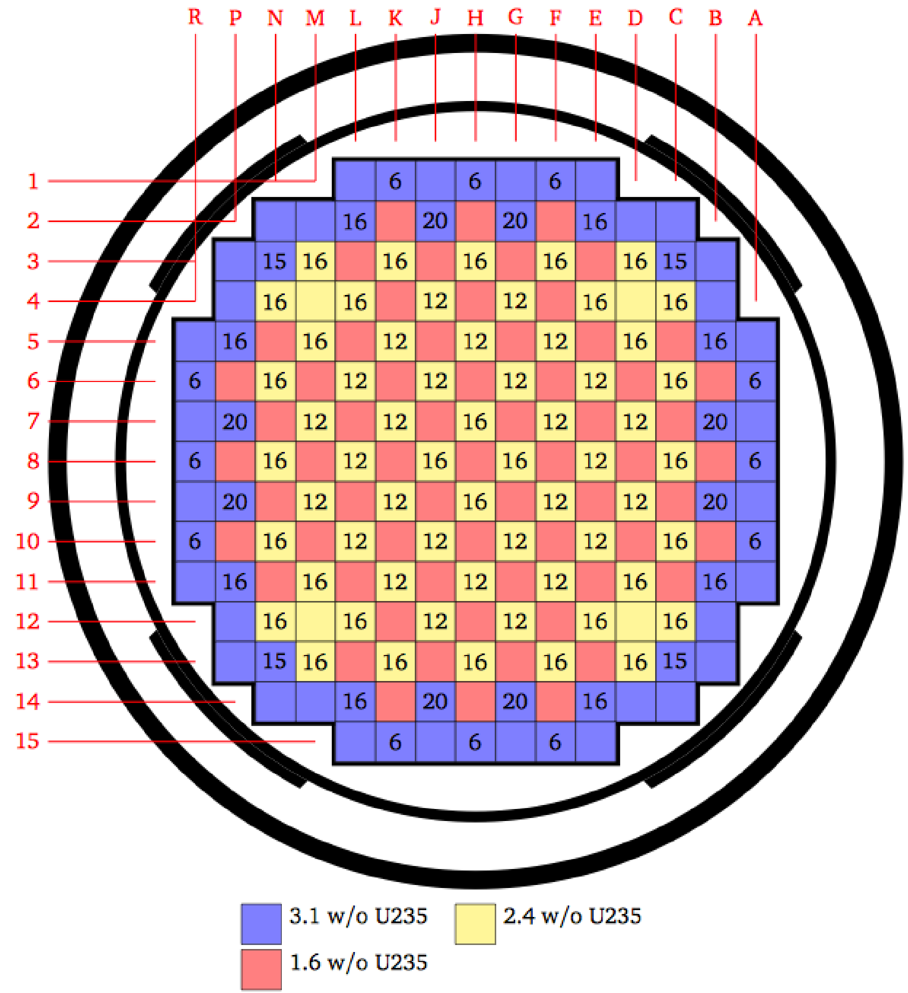
RELEASE rev. 1.1.1

MIT Computational Reactor Physics Group

October 30, 2013



- **Publically available measured reactor data**
- **Model starts in Cycle 1 (easier for people to get started with analysis)**

BEAVRS Full-Core Multi-group Transport Calculations with CASMO-5

CASMO-5 full-core transport in 35 energy groups – about 10 CPU hours per state-point

Reactivity bias/standard deviation using 3D SIMULATE-3 two-group nodal model reduced-data is the same as with full-core 2D CASMO-5 35-group multigroup transport reduced-data.

TABLE I SIMULATE-3 (S3) vs. CASMO-5 (C5): Reactivity Bias

Cycle / Burnup	Enrichment (%)	Fuel Batch (GWd/T)	S3 Bias (pcm)	C5 Bias (pcm)	S3 Bias - C5 Bias (pcm)
1 / BOC	2.4	2.44	-215	-251	36
1 / MOC	2.4	7.39	66	66	0
1 / EOC	2.4	12.62	-50	-50	0
2 / BOC	2.4	18.10	90	119	-29
2 / MOC	2.4	20.88	-347	-230	-117
2 / EOC	2.4	23.29	-197	-167	-30
1 / BOC	3.1	1.87	60	222	-162
1 / MOC	3.1	5.53	0	0	0
1 / EOC	3.1	9.52	14	14	0
2 / BOC	3.1	15.43	432	255	177
2 / MOC	3.1	19.09	160	72	88
2 / EOC	3.1	22.17	198	119	79
2 / BOC	3.2 / 3.4	3.29	-328	-242	-86
2 / MOC	3.2 / 3.4	6.81	-54	0	-54
2 / EOC	3.2 / 3.4	9.85	-75	0	-75
1 / BOC	3.1 @ 2.4_{min}	2.15	0	182	-182
1 / MOC	3.1 @ 2.4_{min}	6.46	100	70	30
1 / EOC	3.1 @ 2.4_{min}	11.07	0	14	-14
		S.D. of Bias	188	152	88
		Mean Bias	-8	11	-19

Eliminates concerns about approximations needed for nodal core calculations:

- Assembly lattice reflective boundary conditions
- Assembly-homogenized, two-group nodal data
- Diffusion theory (vs. transport theory)
- Assembly-wise nodal depletion (vs. pin-wise)
- Macroscopic depletion models (vs. nuclide)
- Detector reaction rate reconstruction

- **SIMULATE-3 is not the source of any “fortuitous cancellation of error” in the inference of sub-batch reactivities**
- **Little uncertainty comes from nodal method approximations.**

Nodal and Lattice Code/Library Independence of Results

Cycle	Enrichment	BEAVRS Calendar Day	PANTHER Calendar Day	Cycle Burnup	Batch Burnup	Min RMS Batch Burnup	ΔE	Δk PANTHER	Δk Lattice Data
	%			GWd/tU	GWd/tU	GWd/tU	GWd/tU	pcm	pcm
1	2.4	187.0	186.7	2.17	2.40	2.28	-0.113	-23.8	-37.3
1	2.4	368.0	380.1	7.51	8.41	8.52	0.113	-37.3	-22.6
1	2.4	468.0	469.5	11.08	12.44	12.55	0.112	-54.0	-54.9
2	2.4	65.0	61.4	2.11	17.02	17.43	0.410	-272.5	-279.5
2	2.4	156.0	156.6	5.23	19.58	19.50	-0.083	56.4	56.0
2	2.4	266.0	271.8	9.36	23.04	22.95	-0.084	56.8	60.9
1	3.1	187.0	186.7	2.17	1.93	1.84	-0.085	42.7	38.6
1	3.1	368.0	380.1	7.51	6.49	6.32	-0.172	152.3	113.2
1	3.1	468.0	469.5	11.08	9.59	9.33	-0.263	183.7	175.9
2	3.1	65.0	61.4	2.11	14.22	13.78	-0.441	347.4	319.1
2	3.1	156.0	156.6	5.23	17.61	17.29	-0.324	252.8	242.3
2	3.1	266.0	271.8	9.36	22.04	21.83	-0.213	161.4	159.4
2	3.2/3.4	65.0	61.4	2.11	2.25	2.57	0.325	-216.2	-214.9
2	3.2/3.4	156.0	156.6	5.23	5.65	5.98	0.328	-257.7	-264.6
2	3.2/3.4	266.0	271.8	9.36	10.16	10.38	0.219	-174.3	-173.4
1	3.1@2.4min	187.0	186.7	2.17	1.93	1.84	-0.085	42.7	38.6
1	3.1@2.4min	368.0	380.1	7.51	6.49	6.32	-0.172	152.3	113.2
1	3.1@2.4min	468.0	469.5	11.08	9.59	9.42	-0.175	122.6	115.1

Table 3: PANTHER fuel batch reactivity uncertainty

	PANTHER	Lattice Data	2014 EPRI, CASMO-5	2014 EPRI, SIMULATE-3
Δk mean (pcm)	29.1	21.4	6.0	-27.0
Δk standard deviation (pcm)	170.4	164.4	158.0	171.0

Table 2: Fuel batch reactivity uncertainty comparison

- **WIMS(JEF-2.2)/PANTHER results similar to CASMO/SIMULATE results**
- **Cross section library and nodal code do not influence results.**

Testing Reactivity Perturbation Techniques

$$\Delta k_{\text{bias}}^{\text{batch}} = -\left(B_{\text{minimum RMS}}^{\text{batch}} - B_{\text{base}}^{\text{batch}}\right)\left(\frac{\partial k_{\text{infinity}}}{\partial B}\right)_{B_{\text{base}}^{\text{batch}}}$$

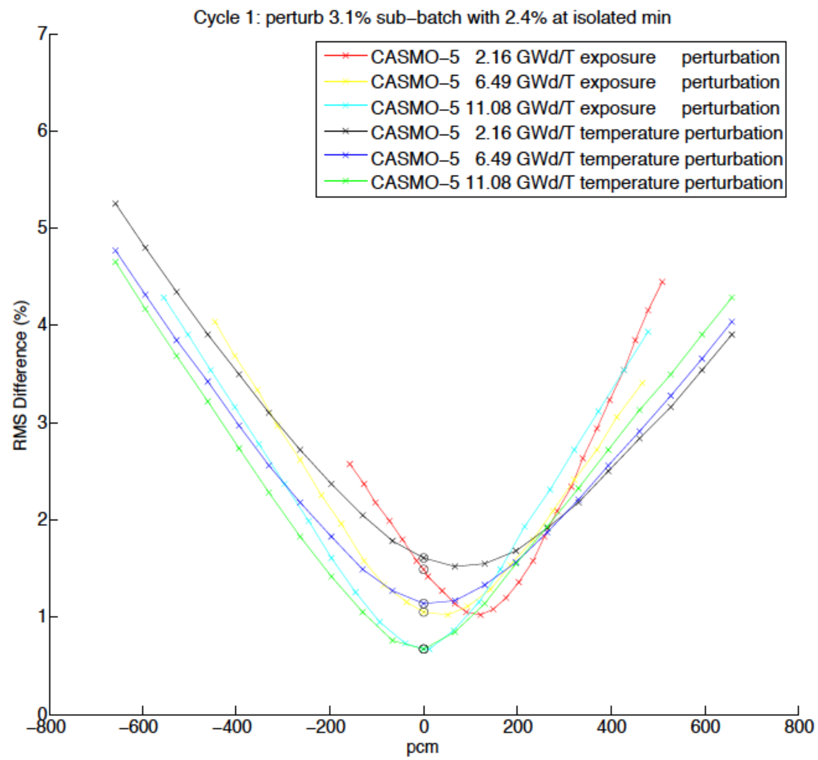
Burnup

$$\Delta k_{\text{bias}}^{\text{batch}} = -\left(T_{\text{minimum RMS}}^{\text{batch}} - T_{\text{base}}^{\text{batch}}\right)\left(\frac{\partial k_{\text{infinity}}}{\partial T}\right)_{T_{\text{base}}^{\text{batch}}}$$

Fuel Temperature

TABLE II Perturbation of Burnup vs. Fuel Temperature: Reactivity Bias

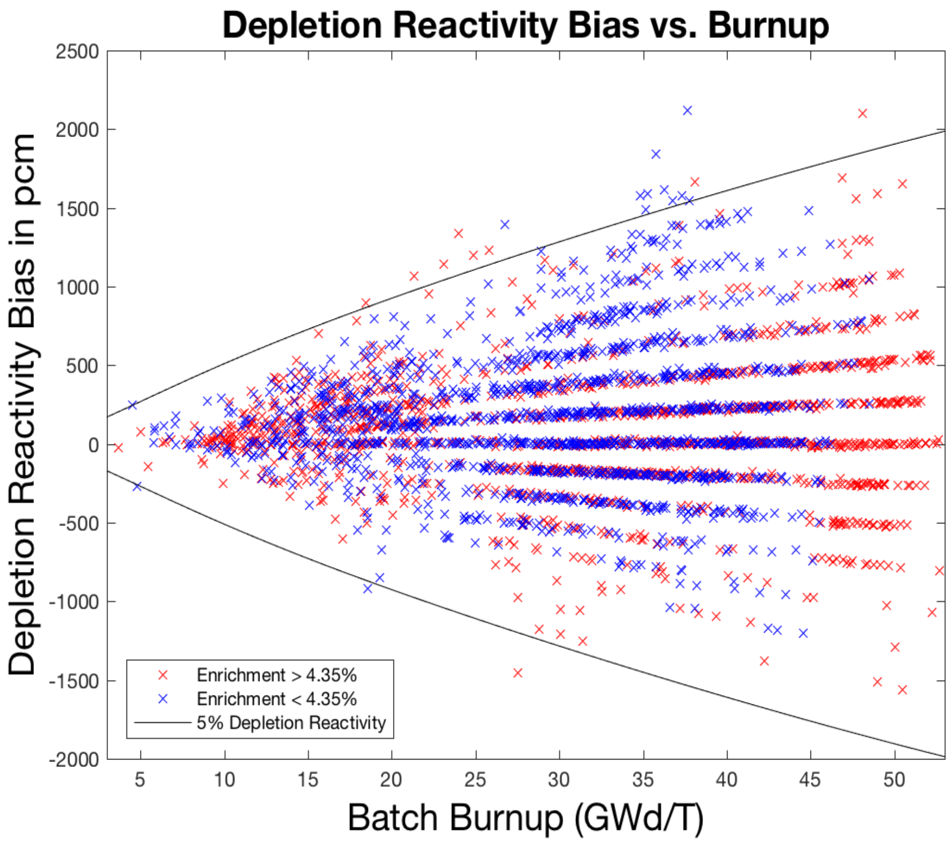
Cycle / Burnup	Enrichment (%)	Fuel Batch (GWd/T)	Burnup Bias (pcm)	Fuel Temp Bias	Burnup - Fuel Temp Bias (pcm)
1 / BOC	2.4	2.44	-251	-182	-69
1 / MOC	2.4	7.39	66	90	-24
1 / EOC	2.4	12.62	-50	-63	13
2 / BOC	2.4	18.10	119	-30	149
2 / MOC	2.4	20.88	-230	-369	139
2 / EOC	2.4	23.29	-167	-302	135
1 / BOC	3.1	1.87	222	198	24
1 / MOC	3.1	5.53	0	0	0
1 / EOC	3.1	9.52	14	0	14
2 / BOC	3.1	15.43	255	300	-45
2 / MOC	3.1	19.09	72	132	-60
2 / EOC	3.1	22.17	119	65	54
2 / BOC	3.2 / 3.4	3.29	-242	-243	1
2 / MOC	3.2 / 3.4	6.81	0	-61	61
2 / EOC	3.2 / 3.4	9.85	0	-62	62
1 / BOC	3.1 @ 2.4_{min}	2.15	182	66	116
1 / MOC	3.1 @ 2.4_{min}	6.46	70	0	70
1 / EOC	3.1 @ 2.4_{min}	11.07	14	0	14
		S.D. of Bias	152	169	67
		Mean Bias	11	-26	36



Reactivity biases using burnup- and fuel-temperature-perturbed data are ~ the same.

Little uncertainty comes from the burnup perturbation technique.

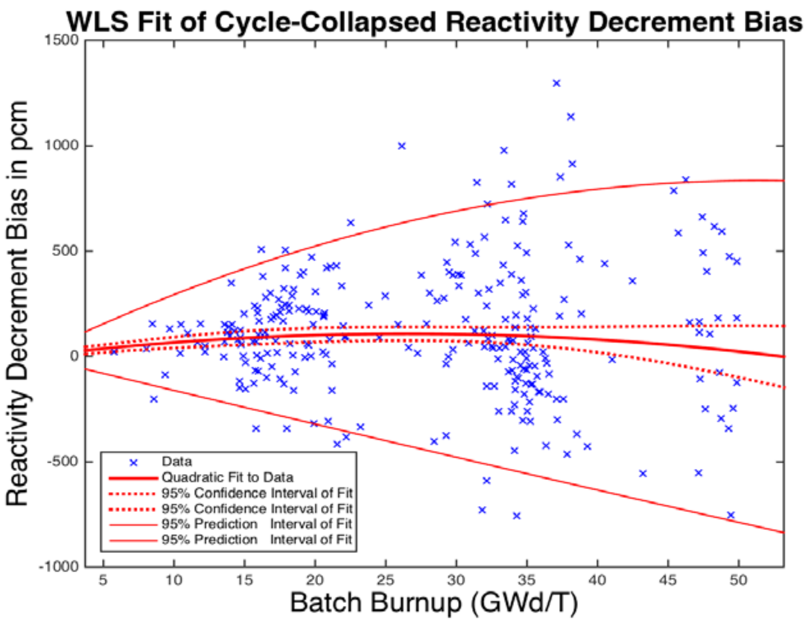
Remember: we are computing only 18 points out of 8000 in this study (full core multi-group transport computer resource limitations)



We have successfully demonstrated that:

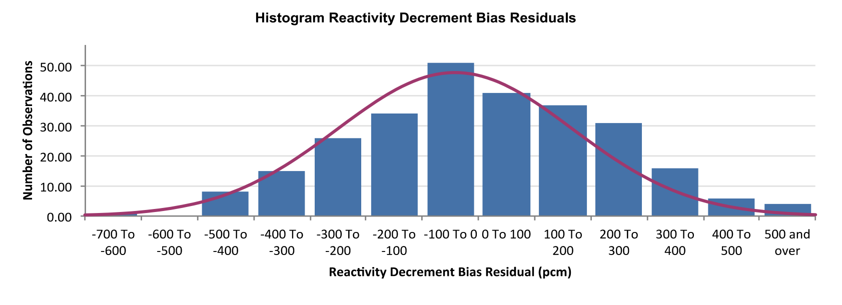
- **Multi-group transport and nodal method data reduction produce similar biases.**
- **Burnup and temperature perturbations of k-infinity produce similar biases.**

Current EPRI Project Status: Final 95/95 Uncertainty Refinements



Normality Tests			
Variable #1 (Reactivity Decrement Bias Residuals)			
Sample Size	270	Mean	8.82425
Standard Deviation	225.28857	Median	0.
Skewness	0.01589	Kurtosis	2.74747
Skewness (Fisher's)	0.01598	Kurtosis (Fisher's)	-0.23471

	Test Statistics	p-level	Conclusion: (5%)
Kolmogorov-Smirnov/Lilliefor Test	0.02319	0.97833	No evidence against normality
Shapiro-Wilk W	0.99461	0.45792	Accept Normality
D'Agostino Skewness	0.10939	0.91289	Accept Normality
D'Agostino Kurtosis	-0.78382	0.43315	Accept Normality
D'Agostino Omnibus	0.62633	0.73113	Accept Normality



Burnup (GWd/T)	10.0	20.0	30.0	40.0	50.0	60.0
CASMO-5 Bias (pcm)	66	101	106	80	22	-64
Cold Tolerance Limit (pcm)	348	537	654	752	831	888
CASMO-5 Bias (% of depletion)	0.58	0.50	0.38	0.23	0.05	-0.13
Cold Tolerance Limit (% of depletion)	3.05	2.66	2.33	2.12	1.95	1.81

1) Kopp Memo's 5.0% uncertainty in burnup reactivity change is conservative.
2) Depletion reactivity 95/95 uncertainty is 3.1% at 10 GWd/T and 1.8% at 60 GWd/T.

EPRI Benchmarks Are Published and Available for Applicants to Establish Biases and Uncertainties for Their Specific SFP Analysis Tools

NRC to soon issue an SER regarding applications of EPRI Benchmarks.

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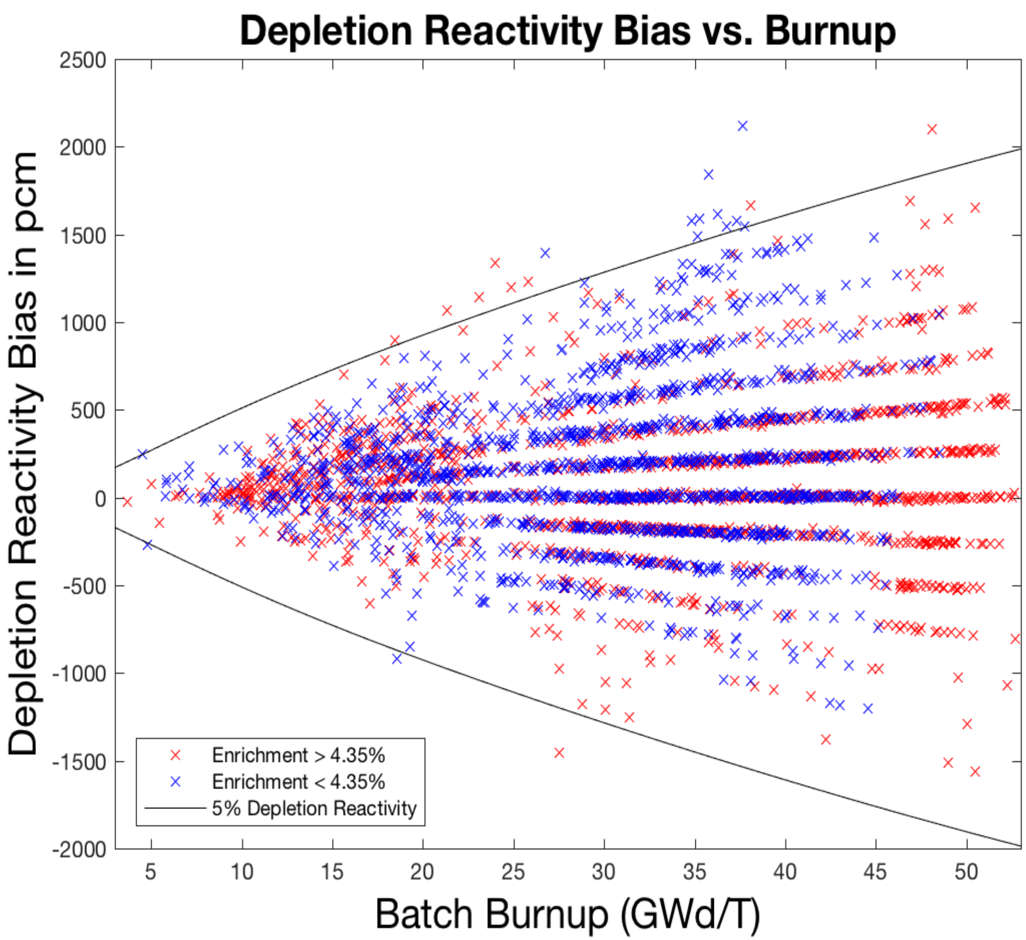

Questions?