CASL Applications and Validation

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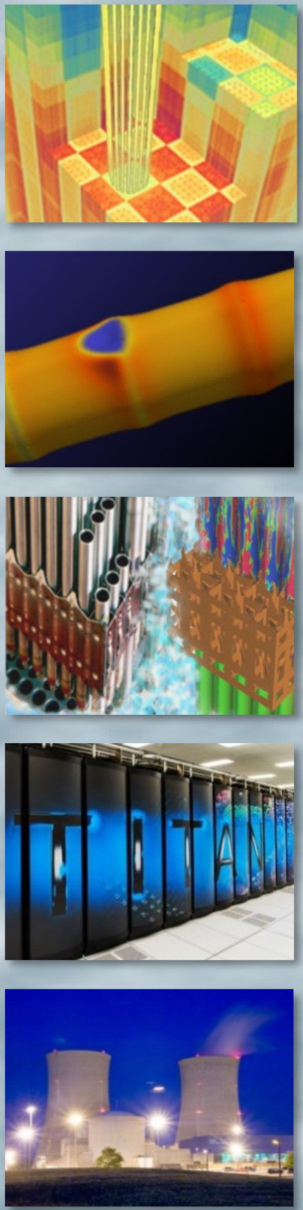
AMA Deputy Lead

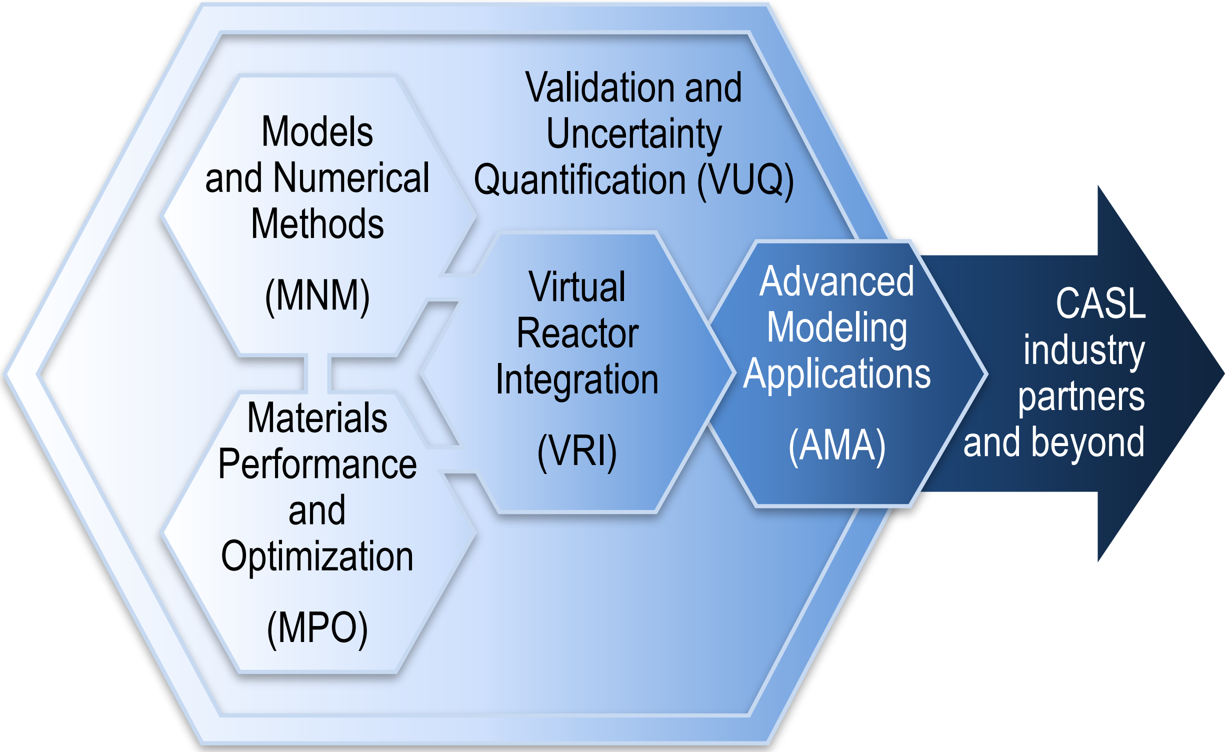
VERA Workshop
February 11, 2019



The Consortium for Advanced Simulation of LWRs
A DOE Energy Innovation Hub

U.S. DEPARTMENT OF ENERGY

Advanced Modeling Applications



Models and Numerical Methods (MNM)

Validation and Uncertainty Quantification (VUQ)

Virtual Reactor Integration (VRI)

Materials Performance and Optimization (MPO)

Advanced Modeling Applications (AMA)

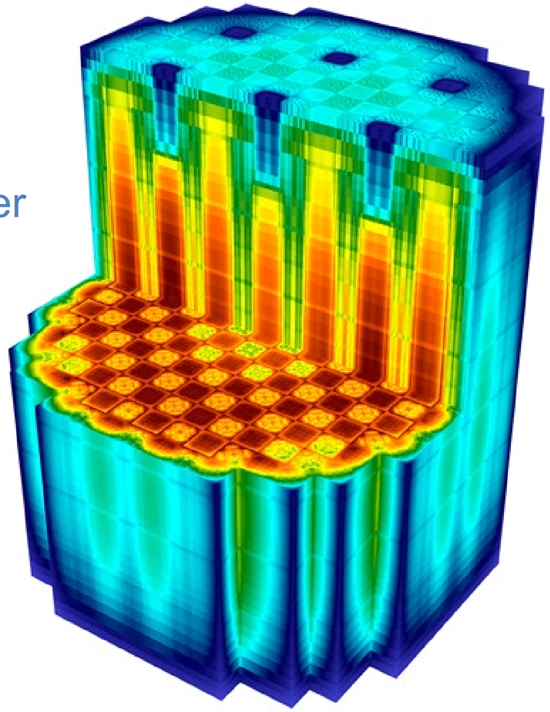
CASL industry partners and beyond

CASL circa 2010

> *“AMA will work closely with the nuclear industry and provide compelling demonstrations of VERA capabilities and workflows.”*
>
> *– Jess Gehin,*
> *former Director*

From the VERA beginning, CASL has maintained a subset of staff devoted to meaningful applications and testing of VERA

Advanced Modeling Applications


Watts Bar 2 Startup Power Distribution

Objectives and Strategies

- Apply VERA to relevant industry problems and demonstrate compelling value for the commercial nuclear power industry
- Provide requirements, priorities, user testing, validation, and benchmarking for VERA from nuclear industry perspective
- Staff composed of industry analysts

Requirements Drivers

- Reactor Benchmarking
- Challenge Problems
- Test Stand Support
- Industry Engagement
- Code testing and feedback

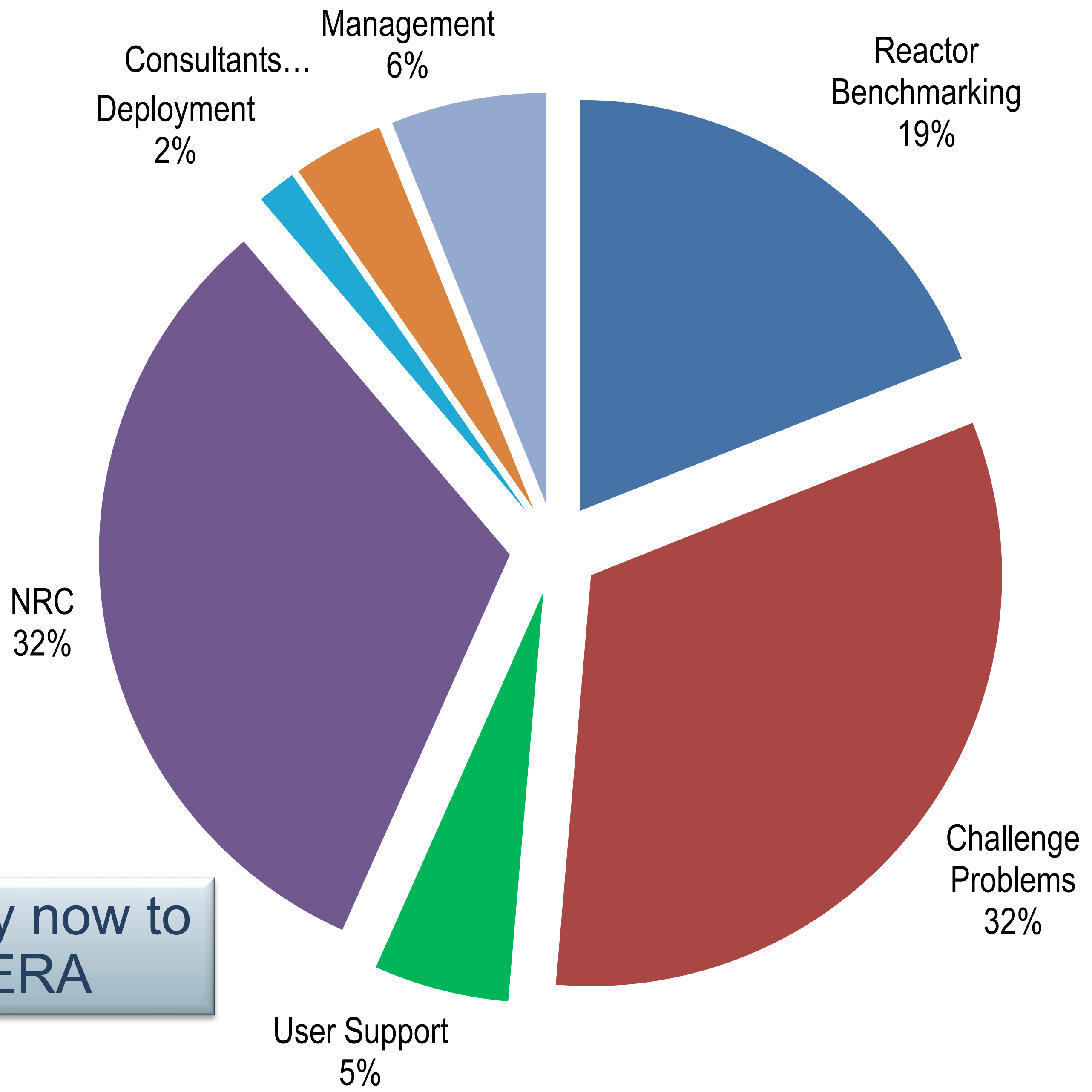
Outcomes and Impact

- Significant value demonstrations
- Collaboration with the nuclear industry
- Obtain data, develop models, generate customer base, facilitate VERA deployment
- Successful testing of Challenge Problem capabilities (CRUD, RIA, PCI, Excore)

AMA in 2019

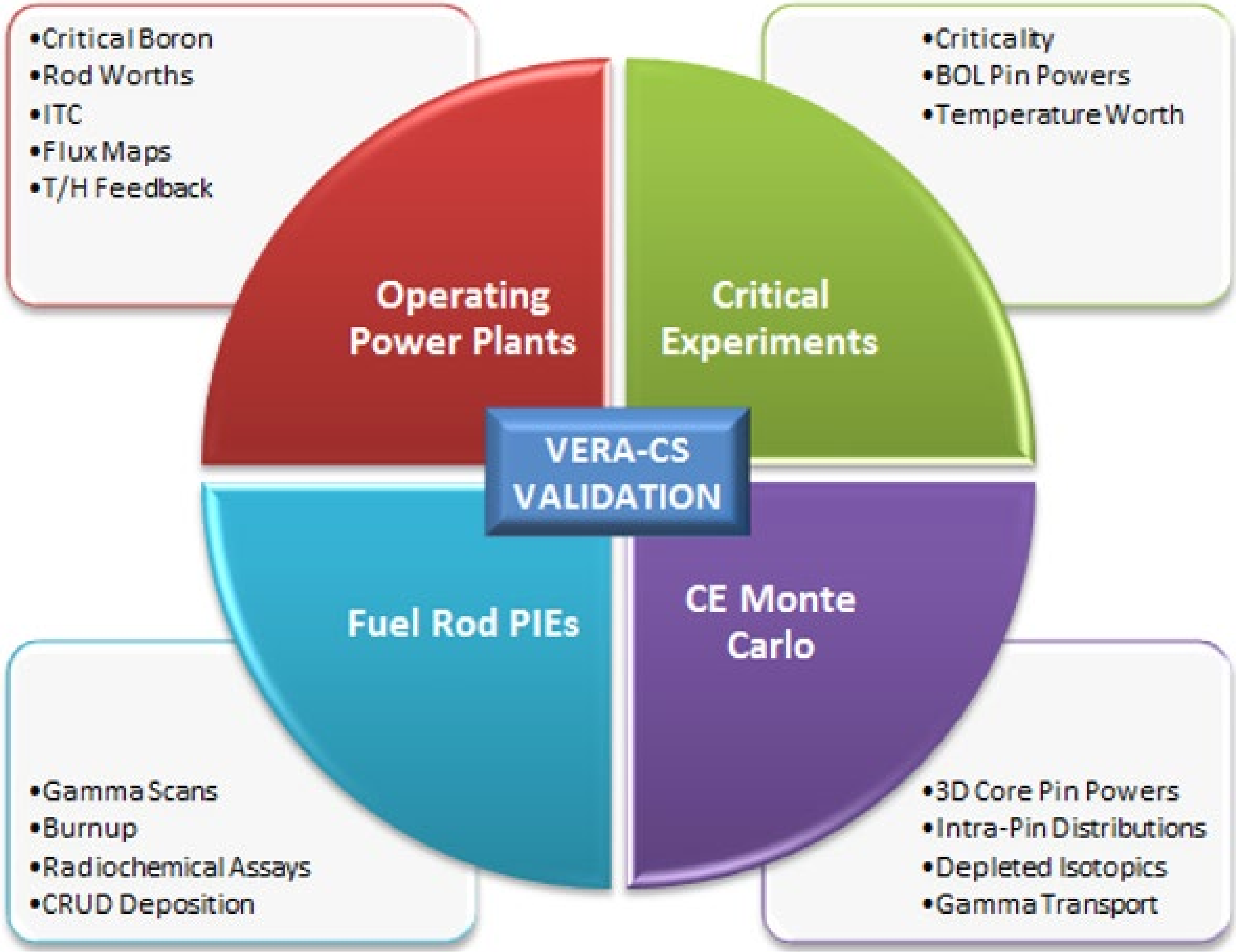
- $5M funding
- 30 staff members
  - 57% industry
  - 30% laboratory
  - 3% university
  - 10% consultants
- ~80 milestones
- Maintaining 21 reactor models
  - >150 fuel cycles

CASL is investing heavily in industry now to ensure long-term success of VERA



VERA Validation Plan

- Power Plant Benchmarking
  - Next slide
- Critical Experiments
  - B&W, Kritz, Dimple, SPERT
- Fuel Rod PIE
  - TMI Cycle 10
  - Catawba MOX LTAs
  - CRUD Scrapes
- Comparisons with CE Monte Carlo Codes
  - MCNP, KENO, Serpent, MC21, etc.



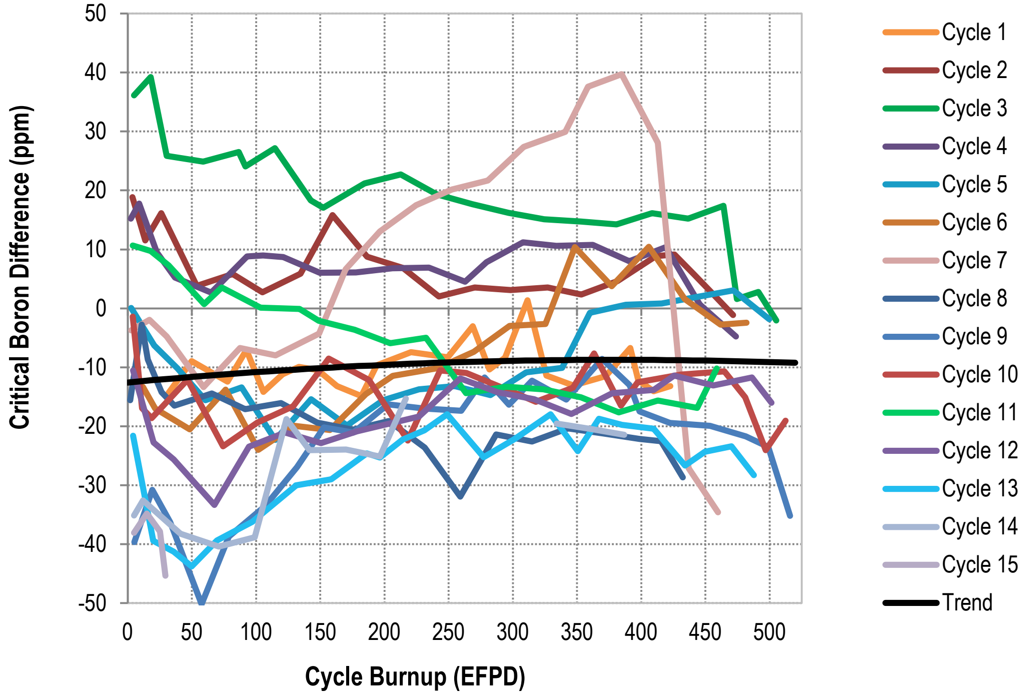
Power Plant Models

	Plants	Cycles	Reactor and Fuel Type
1	AP1000	1-5	W Gen III+ 2-loop 17x17 XL
2	Byron 1	17-21	W 4-loop 17x17
3	Callaway	1-12	W 4-loop 17x17
4	Catawba 1	1-9	W 4-loop 17x17
5	Catawba 2	8-22	W 4-loop 17x17
6	Davis-Besse	12-15	B&W 15x15
7	Farley	23-27	W 3-loop 17x17
8	Haiyang	1	W Gen III+ 2-loop 17x17 XL
9	Krško	1-3,24-28	W 2-loop 16x16
10	NuScale	1-8	SMR
11	Oconee 3	25-30	B&W 15x15
12	Palo Verde 2	1-16	CE System 80 16x16
13	Sanmen	1	W Gen III+ 2-loop 17x17 XL
14	Seabrook	1-5	W 4-loop 17x17
15	Shearon Harris	Surrogate	W 3-loop 17x17
16	South Texas 2	1-8	W 4-loop 17x17 XL
17	TMI	1-10	B&W 15x15
18	V.C. Summer	17-24	W 3-loop 17x17
19	Vogtle 1	7-15	W 4-loop 17x17
20	Watts Bar 1	1-18	W 4-loop 17x17
21	Watts Bar 2	1-2	W 4-loop 17x17

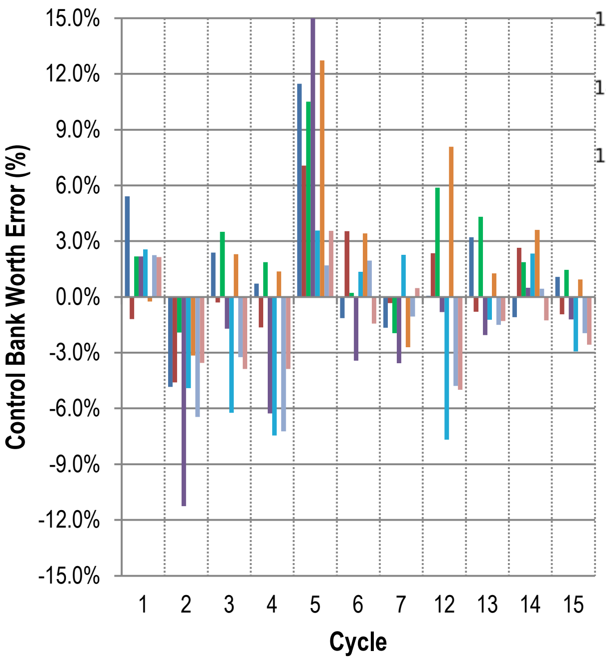
Watts Bar Unit 1 Cycles 1-15 Benchmark

195 in-core flux maps

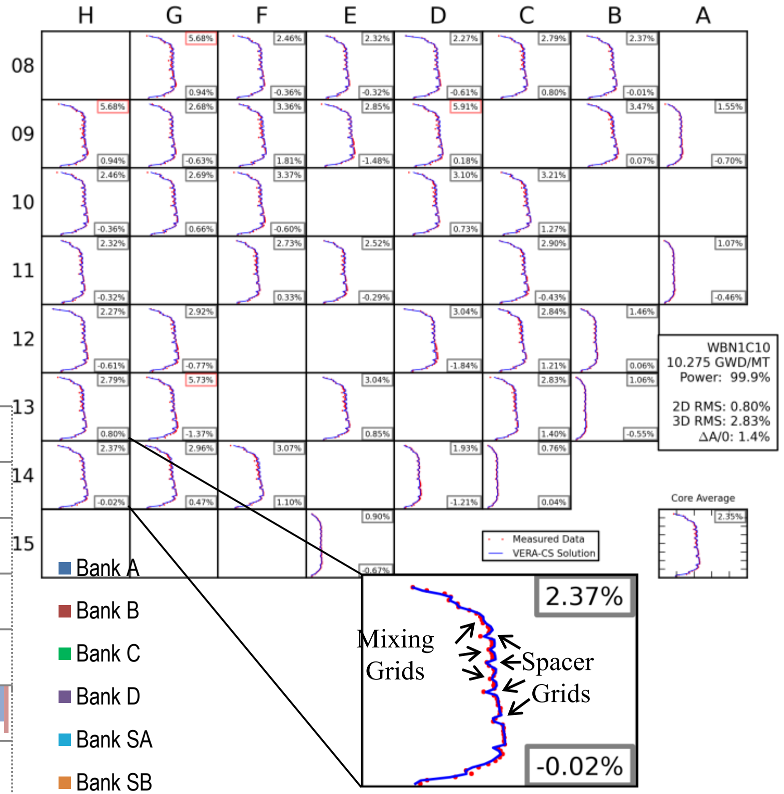
- RCCA bank worths = -0.2 ± 2.0%
- Isothermal temperature coeffs = -1.4 ± 0.7 pcm/F
- Critical boron concentrations = -9 ± 17 ppm
- In-core power distributions = 1.6% radial, 3.4% total, 0.2% AO



critical boron comparisons



bank worths



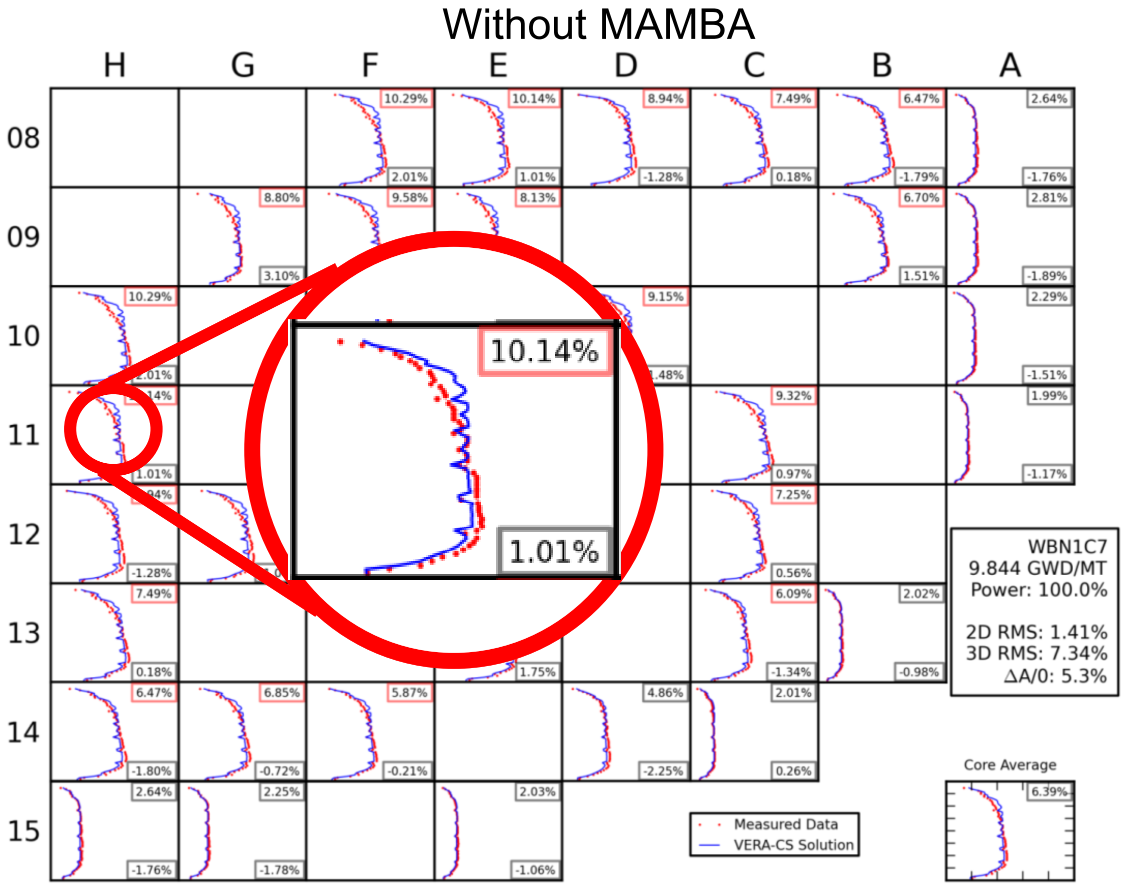
960 processors

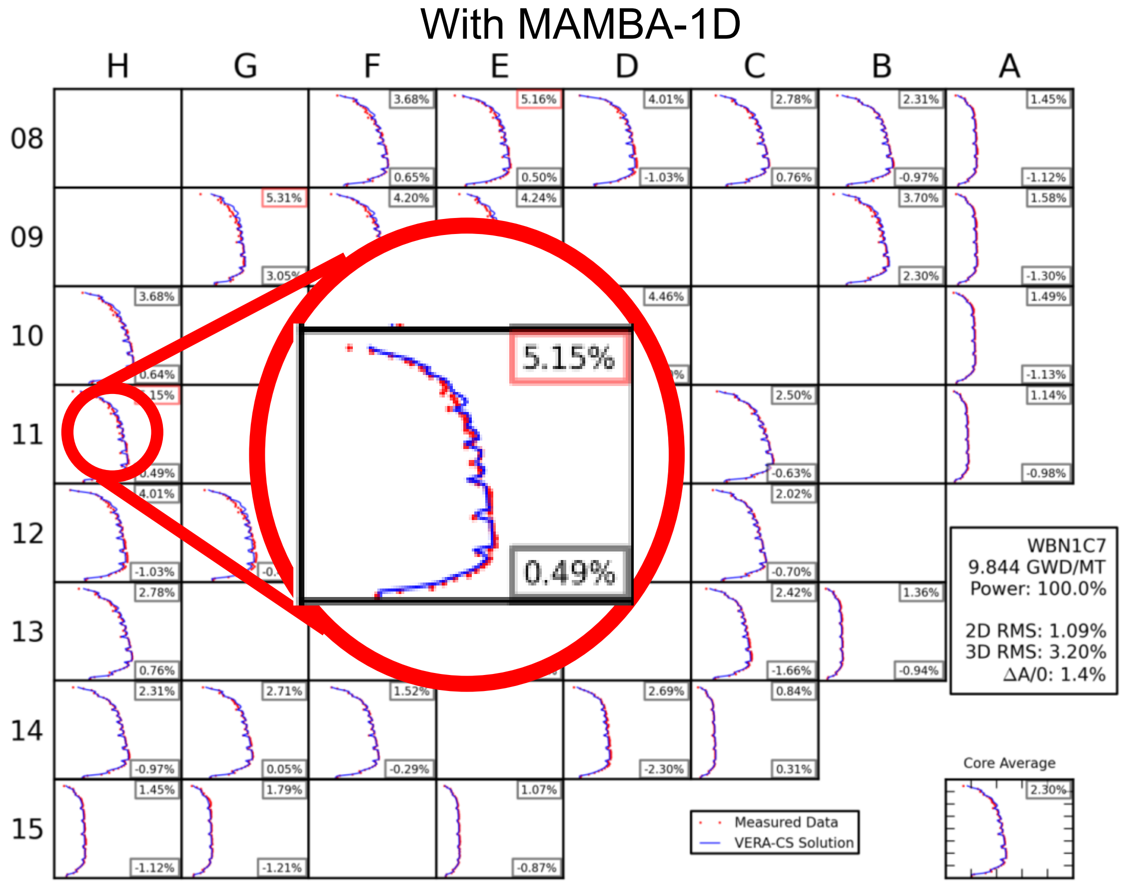
~22 statepoints/cycle

~21 hours per cycle

20,600 core-hours

Watts Bar 1 Cycle 7 - CIPS Calculations

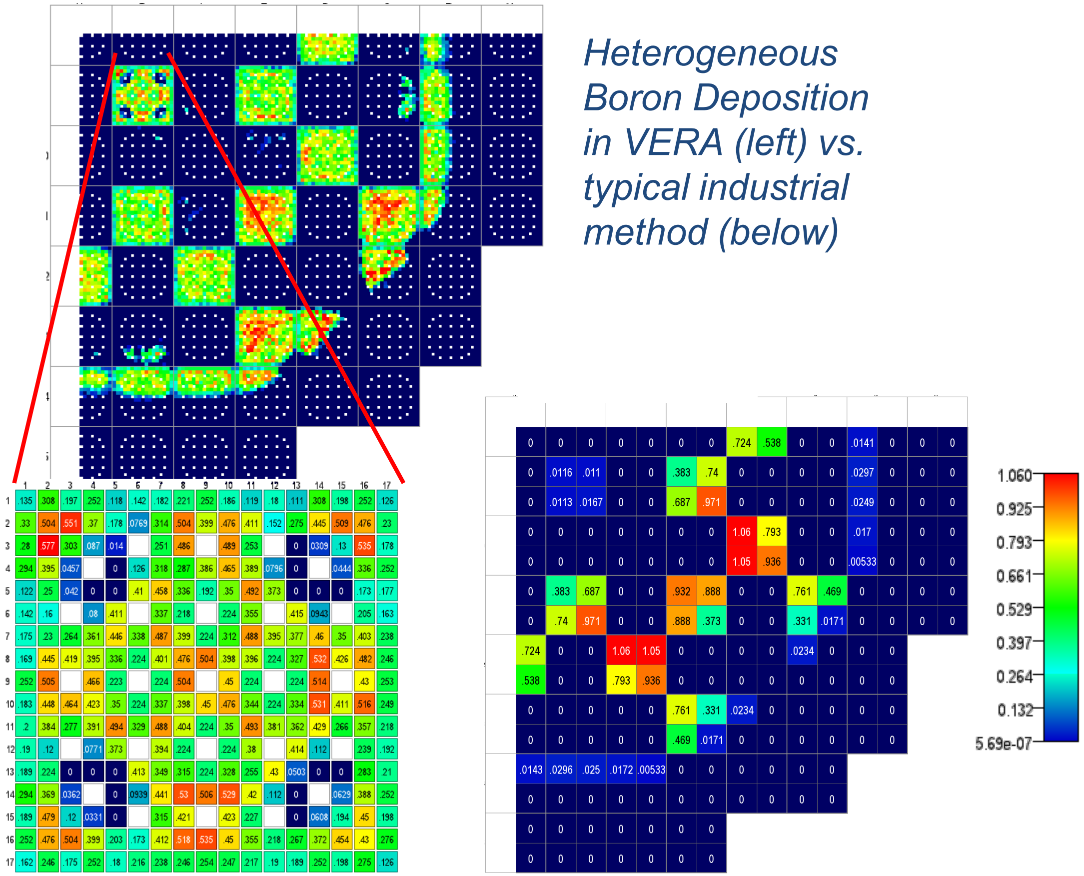




- MAMBA not-predictive at the time but potential benefits are clear
  - ~50% improvement in power distribution comparisons
  - Cycle 7 flux map results are as good as non-CIPS cycles
  - Up to 40% improvement in 1st half of Cycle 8 as well

CIPS Risk Assessment for Catawba 2

- VERA analysis of 3 candidate core designs which had already been screened for CIPS with industrial methods
- Duke selected most conservative design
- VERA results showed increased risk of power shift and loss shutdown margin was likely insignificant
- Most cost effective pattern was:
  - 0.3% difference in axial offset
  - 51 pcm in shutdown margin loss
  - **$250,000 in fuel savings** ($125K-$425K)
- In FY18, performing CILC risk assessment for Oconee 3



Heterogeneous Boron Deposition in VERA (left) vs. typical industrial method (below)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	.135	.308	.197	.252	.118	.142	.182	.221	.252	.186	.119	.18	.111	.308	.198	.252	.126
2	.33	.504	.551	.37	.178	.0769	.314	.504	.399	.476	.411	.152	.275	.445	.509	.476	.23
3	.28	.577	.303	.087	.014		.251	.486		.489	.253		0	.0309	.13	.535	.178
4	.294	.395	.0457		0	.126	.318	.287	.386	.465	.389	.0796	0		.0444	.336	.252
5	.122	.25	.042	0	0	.41	.458	.336	.192	.35	.492	.373	0	0	0	.173	.177
6	.142	.16		.08	.411		.337	.218		.224	.355		.415	.0943		.205	.163
7	.175	.23	.264	.361	.446	.338	.487	.399	.224	.312	.488	.395	.377	.46	.35	.403	.238
8	.169	.445	.419	.395	.336	.224	.401	.476	.504	.398	.396	.224	.327	.532	.426	.482	.246
9	.252	.505		.466	.223		.224	.504		.45	.224		.224	.514		.43	.253
10	.183	.448	.464	.423	.35	.224	.337	.398	.45	.476	.344	.224	.334	.531	.411	.516	.249
11	.2	.384	.277	.391	.494	.329	.488	.404	.224	.35	.493	.381	.362	.429	.266	.357	.218
12	.19	.12		.0771	.373		.394	.224		.224	.38		.414	.112		.239	.192
13	.189	.224	0	0	0	.413	.349	.315	.224	.328	.255	.43	.0503	0	0	.283	.21
14	.294	.369	.0362		0	.0939	.441	.53	.506	.529	.42	.112	0		.0629	.388	.252
15	.189	.479	.12	.0331	0		.315	.421		.423	.227		0	.0608	.194	.45	.198
16	.252	.476	.504	.399	.203	.173	.412	.518	.535	.45	.355	.218	.267	.372	.454	.43	.276
17	.162	.246	.175	.252	.18	.216	.238	.246	.254	.247	.217	.19	.189	.252	.198	.275	.126

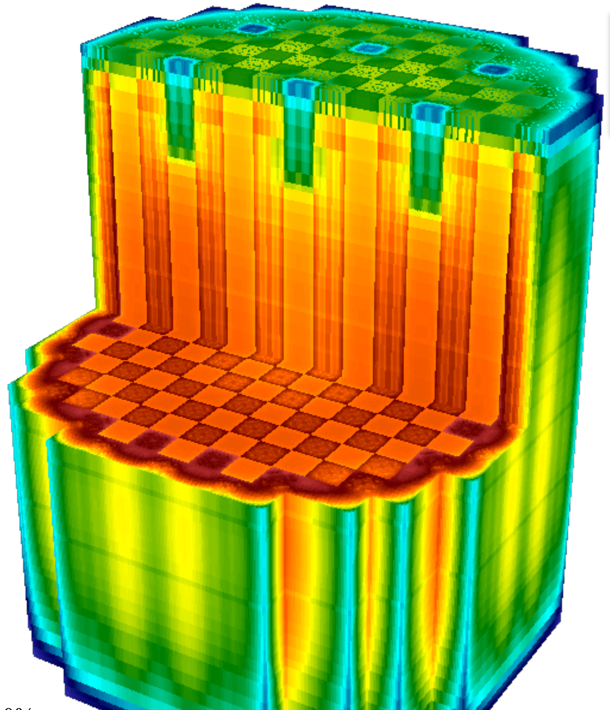
0	0	0	0	0	0	0	.724	.538	0	0	.0141	0	0	0
0	.0116	.011	0	0	.383	.74	0	0	0	0	.0297	0	0	0
0	.0113	.0167	0	0	.687	.971	0	0	0	0	.0249	0	0	0
0	0	0	0	0	0	0	1.06	.793	0	0	.017	0	0	0
0	0	0	0	0	0	0	1.05	.936	0	0	.00533	0	0	0
0	.383	.687	0	0	.932	.888	0	0	.761	.469	0	0	0	0
0	.74	.971	0	0	.888	.373	0	0	.331	.0171	0	0	0	0
.724	0	0	1.06	1.05	0	0	0	0	.0234	0	0	0		
.538	0	0	.793	.936	0	0	0	0	0	0	0	0		
0	0	0	0	0	.761	.331	.0234	0	0	0	0	0		
0	0	0	0	0	.469	.0171	0	0	0	0	0	0		
.0143	.0296	.025	.0172	.00533	0	0	0	0	0	0				
0	0	0	0	0	0	0	0	0	0	0				
0	0	0	0	0	0	0								
0	0	0	0	0	0	0								

"If we would have had this information for cycle 22 we may have chosen differently"

Scott Thomas
Manager Safety Applications
Duke Energy

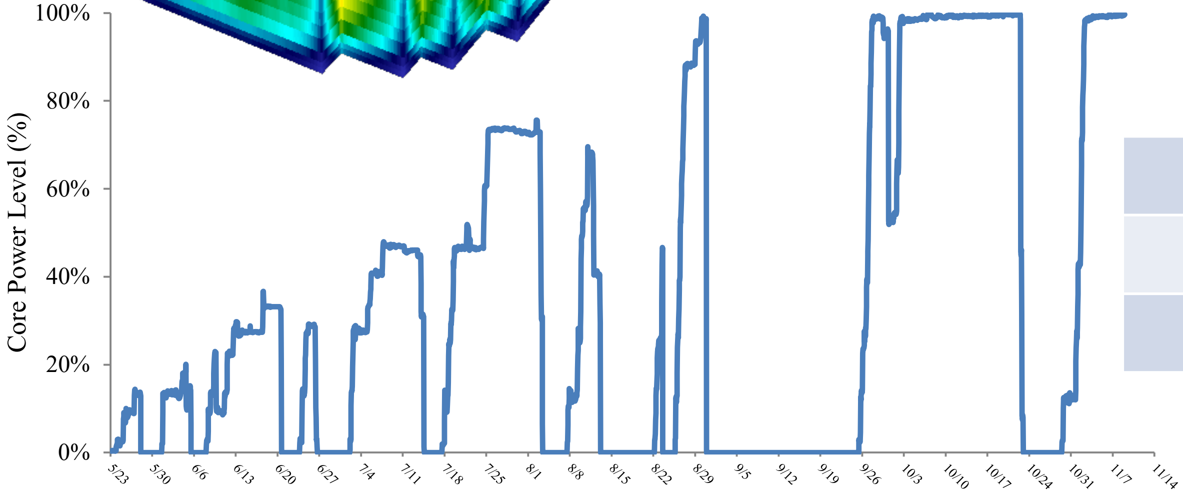
VERA advanced capabilities have potential to reduce the fuel costs of the nuclear industry

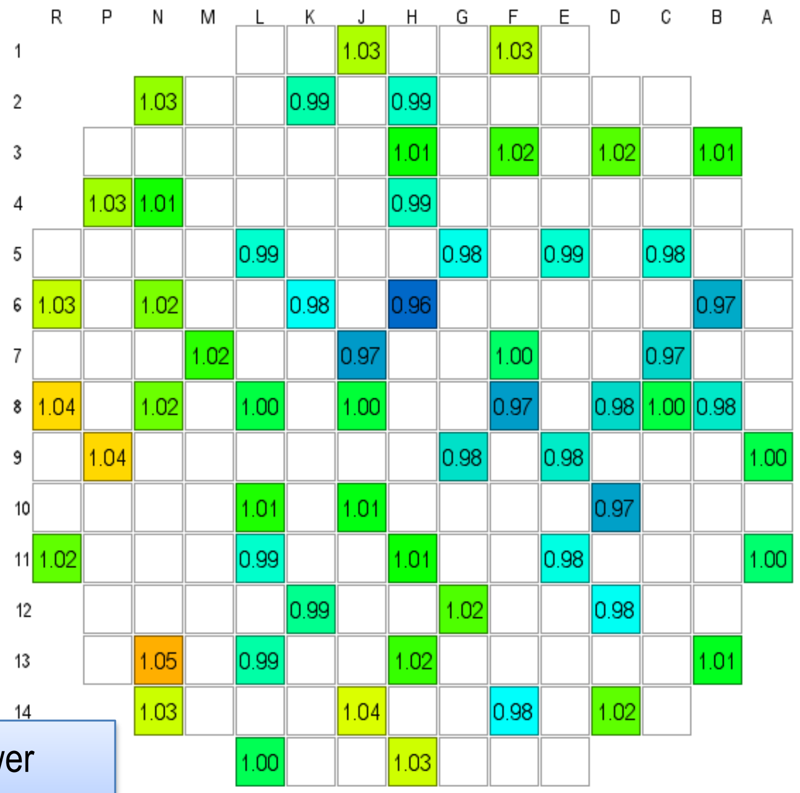
Watts Bar Unit 2 Startup Analysis



Watts Bar 2 transient Xenon-135 distribution at 28% power level

- 4,130 hourly statepoints
- 13.5 days of runtime on 2,784 cores
- 892,837 core-hours
- 16,605 fully-coupled neutronics/TH iterations





	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1							1.03			1.03					
2			1.03			0.99		0.99							
3								1.01		1.02		1.02		1.01	
4		1.03	1.01					0.99							
5					0.99				0.98		0.99		0.98		
6	1.03		1.02			0.98		0.96						0.97	
7				1.02			0.97			1.00			0.97		
8	1.04		1.02		1.00		1.00			0.97		0.98	1.00	0.98	
9		1.04							0.98		0.98				1.00
10					1.01		1.01					0.97			
11	1.02				0.99			1.01			0.98				1.00
12						0.99			1.02			0.98			
13			1.05		0.99			1.02						1.01	
14			1.03				1.04			0.98		1.02			
					1.00			1.03							

xposure 5.856: radial_VERA_detector_current_ratios,

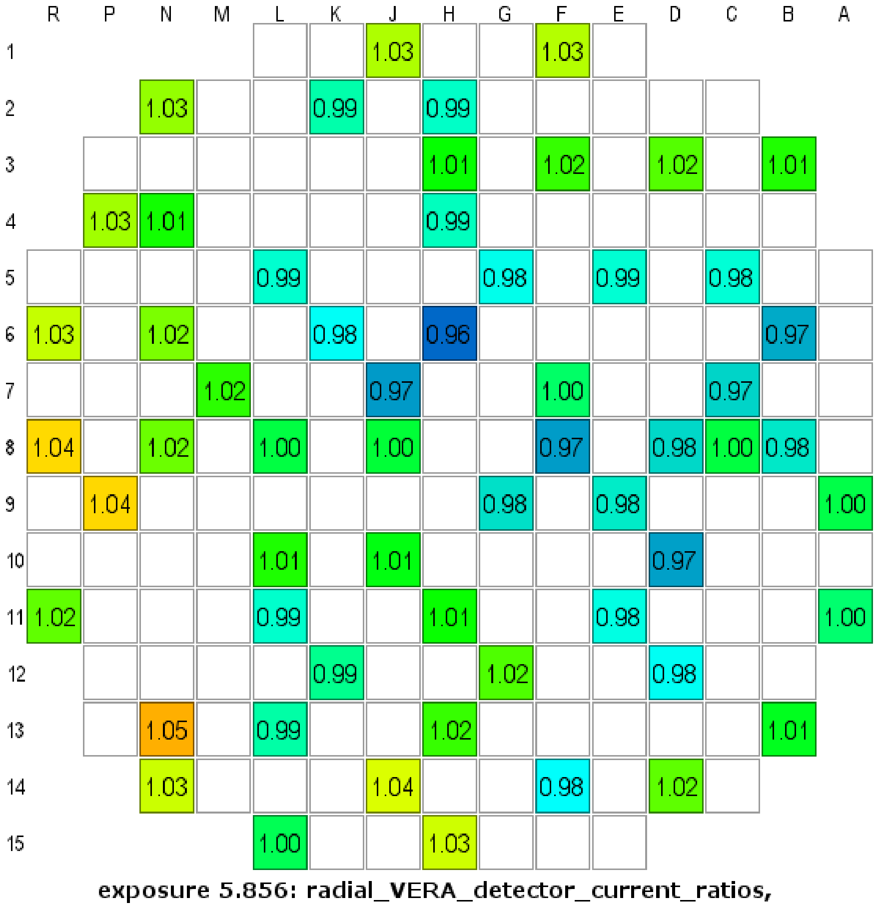
Measured Power Distribution Differences

Vanadium Wire Currents = 0.7 ± 2.4%

Initial Critical Boron Concentration Difference (ppmB)	**-2**
Isothermal Temperature Coefficient Difference (pcm/ºF)	**-0.8**
Average Control Bank Worth Error (%)	**0.7**

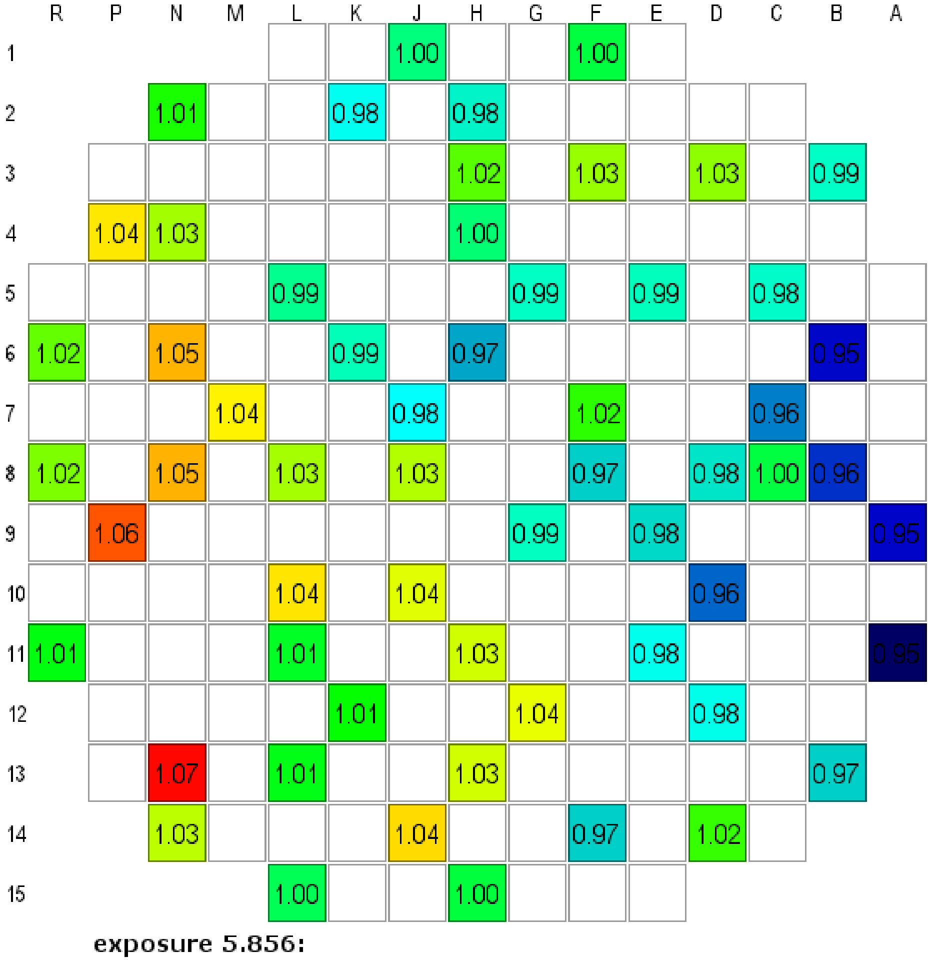
https://www.casl.gov/sites/default/files/docs/CASL-U-2017-1306-000.pdf

WBN2 VERA vs. Online Monitor



	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1							1.03			1.03					
2			1.03			0.99		0.99							
3								1.01		1.02		1.02		1.01	
4		1.03	1.01					0.99							
5					0.99				0.98		0.99		0.98		
6	1.03		1.02			0.98		0.96						0.97	
7				1.02			0.97			1.00			0.97		
8	1.04		1.02		1.00		1.00			0.97		0.98	1.00	0.98	
9		1.04							0.98		0.98				1.00
10					1.01		1.01					0.97			
11	1.02				0.99			1.01			0.98				1.00
12						0.99			1.02			0.98			
13			1.05		0.99			1.02						1.01	
14			1.03				1.04			0.98		1.02			
15					1.00			1.03							

exposure 5.856: radial_VERA_detector_current_ratios,



	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1							1.00			1.00					
2			1.01			0.98		0.98							
3								1.02		1.03		1.03		0.99	
4		1.04	1.03					1.00							
5					0.99				0.99		0.99		0.98		
6	1.02		1.05			0.99		0.97						0.95	
7				1.04			0.98			1.02			0.96		
8	1.02		1.05		1.03		1.03			0.97		0.98	1.00	0.96	
9		1.06							0.99		0.98				0.95
10					1.04		1.04					0.96			
11	1.01				1.01			1.03			0.98				0.95
12						1.01			1.04			0.98			
13			1.07		1.01			1.03						0.97	
14			1.03				1.04			0.97		1.02			
15					1.00			1.00							

exposure 5.856:

VERA

All Wire Currents = 0.7 ± 2.4%

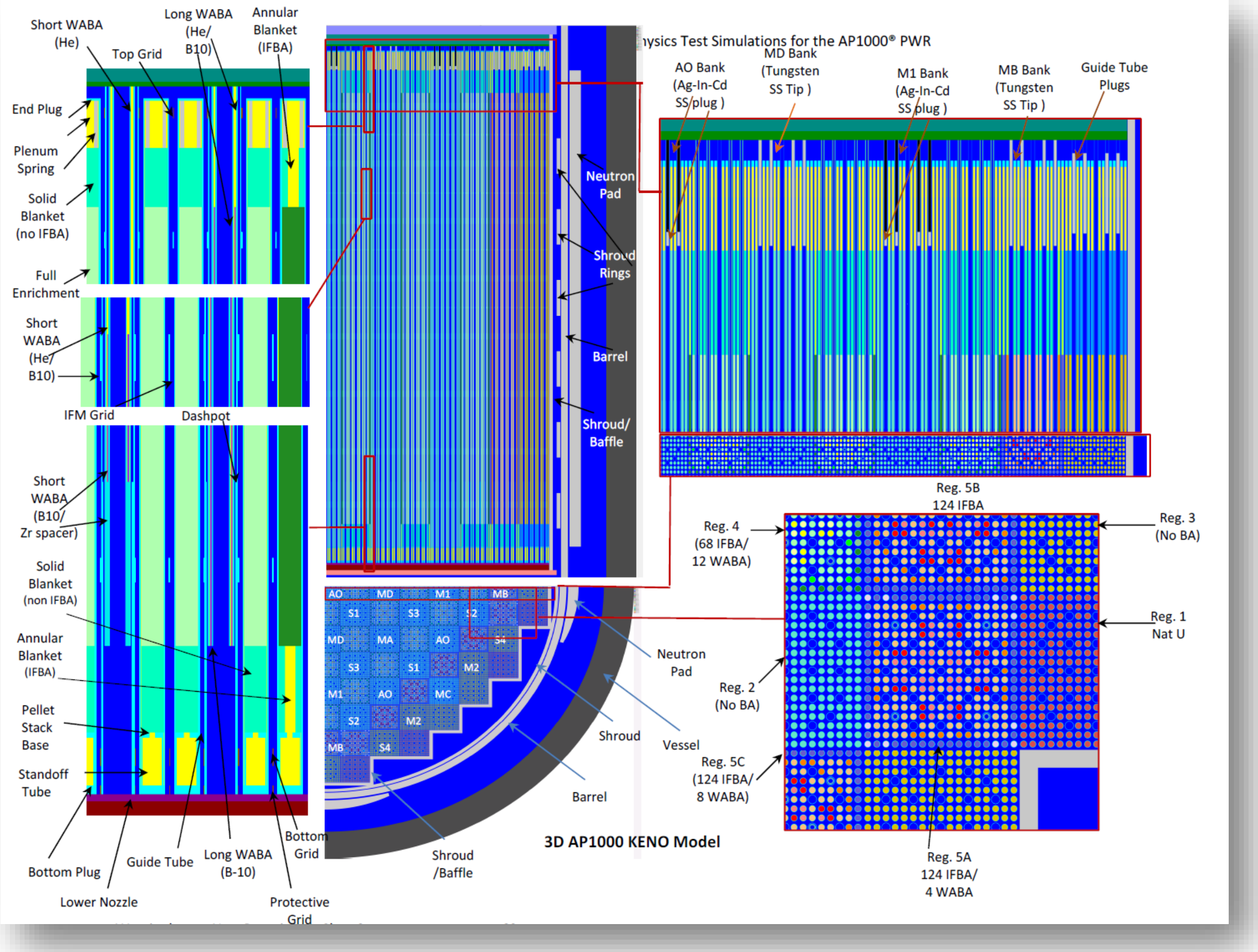
Long Wire Currents = 0.3 ± 2.3%

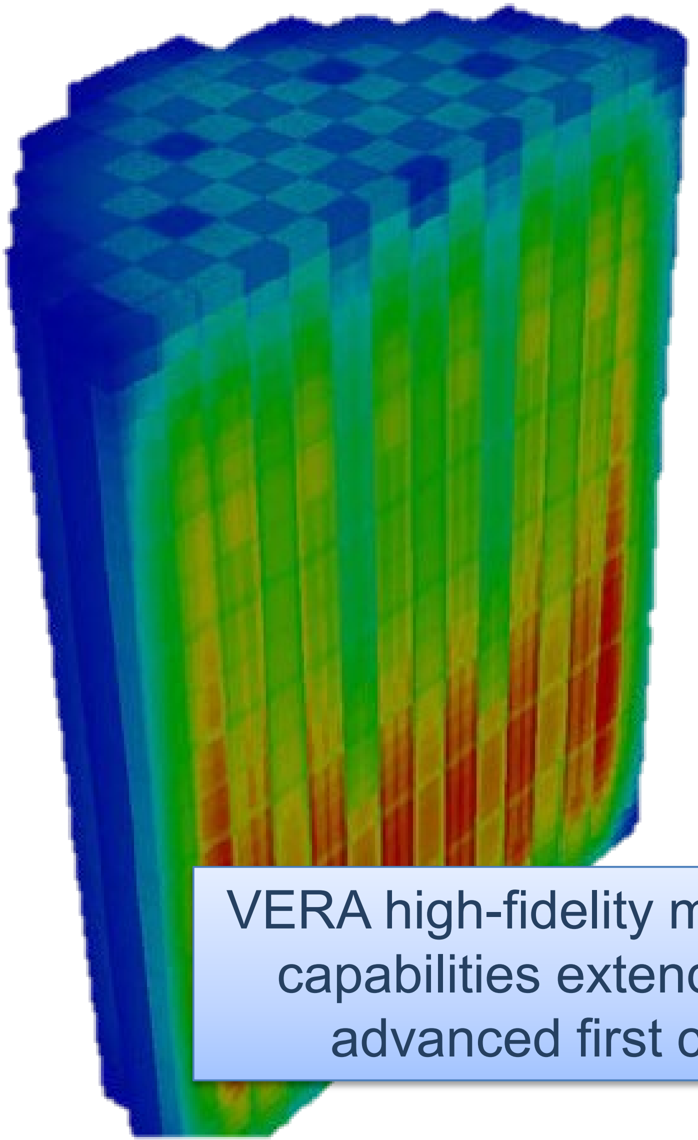
Online Core Monitor

All Wire Currents = -0.1 ± 3.4%

Long Wire Currents = 0.4 ± 3.1%

AP1000® PWR Advanced First Core

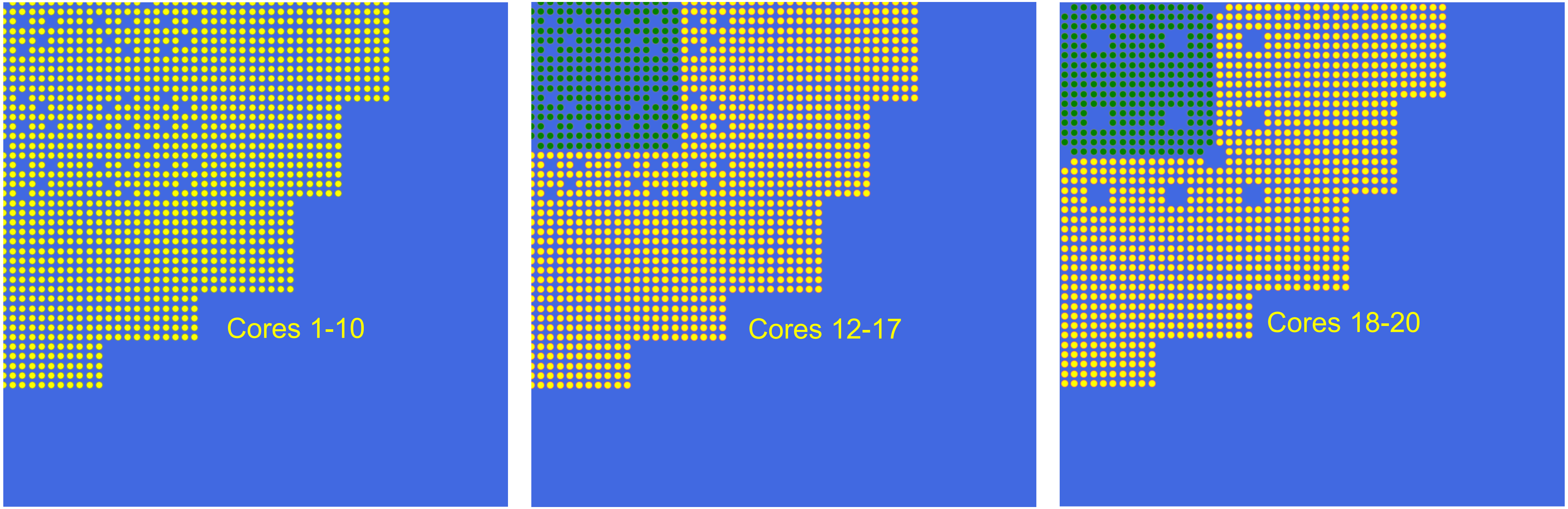




VERA high-fidelity modeling capabilities extended to advanced first core

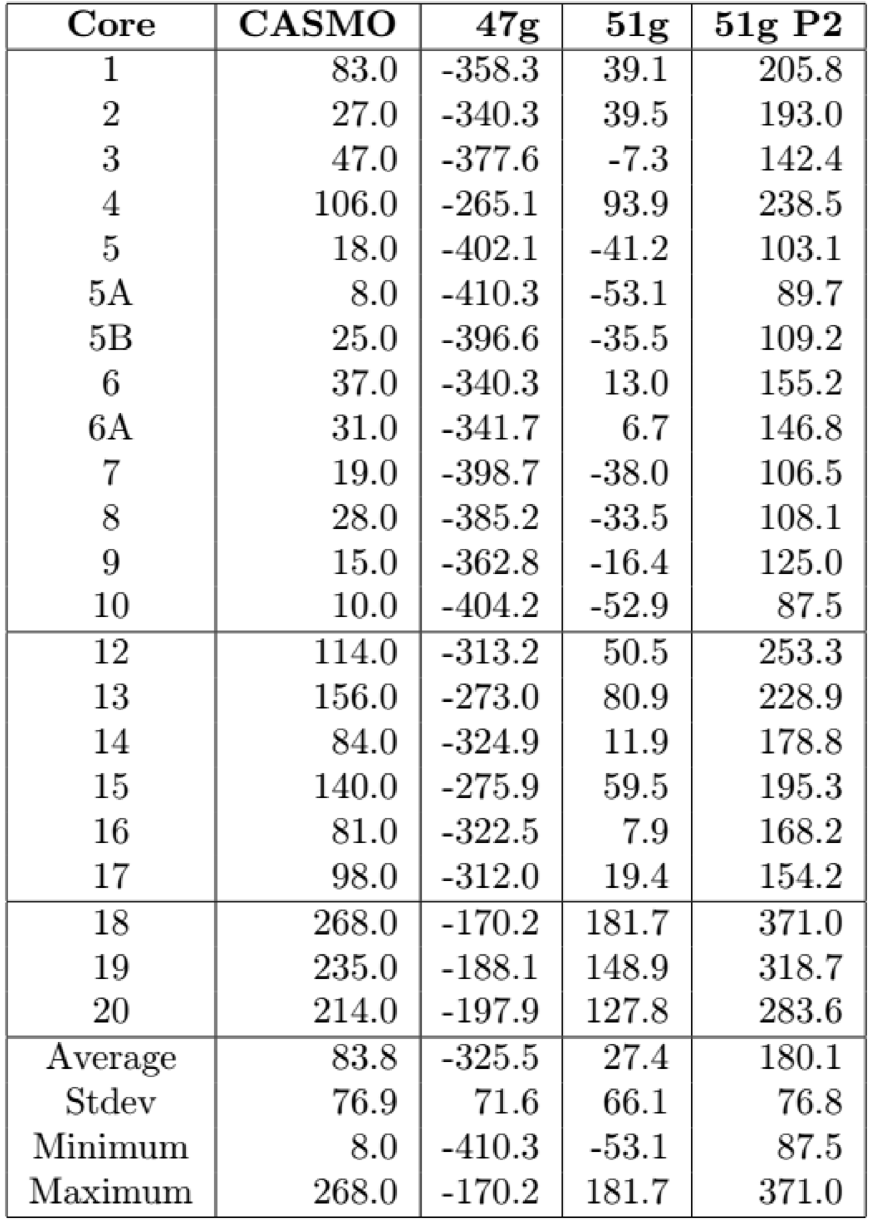
- Extensive applications by Westinghouse to confirm current predictions for the startup of Sanmen and Haiyang Nuclear Plants
- Measurements from these startups will be available later this year

B&W 1810 Critical Experiments



- Critical Experiments Run in early 1980’s
- Main purpose was to test Gadolinia, but also tested other absorbers and two different enrichments
- Limited pin-by-pin measurements

B&W 1810 Results

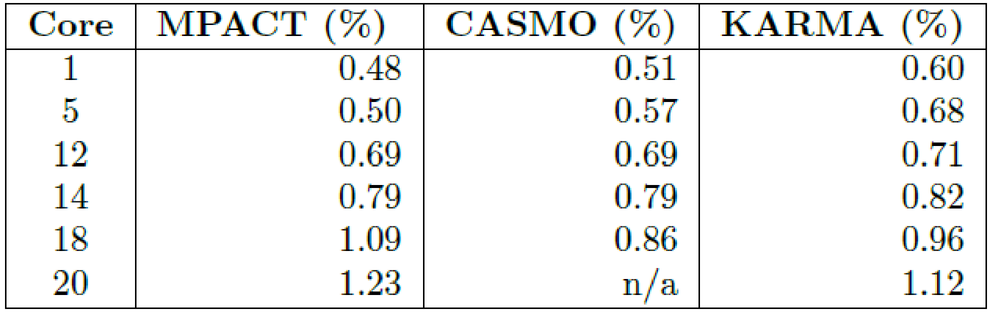


Core	CASMO	47g	51g	51g P2
1	83.0	-358.3	39.1	205.8
2	27.0	-340.3	39.5	193.0
3	47.0	-377.6	-7.3	142.4
4	106.0	-265.1	93.9	238.5
5	18.0	-402.1	-41.2	103.1
5A	8.0	-410.3	-53.1	89.7
5B	25.0	-396.6	-35.5	109.2
6	37.0	-340.3	13.0	155.2
6A	31.0	-341.7	6.7	146.8
7	19.0	-398.7	-38.0	106.5
8	28.0	-385.2	-33.5	108.1
9	15.0	-362.8	-16.4	125.0
10	10.0	-404.2	-52.9	87.5
12	114.0	-313.2	50.5	253.3
13	156.0	-273.0	80.9	228.9
14	84.0	-324.9	11.9	178.8
15	140.0	-275.9	59.5	195.3
16	81.0	-322.5	7.9	168.2
17	98.0	-312.0	19.4	154.2
18	268.0	-170.2	181.7	371.0
19	235.0	-188.1	148.9	318.7
20	214.0	-197.9	127.8	283.6
Average	83.8	-325.5	27.4	180.1
Stdev	76.9	71.6	66.1	76.8
Minimum	8.0	-410.3	-53.1	87.5
Maximum	268.0	-170.2	181.7	371.0

$$\Delta k = (k_{\text{eff}} - 1) \times 10^5 \text{ pcm}$$

- Very good agreement
- Compare well to industry standard codes
- Within +/- 200 pcm target

Pin Power RMS (%)



Core	MPACT (%)	CASMO (%)	KARMA (%)
1	0.48	0.51	0.60
5	0.50	0.57	0.68
12	0.69	0.69	0.71
14	0.79	0.79	0.82
18	1.09	0.86	0.96
20	1.23	n/a	1.12

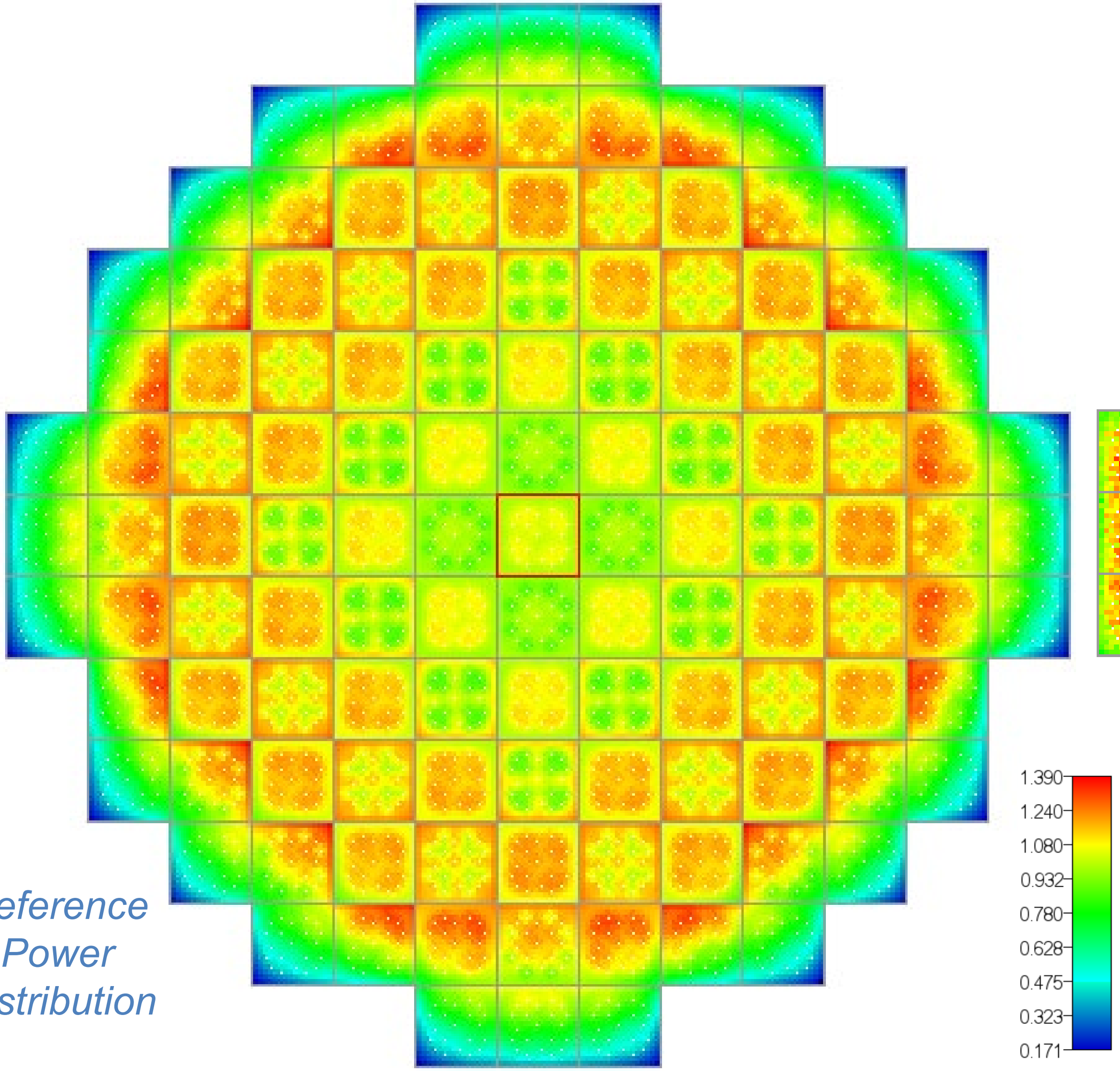
Krško Radial Core Power Distribution

Δk = 15 pcm

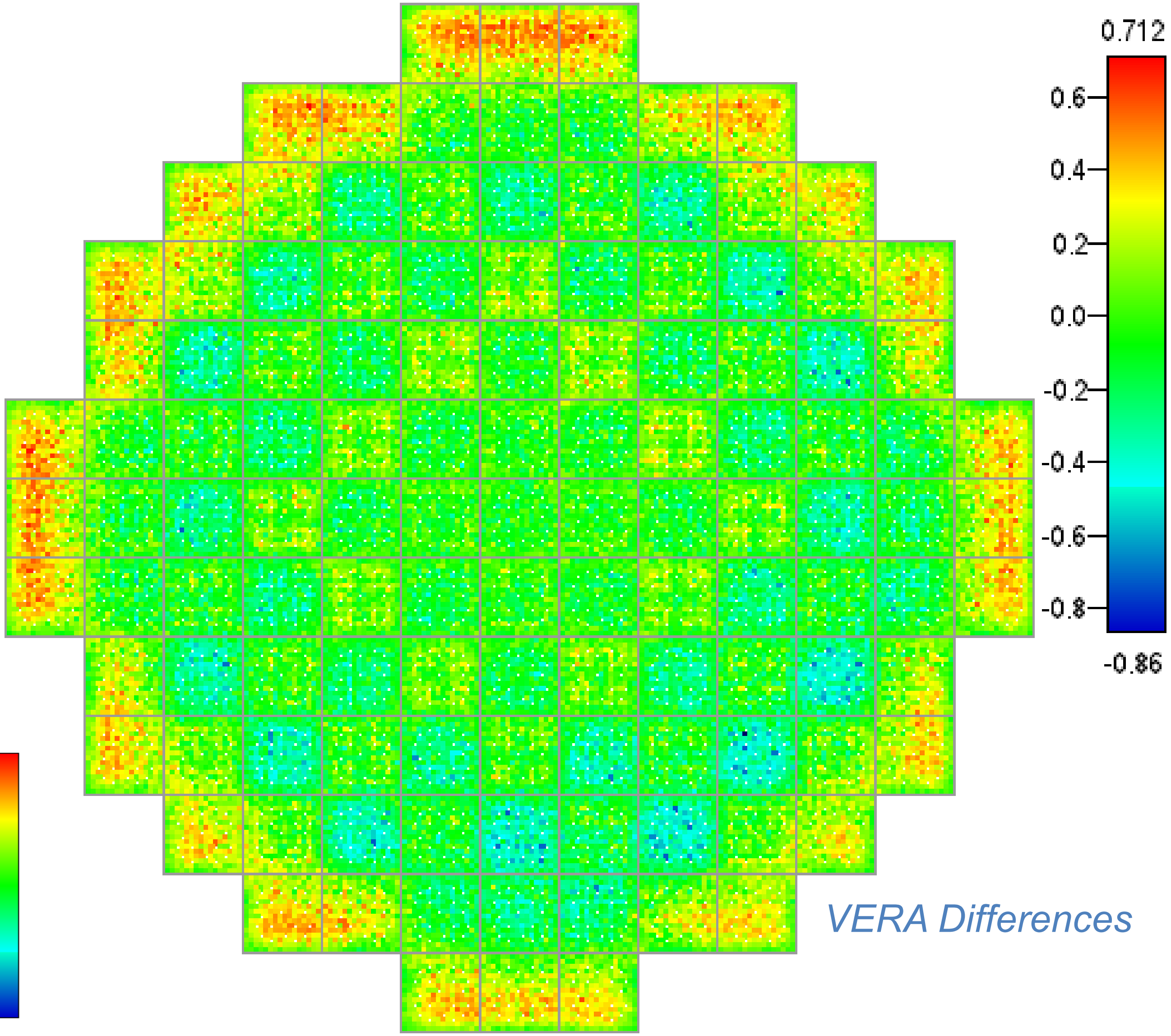
RMS = 0.22%

Max = -0.86%

2D Core Comparison of VERA to CE Monte Carlo results at BOC HZP

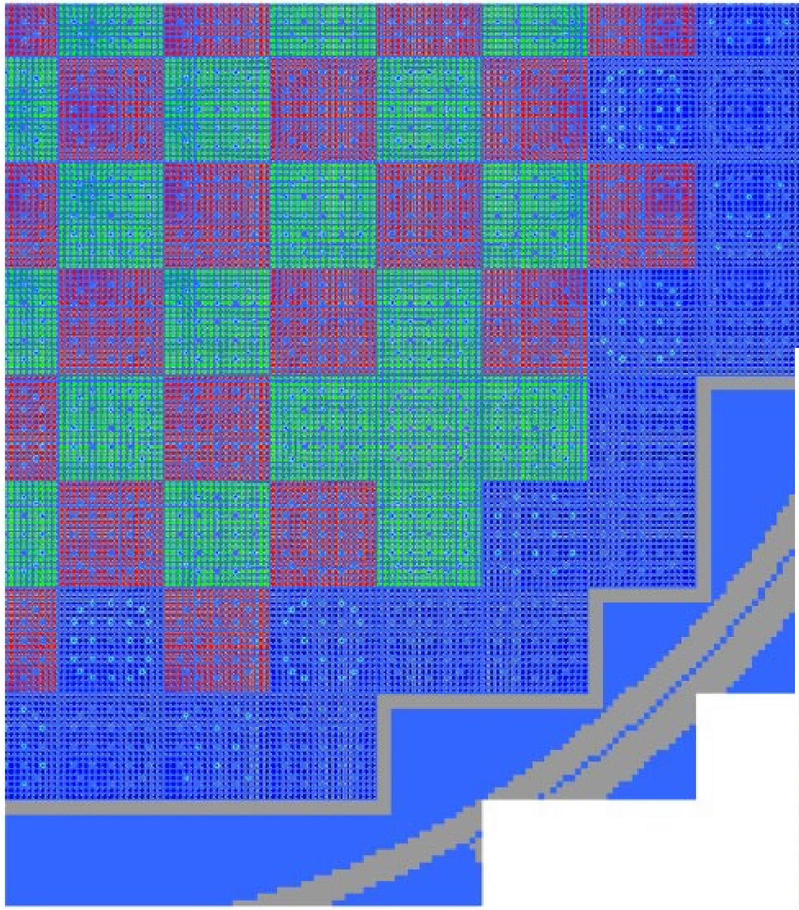


Reference Power Distribution

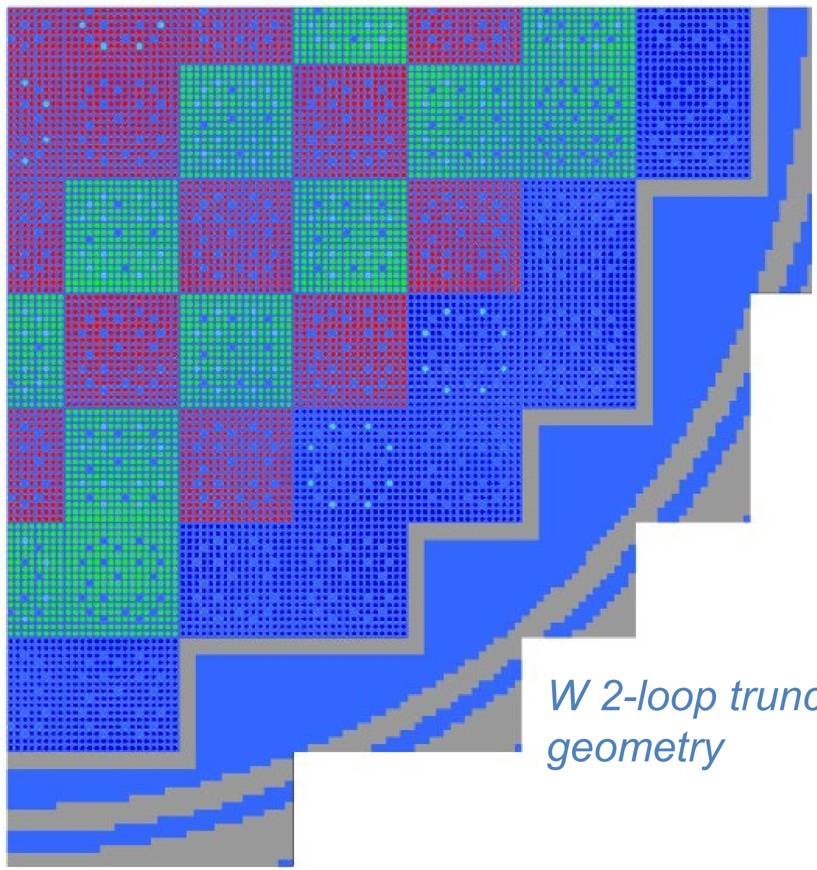


VERA Differences

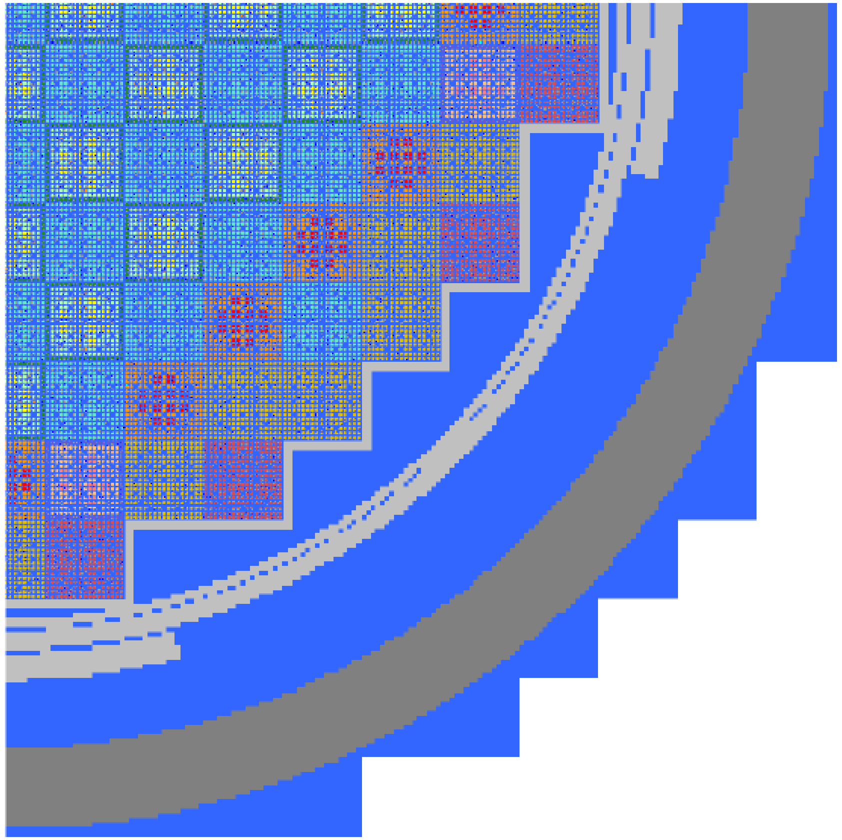
Radial Reflector Modeling



W 4-loop truncated geometry



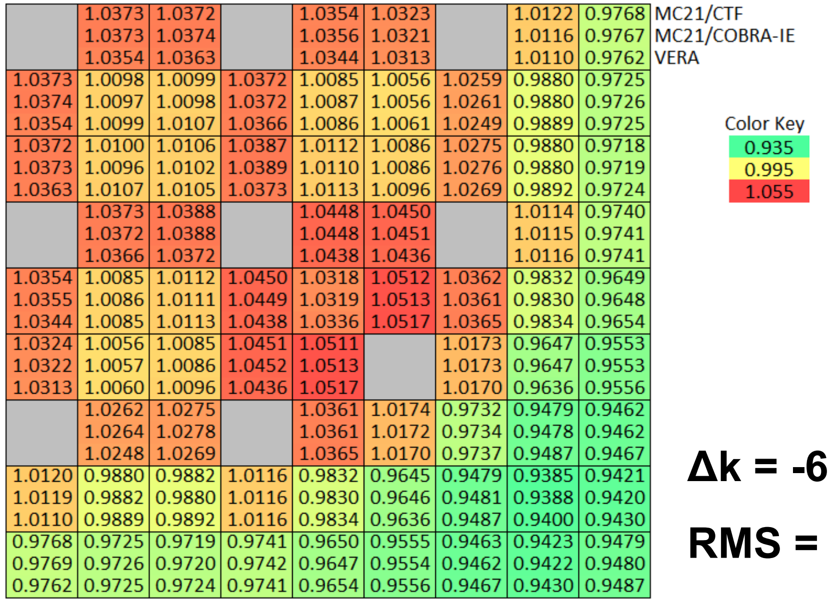
W 2-loop truncated geometry



AP1000 full geometry

NNL Benchmark against MC21

- Single assembly at BOC HFP (Problem 6)
- Reference solution is KAPL's MC21 coupled with COBRA-IE and COBRA-TF



	1.0373 1.0373 1.0354	1.0372 1.0374 1.0363		1.0354 1.0356 1.0344	1.0323 1.0321 1.0313		1.0122 1.0116 1.0110	0.9768 0.9767 0.9762	MC21/CTF MC21/COBRA-IE VERA
1.0373 1.0374 1.0354	1.0098 1.0097 1.0099	1.0099 1.0098 1.0107	1.0372 1.0372 1.0366	1.0085 1.0087 1.0086	1.0056 1.0056 1.0061	1.0259 1.0261 1.0249	0.9880 0.9880 0.9889	0.9725 0.9726 0.9725	
1.0372 1.0373 1.0363	1.0100 1.0096 1.0107	1.0106 1.0102 1.0105	1.0387 1.0389 1.0373	1.0112 1.0110 1.0113	1.0086 1.0086 1.0096	1.0275 1.0276 1.0269	0.9880 0.9880 0.9892	0.9718 0.9719 0.9724	
	1.0373 1.0372 1.0366	1.0388 1.0388 1.0372		1.0448 1.0448 1.0438	1.0450 1.0451 1.0436		1.0114 1.0115 1.0116	0.9740 0.9741 0.9741	
1.0354 1.0355 1.0344	1.0085 1.0086 1.0085	1.0112 1.0111 1.0113	1.0450 1.0449 1.0438	1.0318 1.0319 1.0336	1.0512 1.0513 1.0517	1.0362 1.0361 1.0365	0.9832 0.9830 0.9834	0.9649 0.9648 0.9654	
1.0324 1.0322 1.0313	1.0056 1.0057 1.0060	1.0085 1.0086 1.0096	1.0451 1.0452 1.0436	1.0511 1.0513 1.0517		1.0173 1.0173 1.0170	0.9647 0.9647 0.9636	0.9553 0.9553 0.9556	
	1.0262 1.0264 1.0248	1.0275 1.0278 1.0269		1.0361 1.0361 1.0365	1.0174 1.0172 1.0170	0.9732 0.9734 0.9737	0.9479 0.9478 0.9487	0.9462 0.9462 0.9467	
1.0120 1.0119 1.0110	0.9880 0.9882 0.9889	0.9882 0.9880 0.9892	1.0116 1.0116 1.0116	0.9832 0.9830 0.9834	0.9645 0.9646 0.9636	0.9479 0.9481 0.9487	0.9385 0.9388 0.9400	0.9421 0.9420 0.9430	
0.9768 0.9769 0.9762	0.9725 0.9726 0.9725	0.9719 0.9720 0.9724	0.9741 0.9742 0.9741	0.9650 0.9647 0.9654	0.9555 0.9554 0.9556	0.9463 0.9462 0.9467	0.9423 0.9422 0.9430	0.9479 0.9480 0.9487	

Color Key

🟩 0.935

🟨 0.995

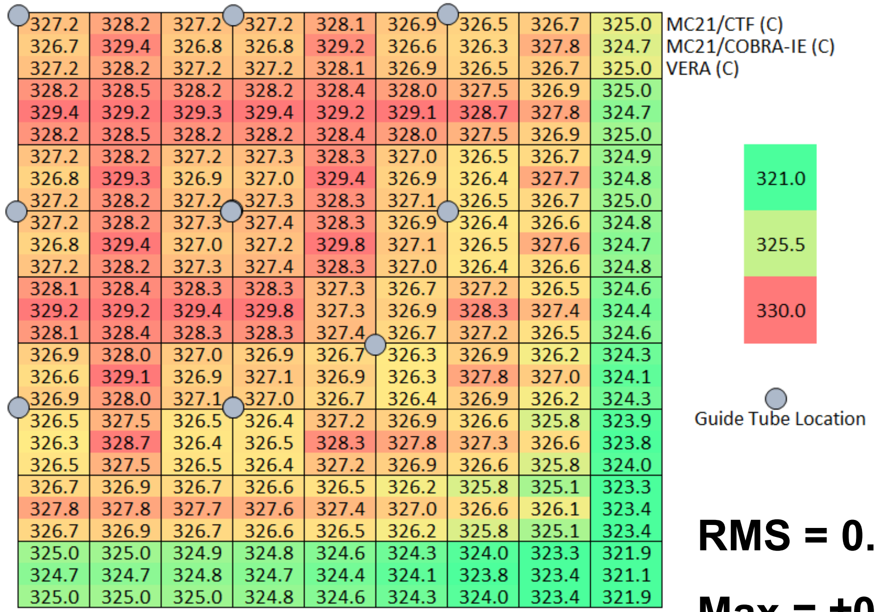
🟥 1.055

Radial Pin Powers

Δk = -63 pcm

RMS = 0.09%

Max = -0.19%



327.2 326.7 327.2	328.2 329.4 328.2	327.2 326.8 327.2	327.2 326.8 327.2	328.1 329.2 328.1	326.9 326.6 326.9	326.5 326.3 326.5	326.7 327.8 326.7	325.0 324.7 325.0	MC21/CTF (C) MC21/COBRA-IE (C) VERA (C)
328.2 329.4 328.2	328.5 329.2 328.5	328.2 329.3 328.2	328.2 329.4 328.2	328.4 329.2 328.4	328.0 329.1 328.0	327.5 328.7 327.5	326.9 327.8 326.9	325.0 324.7 325.0	
327.2 326.8 327.2	328.2 329.3 328.2	327.2 326.9 327.2	327.3 327.0 327.3	328.3 329.4 328.3	327.0 326.9 327.1	326.5 326.4 326.5	326.7 327.7 326.7	324.9 324.8 325.0	
327.2 326.8 327.2	328.2 329.4 328.2	327.3 327.0 327.3	327.4 327.2 327.4	328.3 329.8 328.3	326.9 327.1 327.0	326.4 326.5 326.4	326.6 327.6 326.6	324.8 324.7 324.8	
328.1 329.2 328.1	328.4 329.2 328.4	328.3 329.4 328.3	328.3 329.8 328.3	327.3 327.3 327.4	326.7 326.9 326.7	327.2 328.3 327.2	326.5 327.4 326.5	324.6 324.4 324.6	
326.9 326.6 326.9	328.0 329.1 328.0	327.0 326.9 327.1	326.9 327.1 327.0	326.7 326.9 326.7	326.3 326.3 326.4	326.9 327.8 326.9	326.2 327.0 326.2	324.3 324.1 324.3	
326.5 326.3 326.5	327.5 328.7 327.5	326.5 326.4 326.5	326.4 326.5 326.4	327.2 328.3 327.2	326.9 327.8 326.9	326.6 327.3 326.6	325.8 326.6 325.8	323.9 323.8 324.0	
326.7 327.8 326.7	326.9 327.8 326.9	326.7 327.7 326.7	326.6 327.6 326.6	326.5 327.4 326.5	326.2 327.0 326.2	325.8 326.6 325.8	325.1 326.1 325.1	323.3 323.4 323.4	
325.0 324.7 325.0	325.0 324.7 325.0	324.9 324.8 325.0	324.8 324.7 324.8	324.6 324.4 324.6	324.3 324.1 324.3	324.0 323.8 324.0	323.3 323.4 323.4	321.9 321.1 321.9	

🟩 321.0

🟩 325.5

🟥 330.0

● Guide Tube Location

Exit Coolant Temperatures

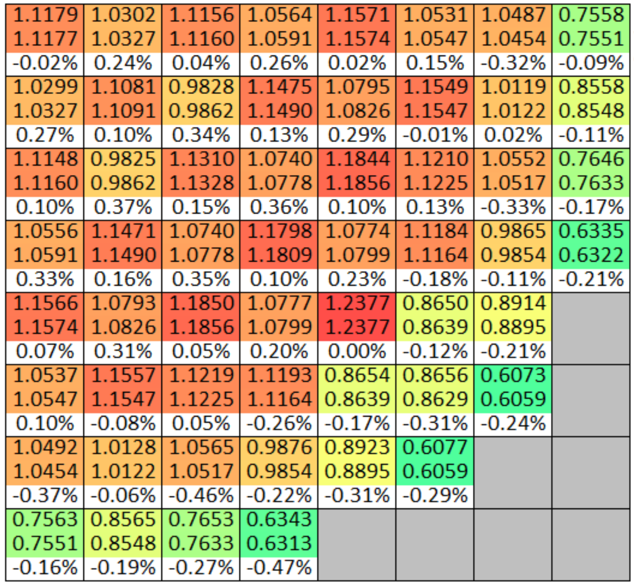
RMS = 0.02 ° C

Max = ±0.1 °C

D. KELLY III, et al., "MC21 / CTF and VERA Multiphysics Solutions to VERA Core Physics Benchmark Progression Problems 6 and 7," Proc. M&C 2017 - International Conference on Mathematics & Computational Methods Applied to Nuclear Science & Engineering, Jeju, Korea, April 16-20, 2017, on USB (2017)

NNL HFP Quarter Core Benchmark

- BOC HFP with eq. Xenon and boron search (Problem 7)
- Reference solution is KAPL’s MC21 coupled with CTF

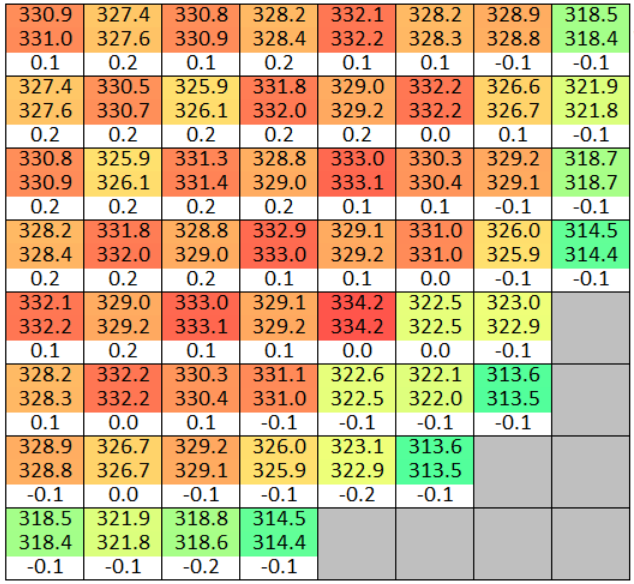


1.1179 1.1177 -0.02%	1.0302 1.0327 0.24%	1.1156 1.1160 0.04%	1.0564 1.0591 0.26%	1.1571 1.1574 0.02%	1.0531 1.0547 0.15%	1.0487 1.0454 -0.32%	0.7558 0.7551 -0.09%
1.0299 1.0327 0.27%	1.1081 1.1091 0.10%	0.9828 0.9862 0.34%	1.1475 1.1490 0.13%	1.0795 1.0826 0.29%	1.1549 1.1547 -0.01%	1.0119 1.0122 0.02%	0.8558 0.8548 -0.11%
1.1148 1.1160 0.10%	0.9825 0.9862 0.37%	1.1310 1.1328 0.15%	1.0740 1.0778 0.36%	1.1844 1.1856 0.10%	1.1210 1.1225 0.13%	1.0552 1.0517 -0.33%	0.7646 0.7633 -0.17%
1.0556 1.0591 0.33%	1.1471 1.1490 0.16%	1.0740 1.0778 0.35%	1.1798 1.1809 0.10%	1.0774 1.0799 0.23%	1.1184 1.1164 -0.18%	0.9865 0.9854 -0.11%	0.6335 0.6322 -0.21%
1.1566 1.1574 0.07%	1.0793 1.0826 0.31%	1.1850 1.1856 0.05%	1.0777 1.0799 0.20%	1.2377 1.2377 0.00%	0.8650 0.8639 -0.12%	0.8914 0.8895 -0.21%	
1.0537 1.0547 0.10%	1.1557 1.1547 -0.08%	1.1219 1.1225 0.05%	1.1193 1.1164 -0.26%	0.8654 0.8639 -0.17%	0.8656 0.8629 -0.31%	0.6073 0.6059 -0.24%	
1.0492 1.0454 -0.37%	1.0128 1.0122 -0.06%	1.0565 1.0517 -0.46%	0.9876 0.9854 -0.22%	0.8923 0.8895 -0.31%	0.6077 0.6059 -0.29%		
0.7563 0.7551 -0.16%	0.8565 0.8548 -0.19%	0.7653 0.7633 -0.27%	0.6343 0.6313 -0.47%				

MC21/CTF
VERA
% diff (VERA vs. MC21/CTF)

Color Key
🟩 0.600
🟨 0.900
🟥 1.250

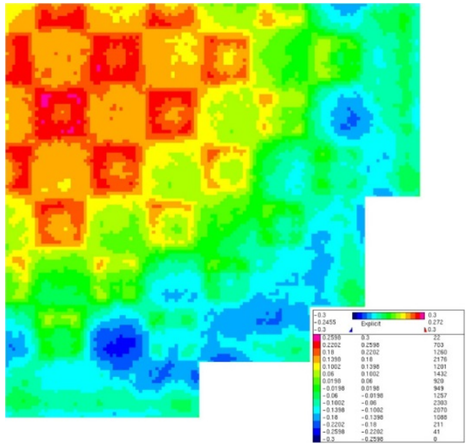
Radial Assembly Powers



330.9 331.0 0.1	327.4 327.6 0.2	330.8 330.9 0.1	328.2 328.4 0.2	332.1 332.2 0.1	328.2 328.3 0.1	328.9 328.8 -0.1	318.5 318.4 -0.1
327.4 327.6 0.2	330.5 330.7 0.2	325.9 326.1 0.2	331.8 332.0 0.2	329.0 329.2 0.2	332.2 332.2 0.0	326.6 326.7 0.1	321.9 321.8 -0.1
330.8 330.9 0.2	325.9 326.1 0.2	331.3 331.4 0.2	328.8 329.0 0.2	333.0 333.1 0.1	330.3 330.4 0.1	329.2 329.1 -0.1	318.7 318.7 -0.1
328.2 328.4 0.2	331.8 332.0 0.2	328.8 329.0 0.2	332.9 333.0 0.1	329.1 329.2 0.1	331.0 331.0 0.0	326.0 325.9 -0.1	314.5 314.4 -0.1
332.1 332.2 0.1	329.0 329.2 0.2	333.0 333.1 0.1	329.1 329.2 0.1	334.2 334.2 0.0	322.5 322.5 0.0	323.0 322.9 -0.1	
328.2 328.3 0.1	332.2 332.2 0.0	330.3 330.4 0.1	331.1 331.0 -0.1	322.6 322.5 -0.1	322.1 322.0 -0.1	313.6 313.5 -0.1	
328.9 328.8 -0.1	326.7 326.7 0.0	329.2 329.1 -0.1	326.0 325.9 -0.1	323.1 322.9 -0.2	313.6 313.5 -0.1		
318.5 318.4 -0.1	321.9 321.8 -0.1	318.8 318.6 -0.2	314.5 314.4 -0.1				

MC21/CTF (C)
VERA (C)
Difference (C): VERA - MC21/CTF

Color Key
🟩 313.00
🟨 324.00
🟥 335.00



Exit Coolant Temperatures

Δk = <1 ppmB

RMS = 0.22%

Max = -0.47%

ΔAO = 0.03%

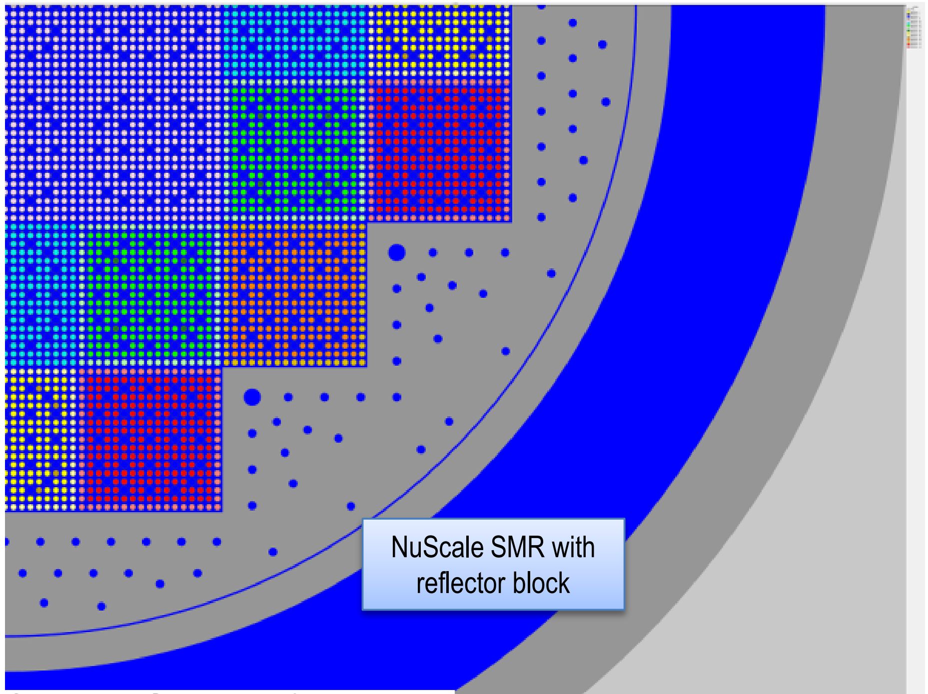
RMS = 0.13 °C

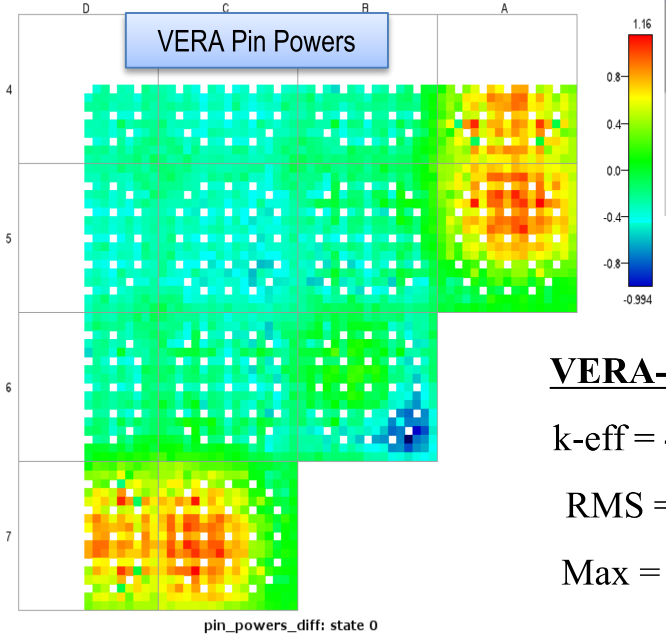
Max = ±0.2 °C

D. KELLY III, et al., “MC21 / CTF and VERA Multiphysics Solutions to VERA Core Physics Benchmark Progression Problems 6 and 7,” Proc. M&C 2017 - International Conference on Mathematics & Computational Methods Applied to Nuclear Science & Engineering, Jeju, Korea, April 16-20, 2017, on USB (2017)

NuScale Test Stand

- NuScale Test Stand completed first phase
  - 8 fuel cycles simulated with VERA
  - Comparisons to licensed industry methods
  - Validation of effects of steel reflector block
  - In-house build of VERA completed in Corvallis
  - VERA training completed in June 2018
- Initial MAMBA-1D application successful in demonstrating multi-physics feedback effects on CRUD generation and boron deposition
- Proprietary report completed and public version available soon


NuScale SMR with reflector block


VERA Pin Powers

pin_powers_diff: state 0

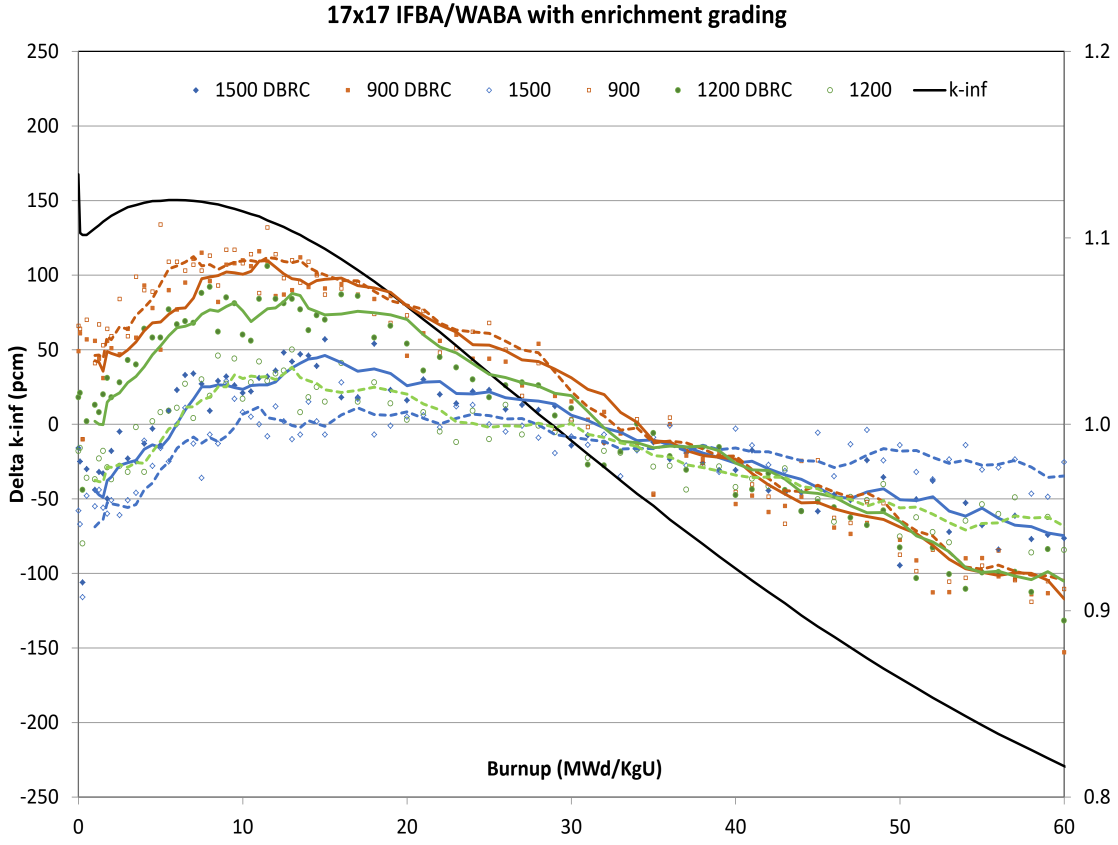
VERA-KENO

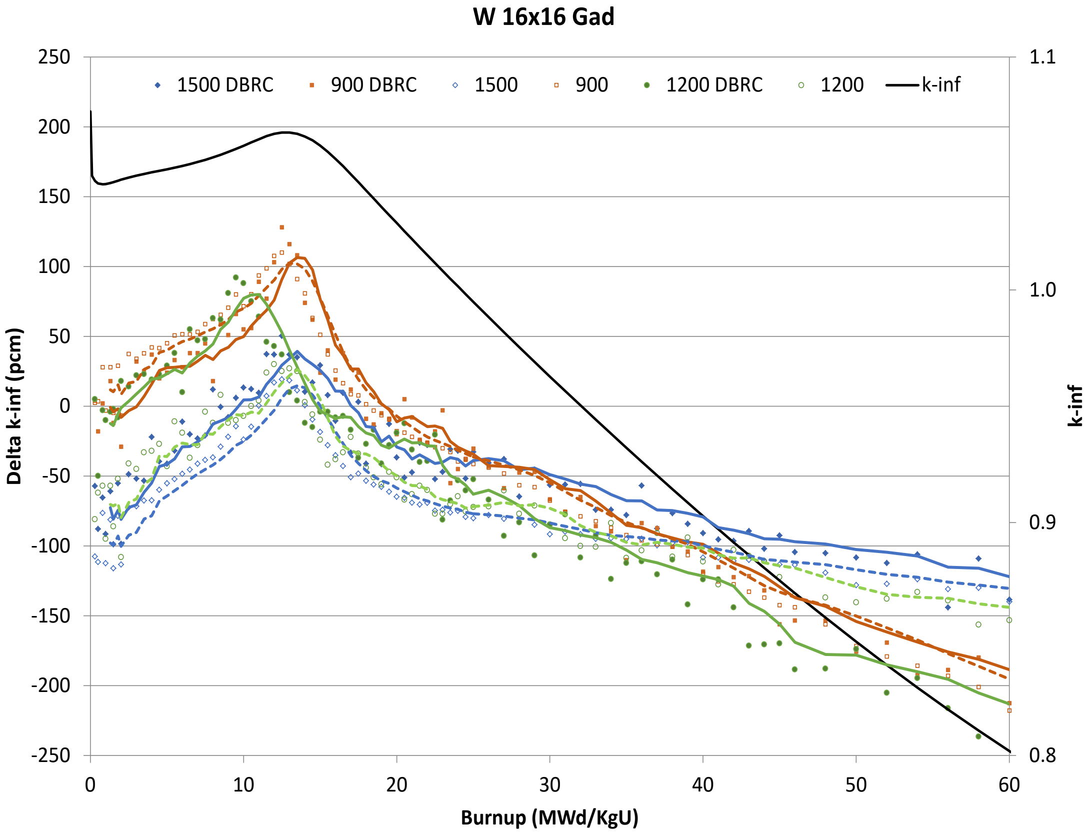
k-eff = 41 pcm

RMS = 0.4%

Max = 1.16%

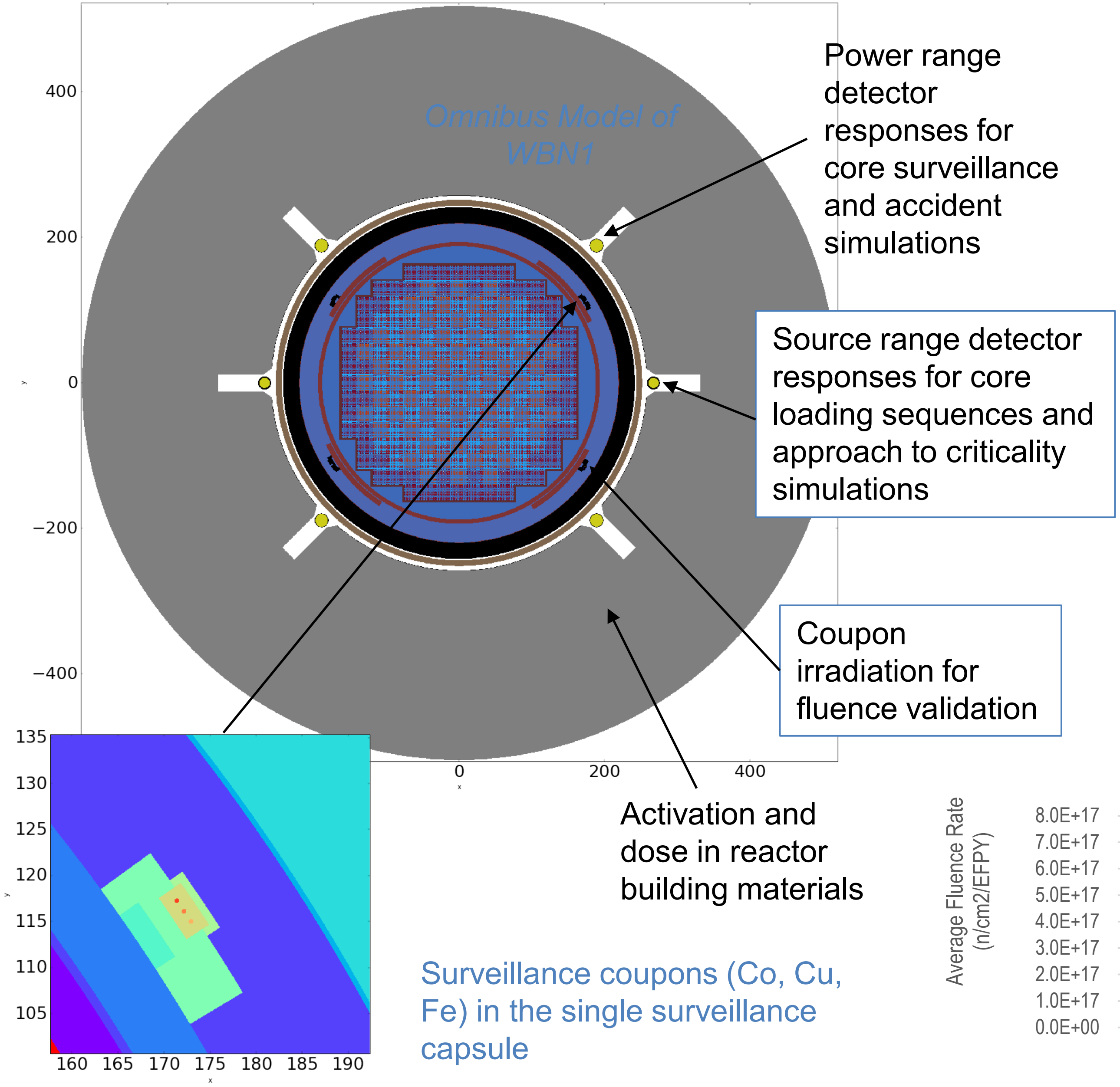
AP1000 Lattice Depletion Benchmarks





- 37 +/- 23 pcm for 900K over 6 fuel and burnable absorber types
- Good agreement with both Serpent continuous-energy Monte Carlo depletion code
- Good agreement with Westinghouse latest lattice physics methods Paragon-2

WB1 Excore Transport Demonstrations



Power range detector responses for core surveillance and accident simulations

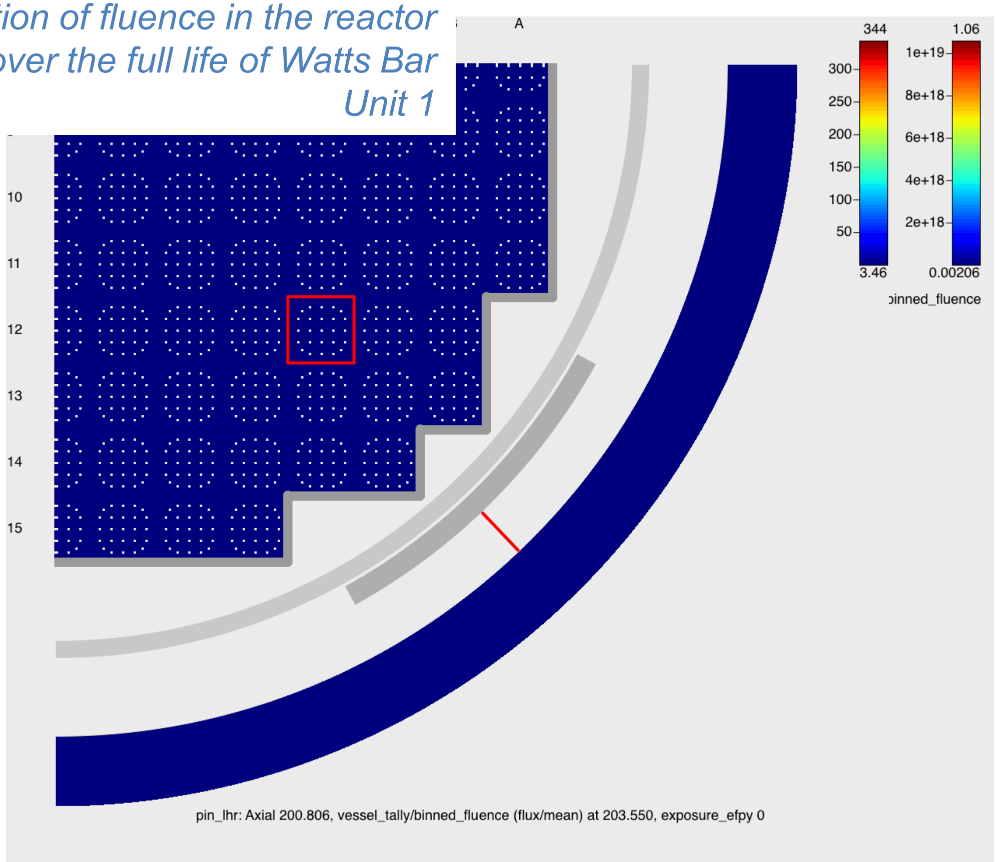
Source range detector responses for core loading sequences and approach to criticality simulations

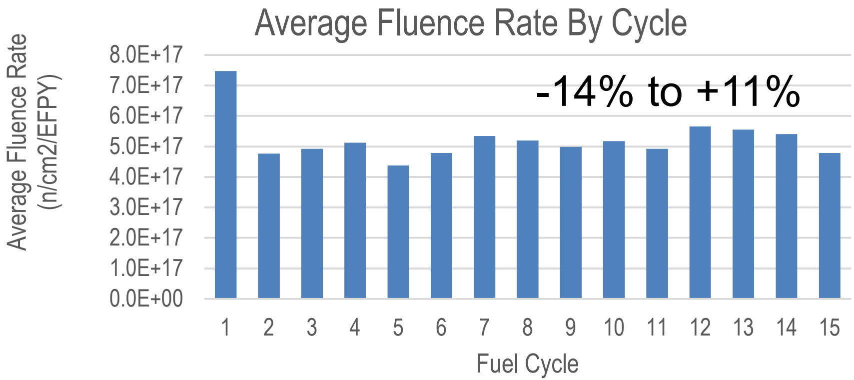
Coupon irradiation for fluence validation

Activation and dose in reactor building materials

Surveillance coupons (Co, Cu, Fe) in the single surveillance capsule

Simulation of fluence in the reactor vessel over the full life of Watts Bar Unit 1

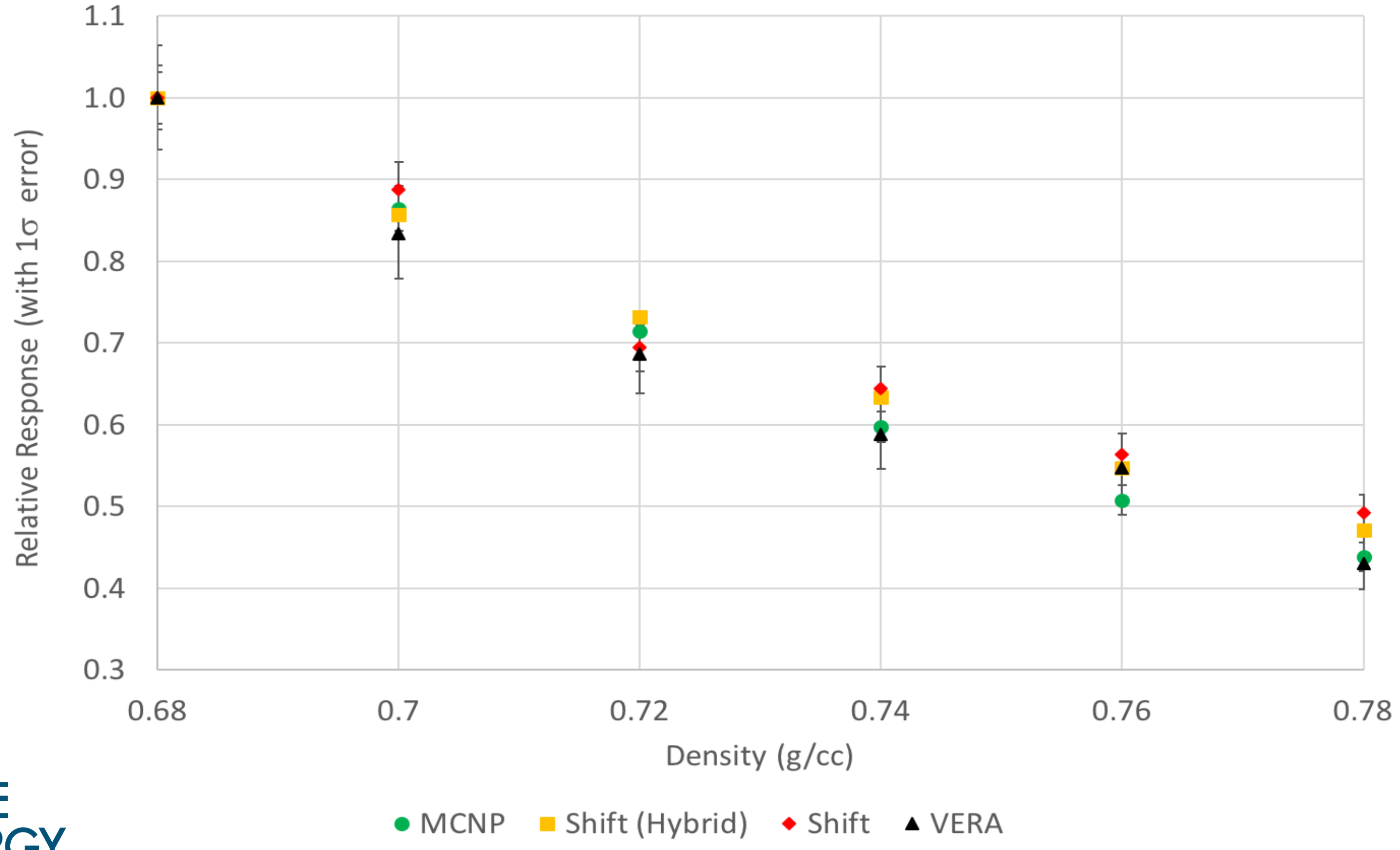


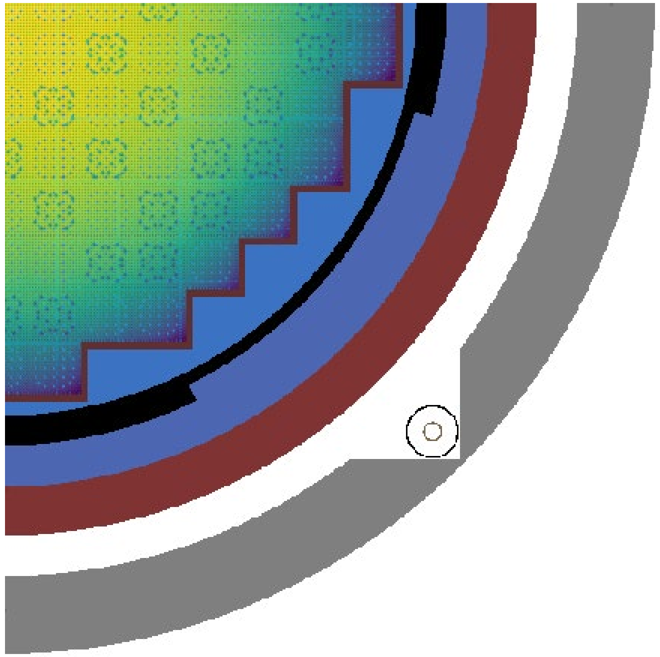


Shearon Harris Downcomer Attenuation

Smith, Davidson – RPSD 2018

- VERA proven capable of direct excore detector response calculations consistent with industry-grade applications



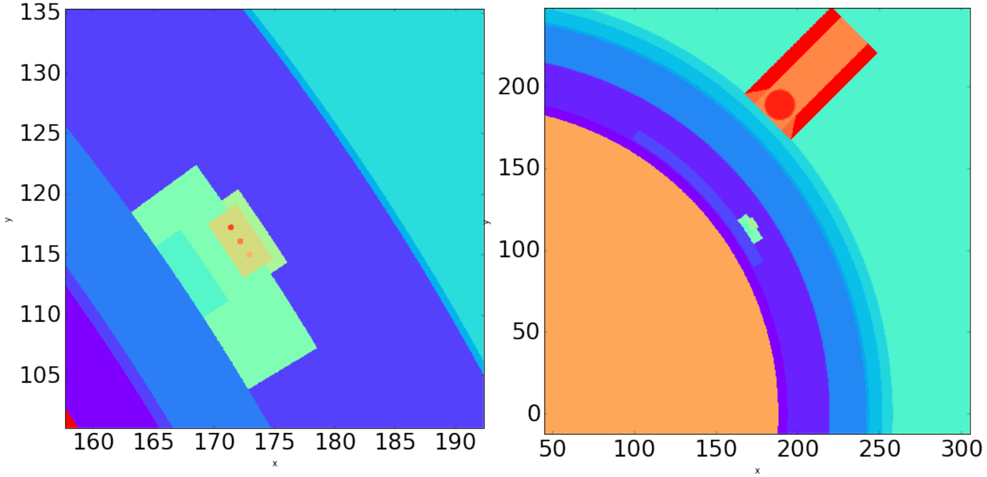


Omnibus Model of Harris with Fission Source from MPACT

Initial Neutron Fluence and Iron dpa Results

Cumulative neutron fluence and total iron dpa in the iron coupon located at the center of the surveillance capsule from cycles 1 to 3

Parameter (Accumulated from Cycles 1 to 3)	VERA – CADIS (1σ %RE)	*REFERENCE	%Difference
Neutron Fluence (E > 1.0 MeV) n/cm^3	9.78×10^{18} (0.8%)	1.072×10^{19}	-8.79%
Neutron Fluence (E > 0.1 MeV) n/cm^3	4.68×10^{19} (0.2%)	5.224×10^{11}	-10.34%
Iron dpa	1.96×10^{-2} (0.3%)	2.205×10^{-02}	-10.99%



*BWXT Services Inc., “Part 1 – Watts Bar Nuclear Plant Unit 1, Reactor Vessel Surveillance Capsule W Test Results & Reactor Vessel Fracture Toughness (J-R) Test Results,” NRC Public Document, ML012900048 (2001).

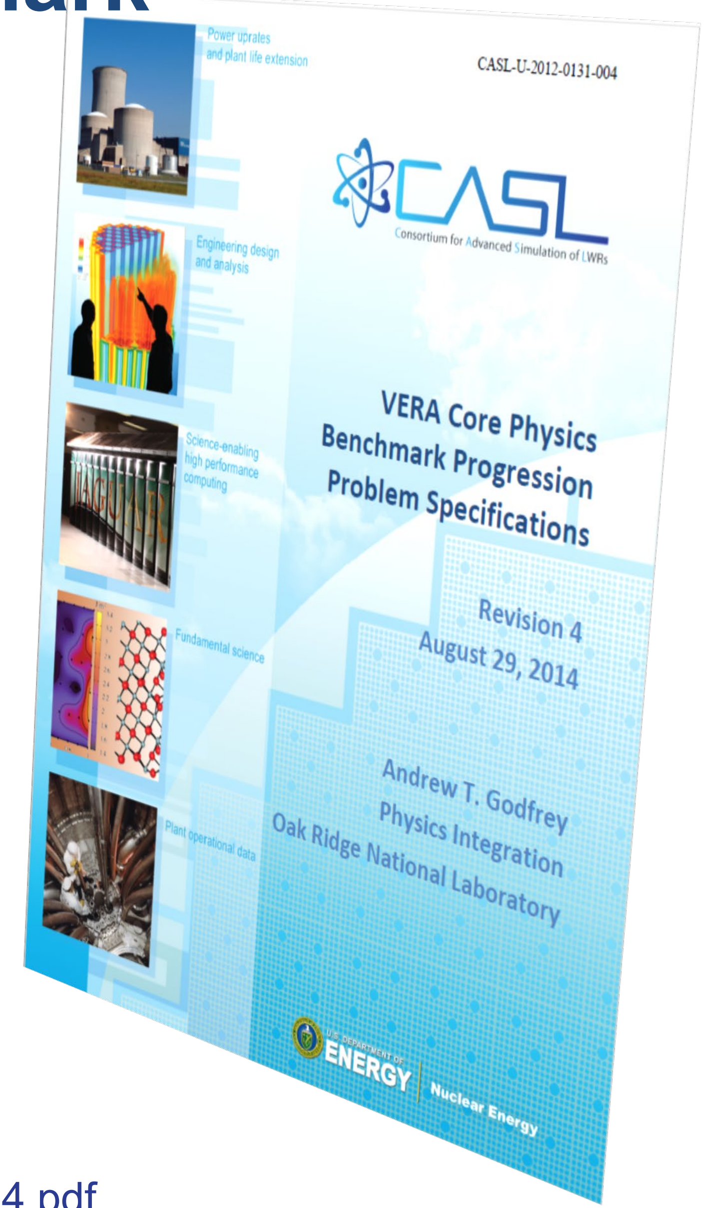
Computational Performance

- 50 million particles per state point in Shift with CADIS
- Weight windows generated at first state point and the same VR parameters are used for all the state points
- Neutron-only transport

	MPACT / CTF [min, max, avg]	MPACT / CTF [cores]	Shift [min, max, avg]	Shift [cores]
Cycle 1 run time per state point (minutes)	22.3, 147.3, 68.3	840	1.1, 1.6, 1.2	400
Cycle 2 run time per state point (minutes)	42.6, 195.1, 89.1	915	1.2, 4.4, 1.5	400
Cycle 3 run time per state point (minutes)	21.8, 204.6, 60.3	992	1.2, 1.5, 1.3	400

Development of Public Reactor Benchmark Specifications

- Public benchmark specs for Cycle 1 released in 2014
- Based on data from Watts Bar and publicly available fuel design data
- Updating in 2019 for:
  - Cycle 2 startup tests and depletion
  - Cycle 3 shuffle and depletion
  - Measured flux maps
- NCSU is developing draft NEA/OECD benchmark specification to be released in 2019



CASL-U-2012-0131-004

CASL
Consortium for Advanced Simulation of LWRs

Power uprates and plant life extension

Engineering design and analysis

Science-enabling high performance computing

Fundamental science

Plant operational data

VERA Core Physics
Benchmark Progression
Problem Specifications

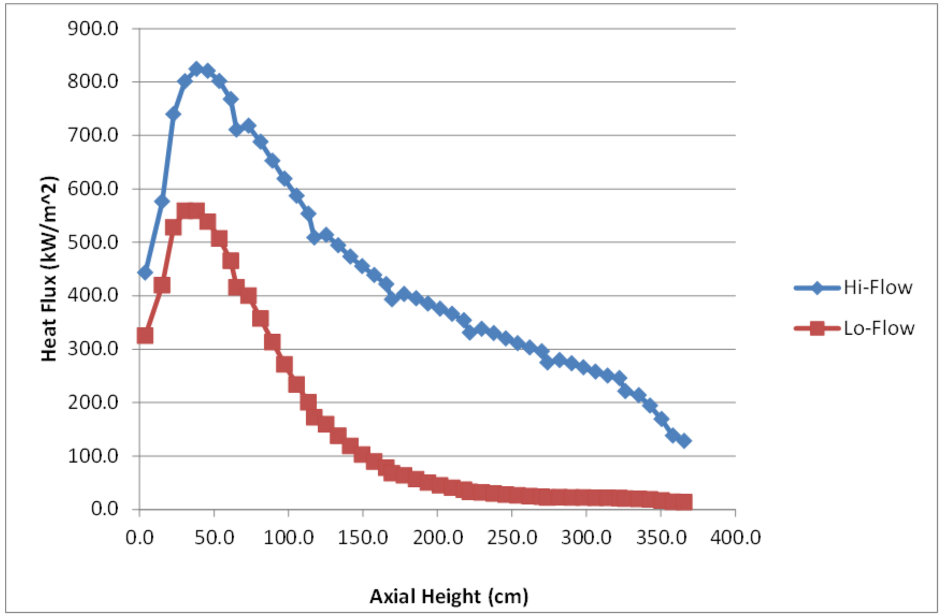
Revision 4
August 29, 2014

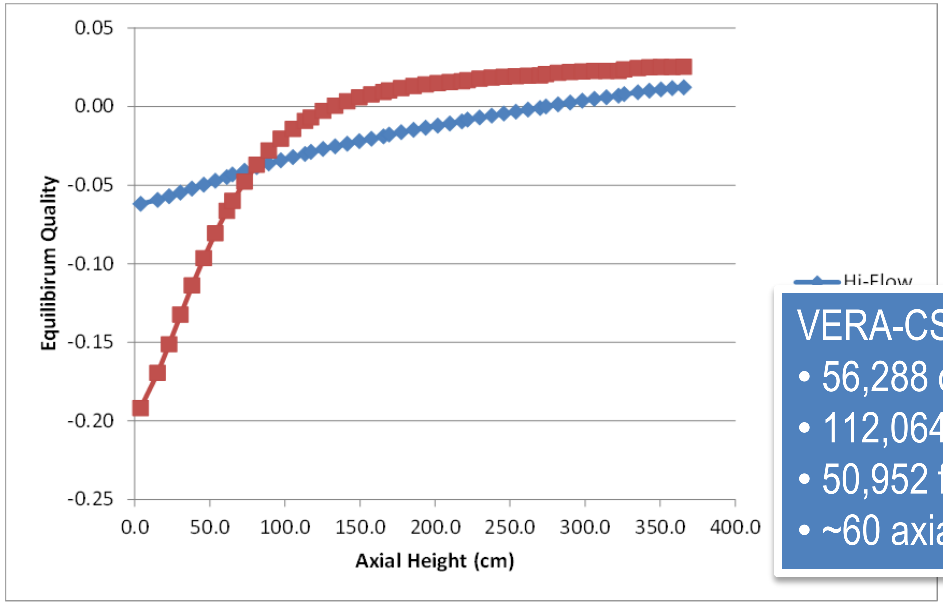
Andrew T. Godfrey
Physics Integration
Oak Ridge National Laboratory

U.S. Department of Energy
ENERGY | Nuclear Energy

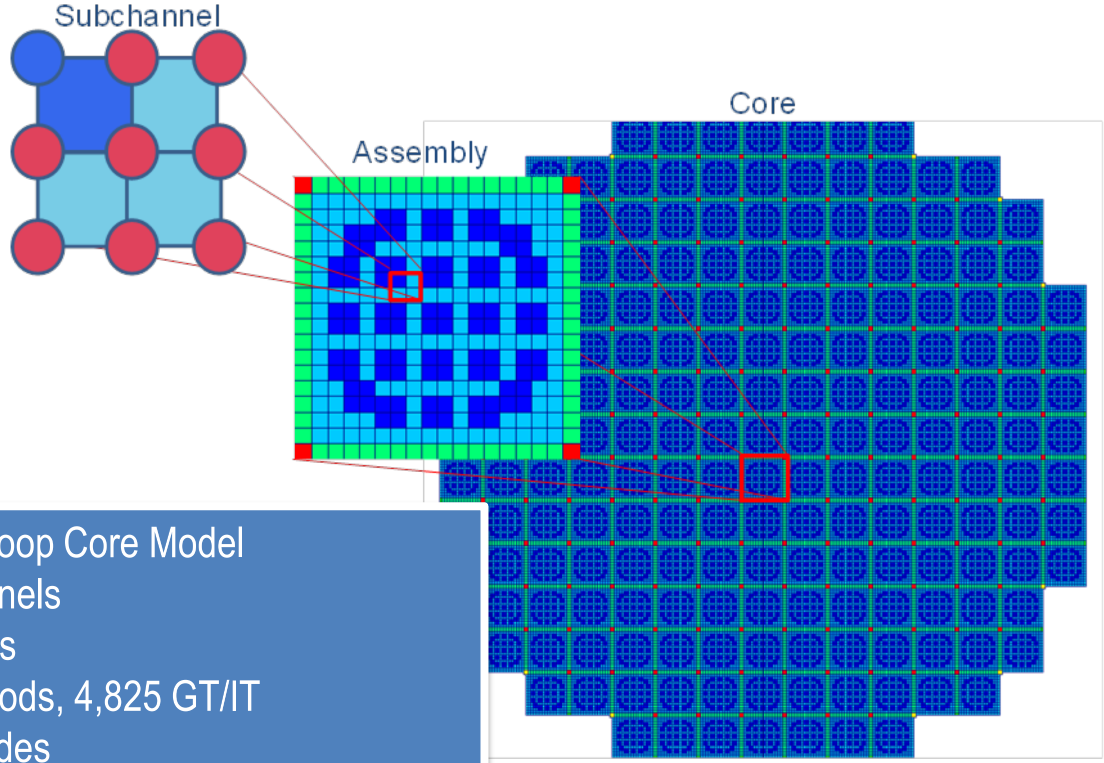
https://www.casl.gov/sites/default/files/docs/CASL-U-2012-0131-004.pdf

Study of HZP SLB DNB Limiting Case



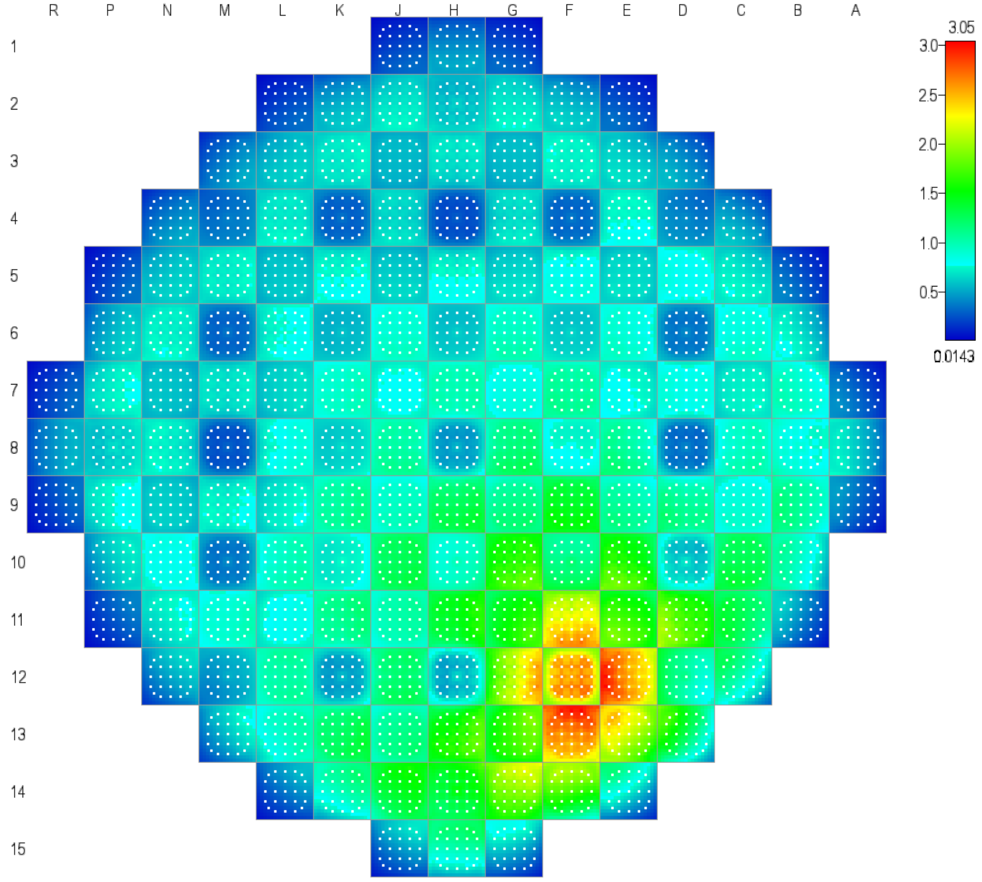


Parameter	High-Flow	Low-Flow
DNB Limiting Elevation (cm)	45.9	30.5
Max. Pin Linear Power (W/cm)	264.3	178.5
Heat Flux (W/m^2)	801.4	558.7
Equilibrium Quality	-0.047	-0.114
Mass Flux (kg/m^2/s)	4529.1	466.9

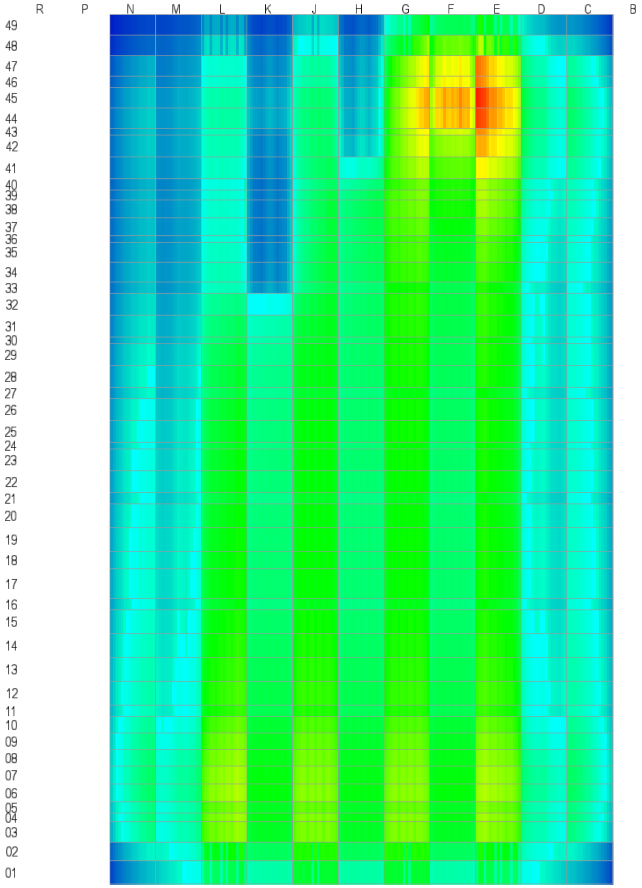


VERA-CS 4-Loop Core Model
- 56,288 channels
- 112,064 gaps
- 50,952 fuel rods, 4,825 GT/IT
- ~60 axial nodes

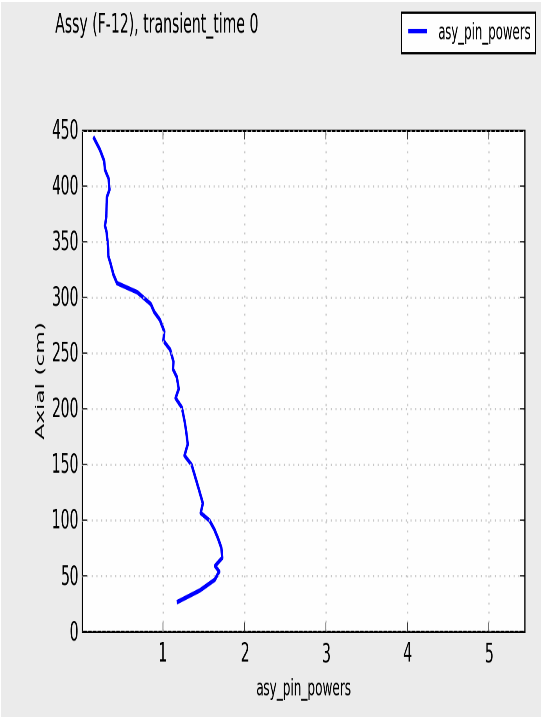
AP1000 Rod Ejection at HFP



pin_powers: Axial 406.453, transient_time 0.06487



pin_powers: Assy Row 12, Pin Row 8, transient_time 0.06487

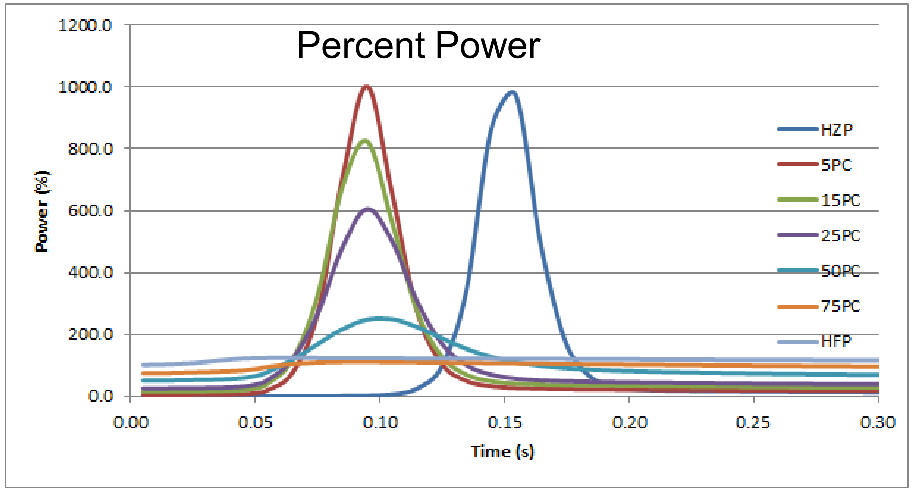


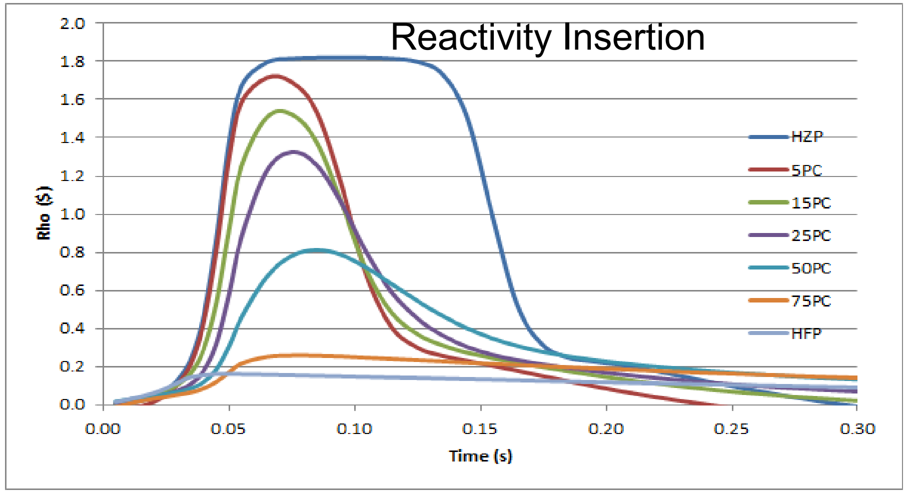
Highly skewed axial power initially with partially inserted rod

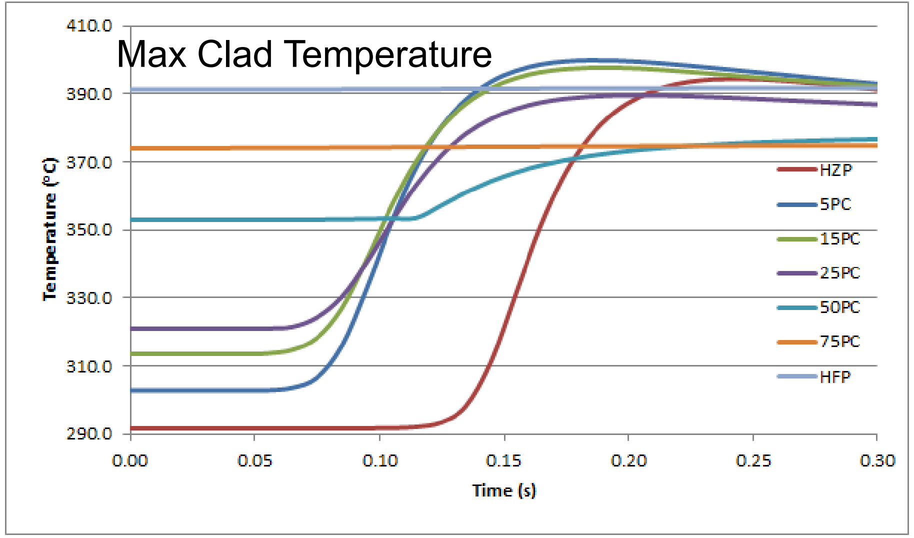
- Highly asymmetric power distribution
- High power clustered in and around the ejected rod, and tapers off away from the ejected rod.
- The max. power peaking factor of ~17.3 at the peak of the pulse.

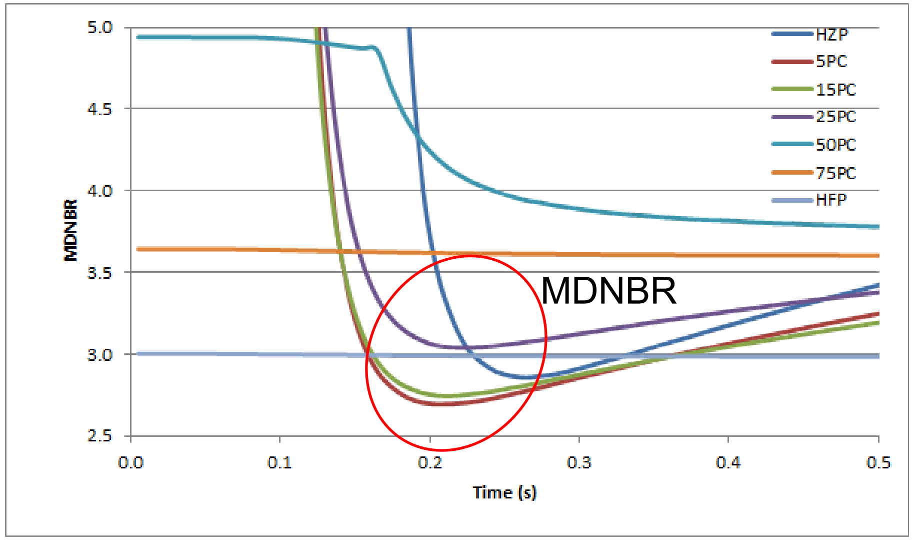
AP1000 Rod Ejection at Part-Power

Additional simulations starting at 5%, 15%, 25%, 50%, and 75% power





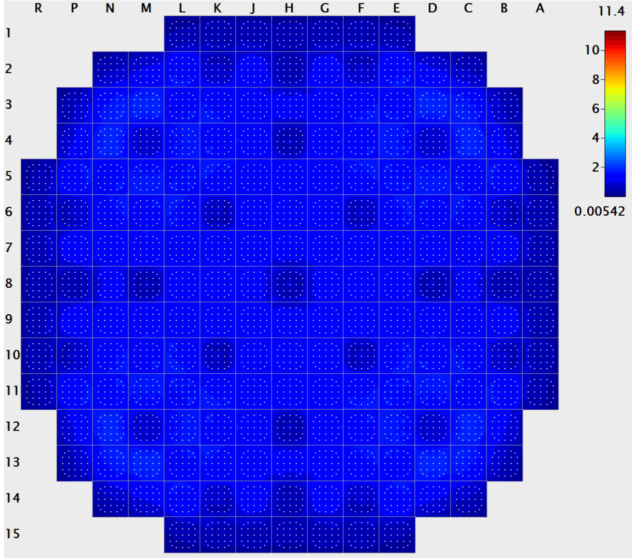




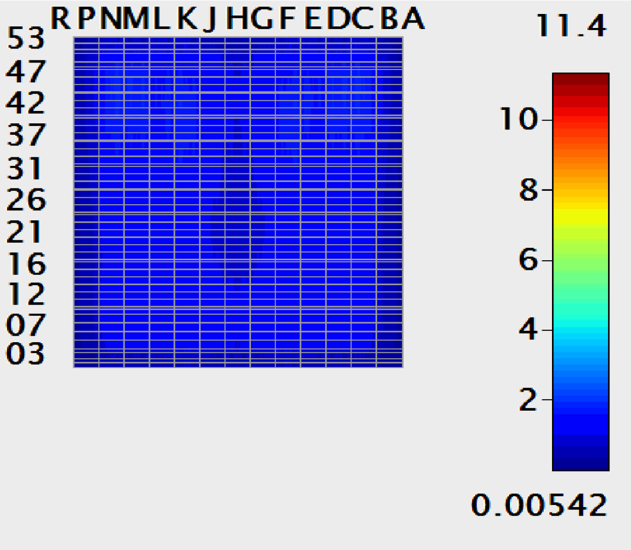
- **5% power case appears to be most limiting in VERA results**

Reactivity Insertion Accident with VERA

- Fully coupled neutronics/ thermal-hydraulics transient solution
- Internal simplified fuel rod model with dynamic gap
- Existing commercial Westinghouse 4-loop core design at End-of-Cycle
- Conservatism on Beta
- Initiated from HZP conditions – core power reached 904% FP with $1.5 ejected rod worth
- 6480 cores in 36 hours



ez_0|pin_powers: Axial 322.667, transient_time 0



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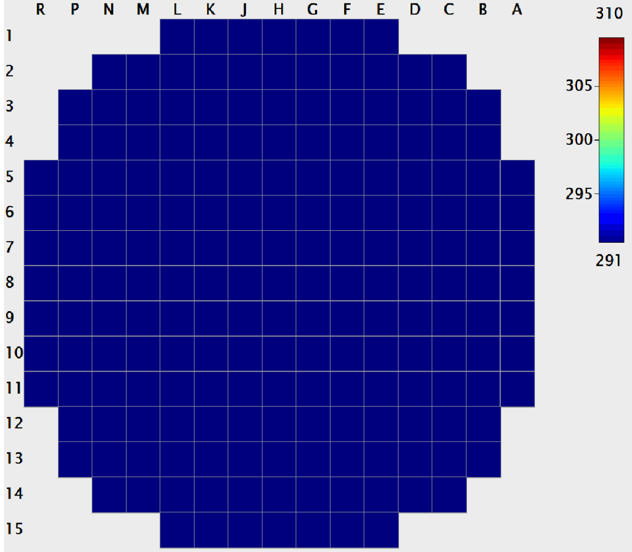

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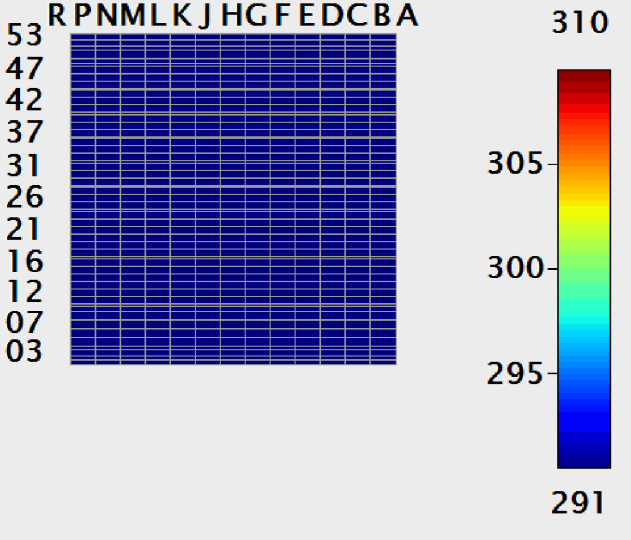
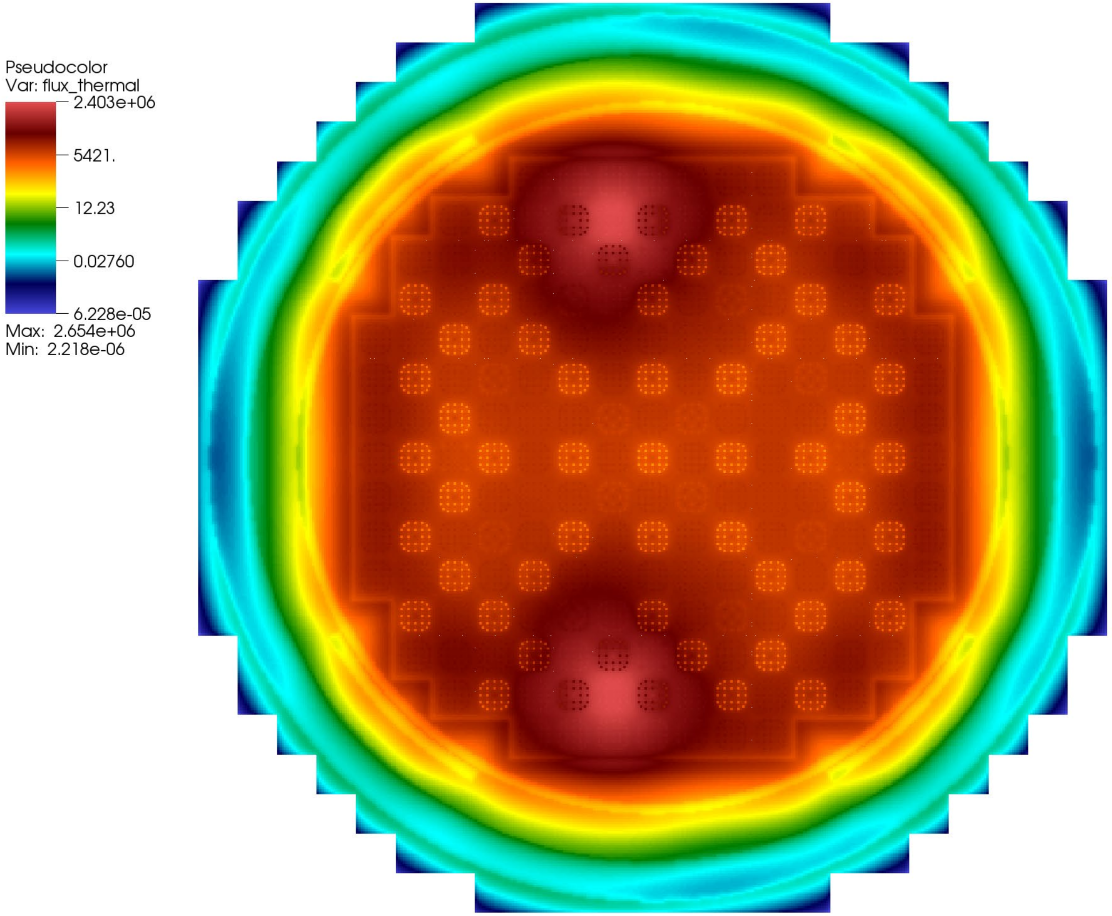


ez.ctf_0|channel_liquid_temps: Assy Row 13, Chan Col 4, transient_time 0

Subcritical, Source-Driven Application

- Subcritical, source-driven problem to simulate excore detector response during core refueling
- Neutron sources from burned fuel (ORIGEN) and activated secondary source rods (Sb-Be)
  - Photoneutron reaction correlation developed with ORIGEN and MCNP
- MPACT pin-wise diffusion used for sub-critical multiplication
- Shift hybrid MC transport used for source-range detector response



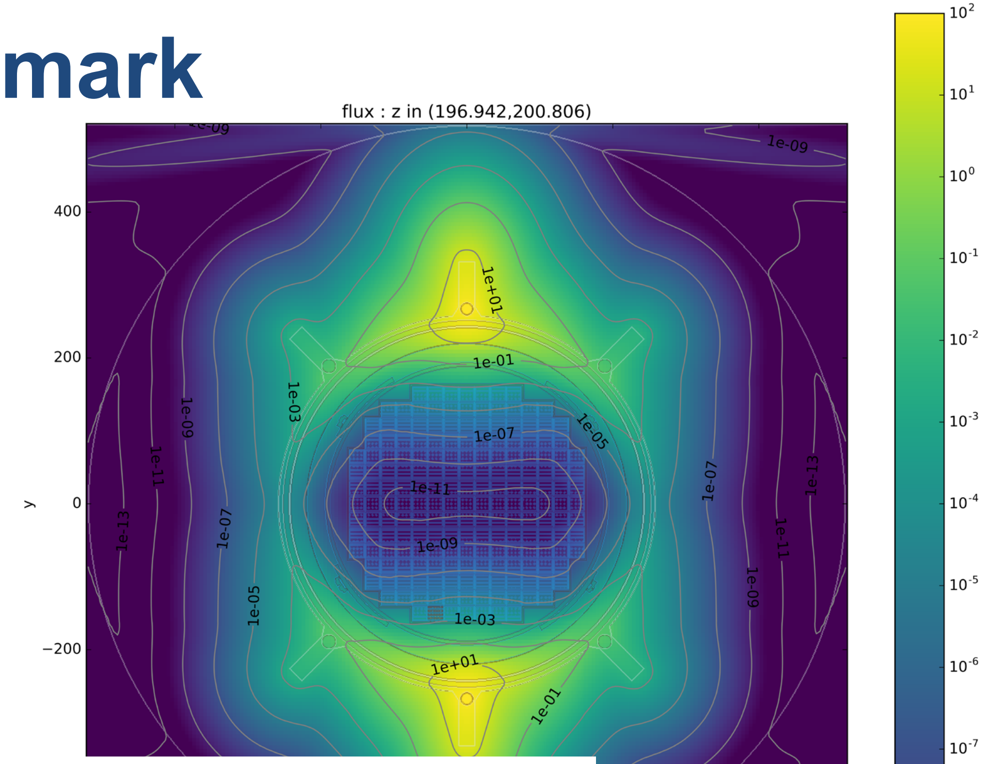
Subcritical thermal neutron flux in WB1C8 when fully loaded, including secondary neutron sources (log scale)

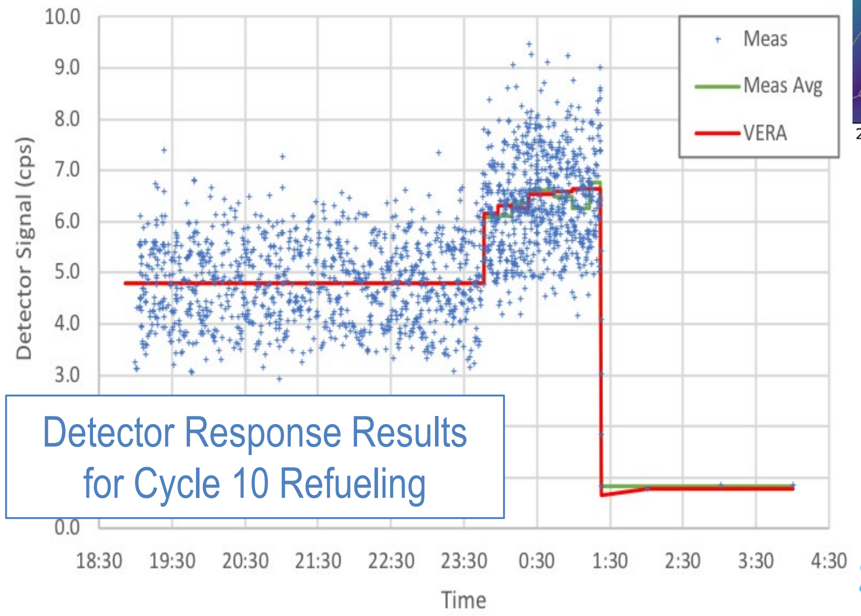
Ex-Core Detector Response Benchmark

- VERA used to predict detector response outside of the pressure vessel in Watts Bar Unit 1
- Relative comparisons to measured source range detector signals
- Excellent agreement between calculations and measurements: -**0.3±3.9%** over ~17,000 measured points averaged over 140 total intervals (8 fuel cycles)
- Report available soon for public release

State-of-the-Art Capability for Coupled In-Core and Ex-Core Neutron Transport Analyses

Adjoint Flux for Source Range Detectors





Detector Response Results for Cycle 10 Refueling

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