CASL-U-2015-0171-000

Improved Diffusion Coefficients for SPN Axial Solvers In the MPACT 2D/1D Method Applied to the AP1000® PWR Start-Up Core Models

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Thomas Downar
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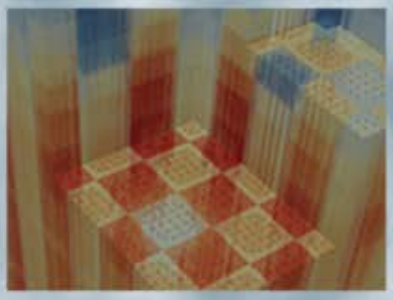
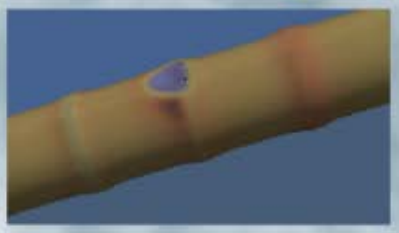
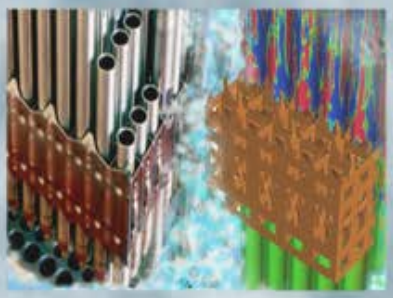
April 19, 2015







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April 21, 2015 – *M&C 2015* – Nashville, TN

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Outline

- VERA-CS and MPACT
  - 2D/1D Method
  - 1D Axial Solvers
- AP1000® Core Geometry
  - Initial Accuracy Issues
- Transport-correction options for diffusion coefficients
- Results
  - Single Assembly (565 K)
  - Quarter-Core
    - ARO at 565 K
    - Multirodded (600 K moderator, 900 K fuel)
- Summary/Conclusions

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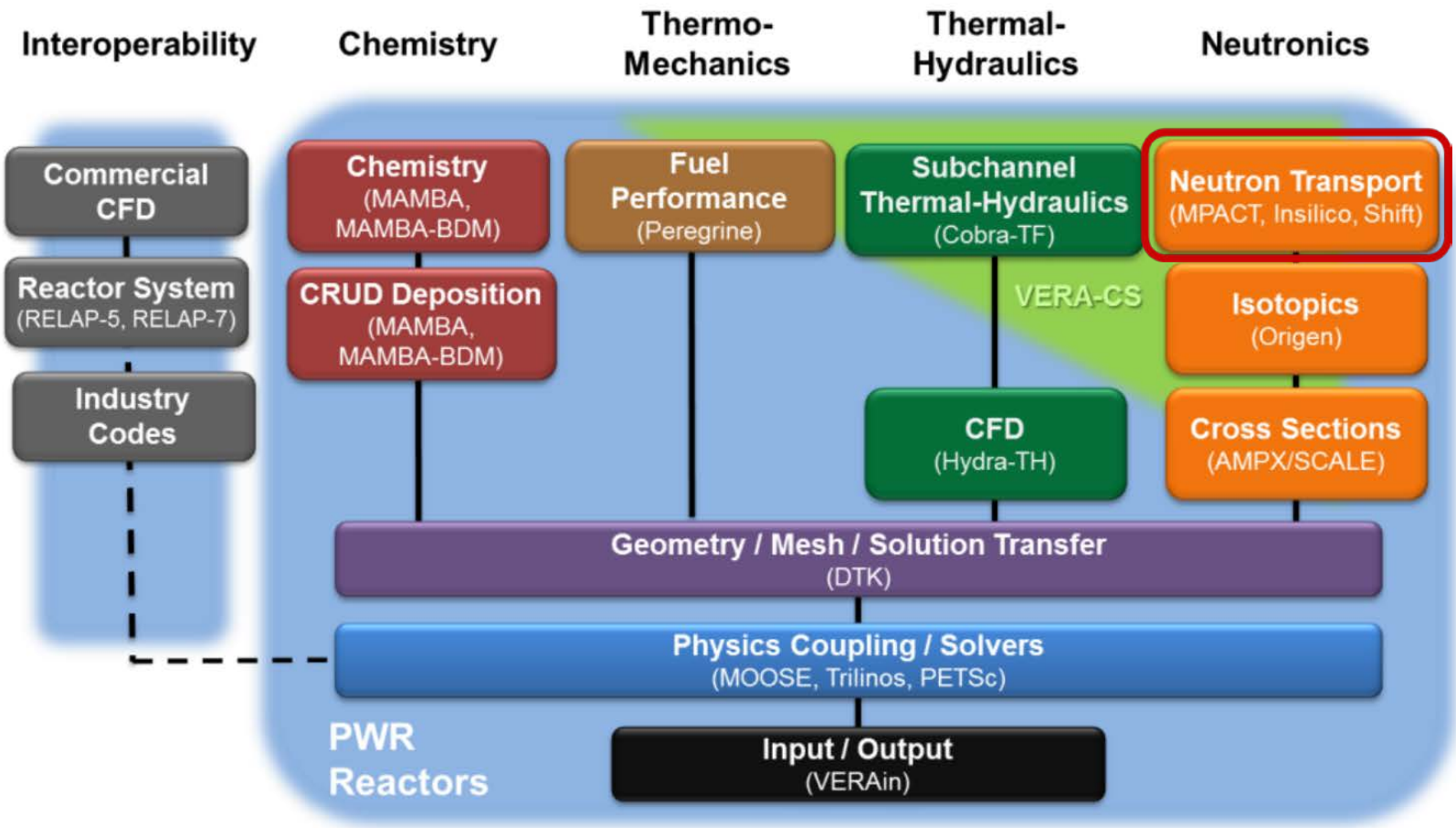
VERA-CS



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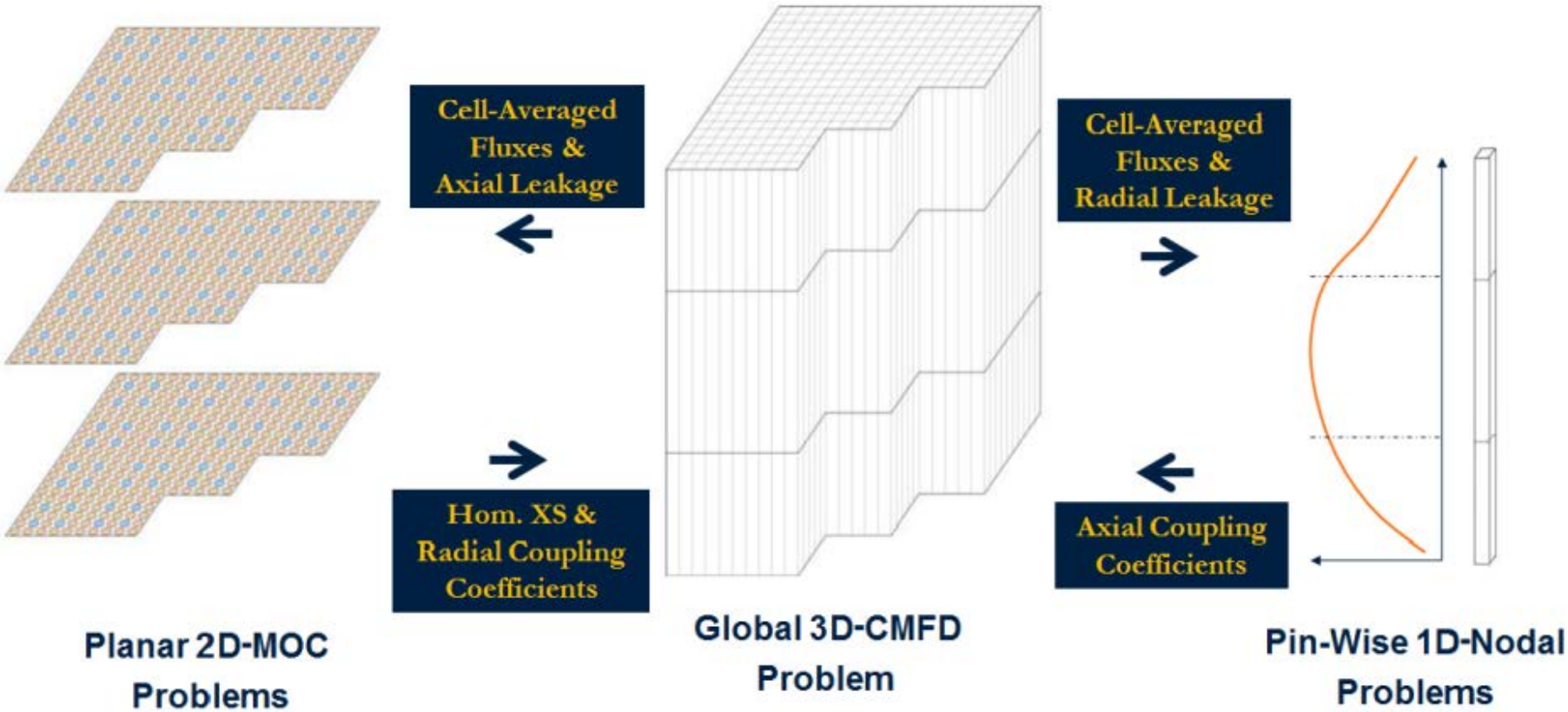
MPACT and the 2D/1D Method



- To highlight the modifications to the diffusion coefficients in the axial solvers, P_2 scattering is used in the MOC solver for all cases

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Axial Transport Solvers in MPACT

- Nodal Expansion Method (NEM)
  - Two-node kernel
  - Based on 1D-Diffusion Eq.:

$$-\frac{4D_g}{h^2}\frac{d^2}{d\xi^2}\phi_g(\xi) + \Sigma_{r,g}\phi(\xi) = Q_g(\xi)$$

$$D_g = \frac{1}{3\Sigma_{tr,g}}$$

  - Quartic flux expansion: $\phi_g(\xi) = \sum_{i=0}^{4} a_{g,i}P_i(\xi)$
  - Quadratic source expansion: $Q_g(\xi) = \sum_{i=0}^{2} q_{g,i}P_i(\xi)$

H. Finnemann, F. Bennewitz, and M. R. Wagner, “Interface nodal current technique for multi-dimensional reactor calculations,” Atomkernenergie, **Vol. 30**, pp. 123-128 (1977).

Axial Transport Solvers in MPACT

- Simplified P_N (SP_N)
  - Uses an Nth order polar expansion for the angular flux:

$$\varphi_g(z,\mu) = \sum_{m=0}^{N_{mom}} \frac{2m+1}{2} \varphi_{m,g}(z) P_m(\mu)$$

  - Wraps one-node NEM kernel for spatial representation
  - NEM-SP_3:

$$-\frac{4D_{0,\mathrm{g}}}{h^2}\frac{d^2}{d\xi}\Phi_{0,g}(\xi) + \Sigma_{r,g}\Phi_{0,g}(\xi) = Q_g(\xi) + 2\Sigma_{r,g}\Phi_{2,g}(\xi)$$

$$-\frac{4D_{2,\mathrm{g}}}{h^2}\frac{d^2}{d\xi}\Phi_{2,g}(\xi) + \left(\Sigma_{t,g} + \frac{4}{5}\Sigma_{r,g}\right)\Phi_{2,g}(\xi) = -\frac{2}{5}\left(Q_g(\xi) - \Sigma_{r,g}\Phi_{0,g}(\xi)\right)$$

$$D_{0,g} = \frac{1}{3\Sigma_{tr,g}} \qquad D_{2,g} = \frac{9}{35\Sigma_{t,g}}$$

R. G. McClarren, "Theoretical Aspects of the Simplified P_n Equations," *Transport Theory and Statistical Physics*, **Vol. 39**, pp. 73-109 (2011).

AP1000® Reactor Models

- Highly heterogeneous axially
- Start-up cores use two burnable absorbers to control reactivity and power shape
  - Integral Fuel Burnable Absorber (IFBA)
  - Wet Annular Burnable Absorber (WABA)
    - Three different length rods (short, intermediate, and long)
- Severe accuracy issues initially observed in cases with WABA rods
  - Using out-scatter approximation for transport cross section
  - Also recreated using other partial length burnable absorbers (not specific to WABA)

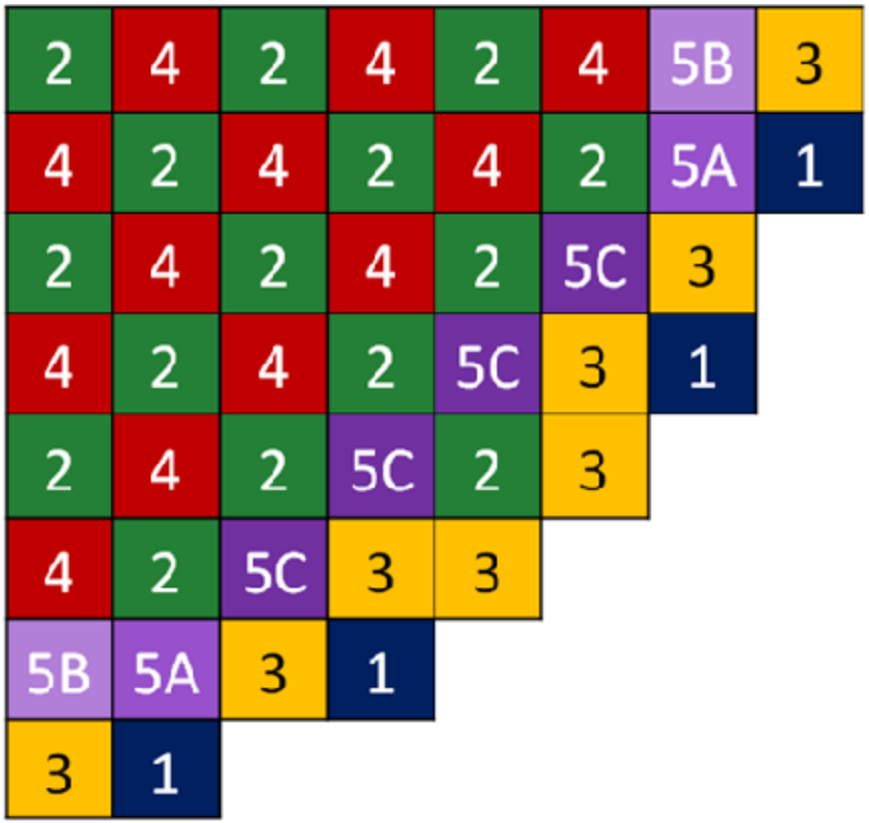
J. R. Secker and J. A. Brown, "PWR Burnable Absorber Evolution and Usage," ANS Winter Meeting, San Diego, CA, November 9 (2010).

F. Franceschini et al., "AP1000 PWR Reactor Physics Analysis with VERA-CS and KENO-VI – Part II: Power Distribution," *Proc. PHYSOR 2014*, Kyoto, Japan, September 28–October 3 (2014).

AP1000® Geometry – Radial Layout

- Seven assembly types
- Wide range of enrichments

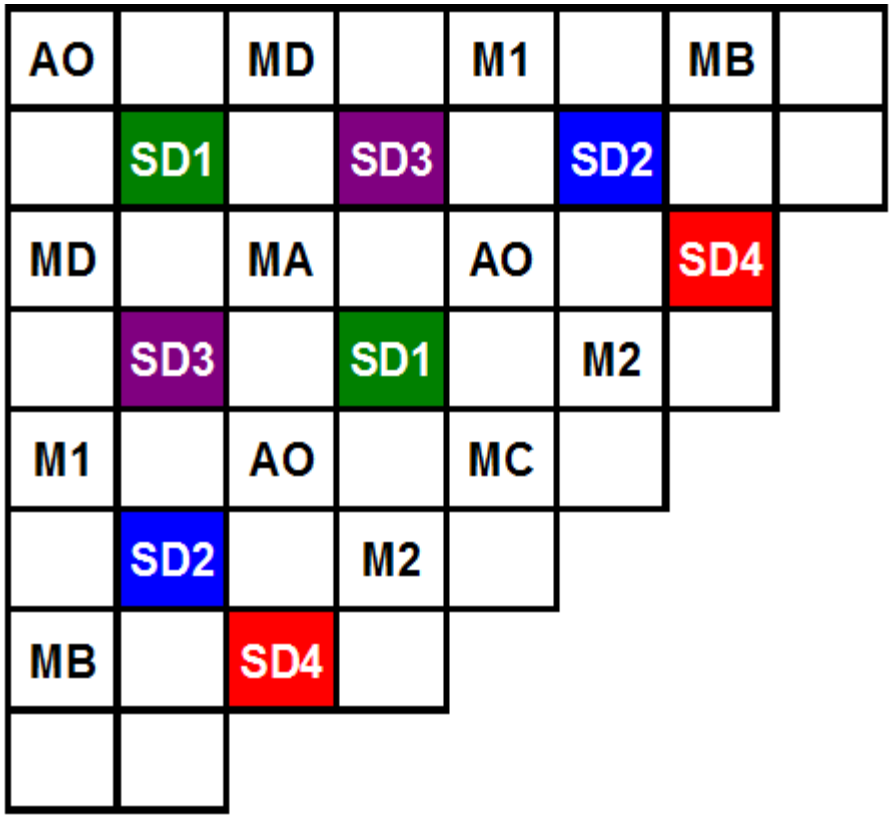
Assy. #	Percent of Core	U-235 AVG	U-235 BLKT	IFBA Rods	WABA Rods
1	10%	0.740	Absent	0	0
2	31%	1.580	Absent	0	0
3	18%	3.200	1.580	0	0
4	23%	3.776	3.200	68	8L+4S
5A	5%	4.376	3.200	88	4I
5B	3%	4.376	3.200	124	0
5C	10%	4.376	3.200	124	8I



F. Franceschini et al., "Zero Power Physics Test Simulations for the AP1000® PWR," CASL-U-2014-0012-001, March 6 (2014).

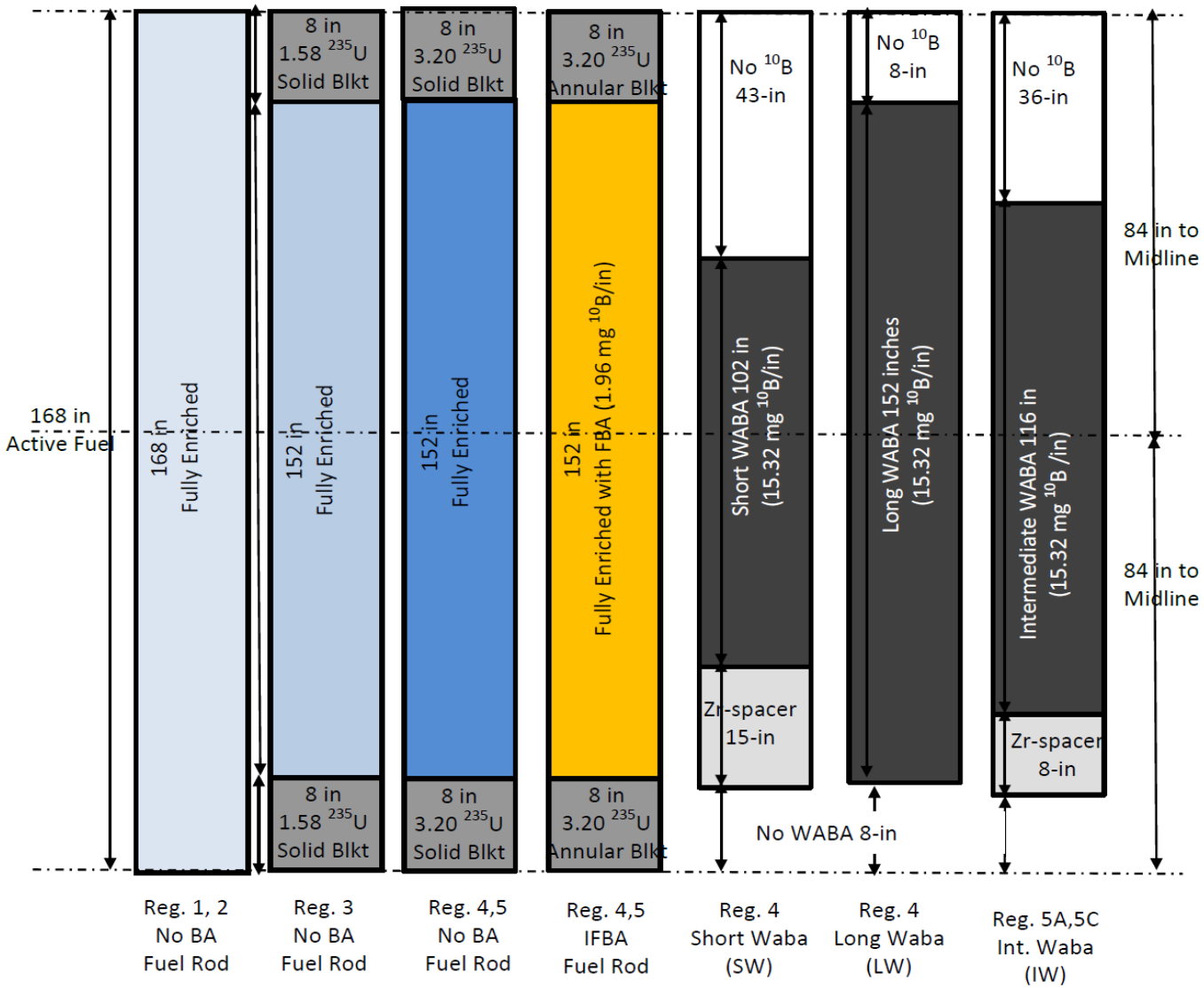
AP1000® Geometry – Control Rod Banks

- 11 control rod banks
- In the quarter-core case shown later
  - AO is 85% withdrawn
  - MD is 34% withdrawn



F. Franceschini et al., "Zero Power Physics Test Simulations for the AP1000® PWR," CASL-U-2014-0012-001, March 6 (2014).

AP1000® Geometry – Axial Assy. Layout



F. Franceschini et al., "Zero Power Physics Test Simulations for the AP1000® PWR," CASL-U-2014-0012-001, March 6 (2014).

AP1000® Geometry – Assembly 4 Lattice

LI	L	LI	L	LI	L	LI	L	LI	L	LI	L	LI	L	LI	L	LI
L	MI	M	M	M	MI	M	M	M	M	M	MI	M	M	M	MI	L
LI	M	M	M	M	GT	M	M	LW	M	M	GT	M	M	M	M	LI
L	M	M	LW	M	M	HI	H	M	H	HI	M	M	LW	M	M	L
LI	M	M	M	M	M	HI	H	M	H	HI	M	M	M	M	M	LI
L	MI	GT	M	M	GT	M	M	SW	M	M	GT	M	M	GT	MI	L
LI	M	M	HI	HI	M	HI	H	M	H	HI	M	HI	HI	M	M	LI
L	M	M	H	H	M	H	HI	M	HI	H	M	H	H	M	M	L
LI	M	LW	M	M	SW	M	M	IT	M	M	SW	M	M	LW	M	LI
L	M	M	H	H	M	H	HI	M	HI	H	M	H	H	M	M	L
LI	M	M	HI	HI	M	HI	H	M	H	HI	M	HI	HI	M	M	LI
L	MI	GT	M	M	GT	M	M	SW	M	M	GT	M	M	GT	MI	L
LI	M	M	M	M	M	HI	H	M	H	HI	M	M	M	M	M	LI
L	M	M	LW	M	M	HI	H	M	H	HI	M	M	LW	M	M	L
LI	M	M	M	M	GT	M	M	LW	M	M	GT	M	M	M	M	LI
L	MI	M	M	M	MI	M	M	M	M	M	MI	M	M	M	MI	L
LI	L	LI	L	LI	L	LI	L	LI	L	LI	L	LI	L	LI	L	LI

68 IFBA + 12 WABA

	No. Pins	Enr.	BA
L	32	3.40	No BA
LI	32	3.40	IFBA
M	140	3.80	No BA
MI	12	3.80	IFBA
H	24	4.20	No BA
HI	24	4.20	IFBA
SW	4		WABA
LW	8		WABA
GT	12		
IT	1		

F. Franceschini et al., "Zero Power Physics Test Simulations for the AP1000® PWR," CASL-U-2014-0012-001, March 6 (2014).

Transport Correction Options for Diffusion Coefficients

- Out-scatter

$$\Sigma_{tr,g} = \Sigma_{t,g} - \sum_{g'=1}^{N_{grp}} \Sigma_{s1,g\to g'}$$

- In-scatter
  - Based on P_1 Equation: $\frac{1}{3}\phi_g - \Sigma_{t,g} D_g \phi_g = -\sum_{g'=1}^{N_{grp}} \Sigma_{s1,g'\to g} D_{g'} \phi_{g'}$
  - A representative flux spectrum (ϕ_g) is input
  - Transport cross section is obtained by solving for D_g:

$$\Sigma_{tr,g} = \frac{1}{3D_g}$$

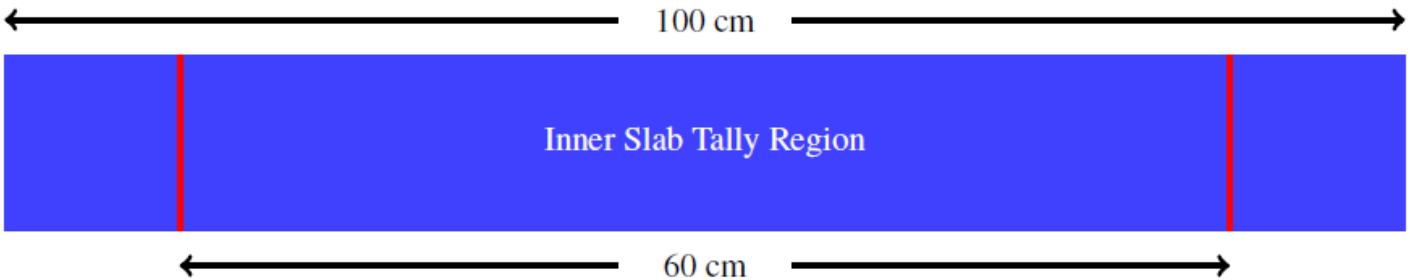
A. Yamamoto, Y. Kitamura, and Y. Yamane, “Simplified Treatments of Anisotropic Scattering in LWR Core Calculations,” *Journal of Nuclear Science and Technology*, **Vol. 45**, No. 3, pp. 217–229 (2008).

M. Ryu et al., “Incorporation of Anisotropic Scattering in nTRACER,” *Trans. of the Kor. Nucl. Soc.*, Autumn Meeting, Pyeongchang, Korea, October 30–31 (2014).

Transport Correction Options for Diffusion Coefficients

- "Neutron Leakage Conservation" (NLC)
  - Based on a uniform, hydrogen slab buckling problem:

$$J_{right,g} - J_{left,g} = D_g B^2 \phi_g W$$



  - The flux and currents (at red boundaries) are determined and are used to solve for the transport cross section:

$$\Sigma_{tr,g} = \frac{1}{3D_g} = \frac{B^2 \phi_g W}{3\left(J_{right,g} - J_{left,g}\right)}$$

B. R. Herman et al., "Improved Diffusion Coefficients Generated From Monte Carlo Codes," *Proc. M&C 2013*, Sun Valley, Idaho, May 5–9 (2013).

K. S. Kim et al., "Development of a New 47-Group Library for the CASL Neutronics Simulators," *Proc. M&C 2015*, Nashville, Tennessee, April 19–23 (2015).

Single Assembly Results

Assy.	Axial Trans. Corr.	NEM (diff.)				NEM-SP_3				NEM-SP_5			
		Δk (pcm)	ΔF RMS (%)	ΔF MAX (%)	ΔAO (%)	Δk (pcm)	ΔF RMS (%)	ΔF MAX (%)	ΔAO (%)	Δk (pcm)	ΔF RMS (%)	ΔF MAX (%)	ΔAO (%)
1	Out-Scat.	-242	0.21	1.55	-0.02	-241	0.16	0.51	0.03	-241	0.16	0.49	0.03
	In-Scat.	-226	0.24	0.72	-0.09	-225	0.17	0.54	-0.07	-225	0.17	0.52	-0.07
	NLC	-228	0.23	1.45	-0.11	-227	0.18	0.51	-0.06	-227	0.18	0.49	-0.06
2	Out-Scat.	-170	0.15	0.67	-0.07	-169	0.18	0.72	0.11	-169	0.18	0.72	0.11
	In-Scat.	-151	0.17	0.60	-0.06	-150	0.20	0.62	0.13	-151	0.20	0.62	0.13
	NLC	-155	0.17	0.57	-0.07	-154	0.20	0.56	0.12	-154	0.20	0.56	0.12
3	Out-Scat.	-66	0.37	0.82	-0.28	-66	0.30	0.97	-0.16	-66	0.30	0.97	-0.16
	In-Scat.	-44	0.25	0.97	-0.16	-44	0.13	0.46	-0.02	-44	0.13	0.46	-0.02
	NLC	-48	0.26	0.80	-0.19	-49	0.12	0.54	-0.05	-49	0.12	0.54	-0.05
4	Out-Scat.	-252	6.69	17.86	-3.21	-232	5.09	12.76	-2.62	-232	5.09	12.76	-2.62
	In-Scat.	-155	0.88	3.97	0.39	-138	1.51	3.93	0.81	-138	1.51	3.93	0.81
	NLC	-179	1.75	6.58	-0.44	-162	0.36	1.73	0.02	-162	0.36	1.73	0.02
5A	Out-Scat.	-151	5.86	14.04	-3.97	-145	4.85	11.68	-3.36	-145	4.85	11.68	-3.36
	In-Scat.	-96	1.24	4.09	0.97	-91	1.93	5.22	1.34	-91	1.93	5.22	1.34
	NLC	-109	0.64	1.82	-0.24	-104	0.34	1.28	0.24	-104	0.34	1.28	0.24
5B	Out-Scat.	-156	0.24	1.02	-0.11	-155	0.14	0.73	0.00	-155	0.14	0.73	0.00
	In-Scat.	-135	0.24	1.20	-0.10	-134	0.14	0.50	0.04	-135	0.14	0.50	0.04
	NLC	-139	0.25	1.10	-0.11	-139	0.14	0.60	0.03	-139	0.14	0.60	0.03
5C	Out-Scat.	-279	5.45	14.89	-1.44	-255	4.24	11.84	-1.16	-255	4.24	11.84	-1.16
	In-Scat.	-142	0.70	4.50	0.10	-123	1.14	4.71	0.32	-123	1.38	4.71	0.32
	NLC	-174	1.12	4.20	-0.21	-155	0.26	1.62	0.00	-155	0.26	1.62	0.00

- Highlighted assemblies have WABA rods
- KENO-CE was used as the reference solution

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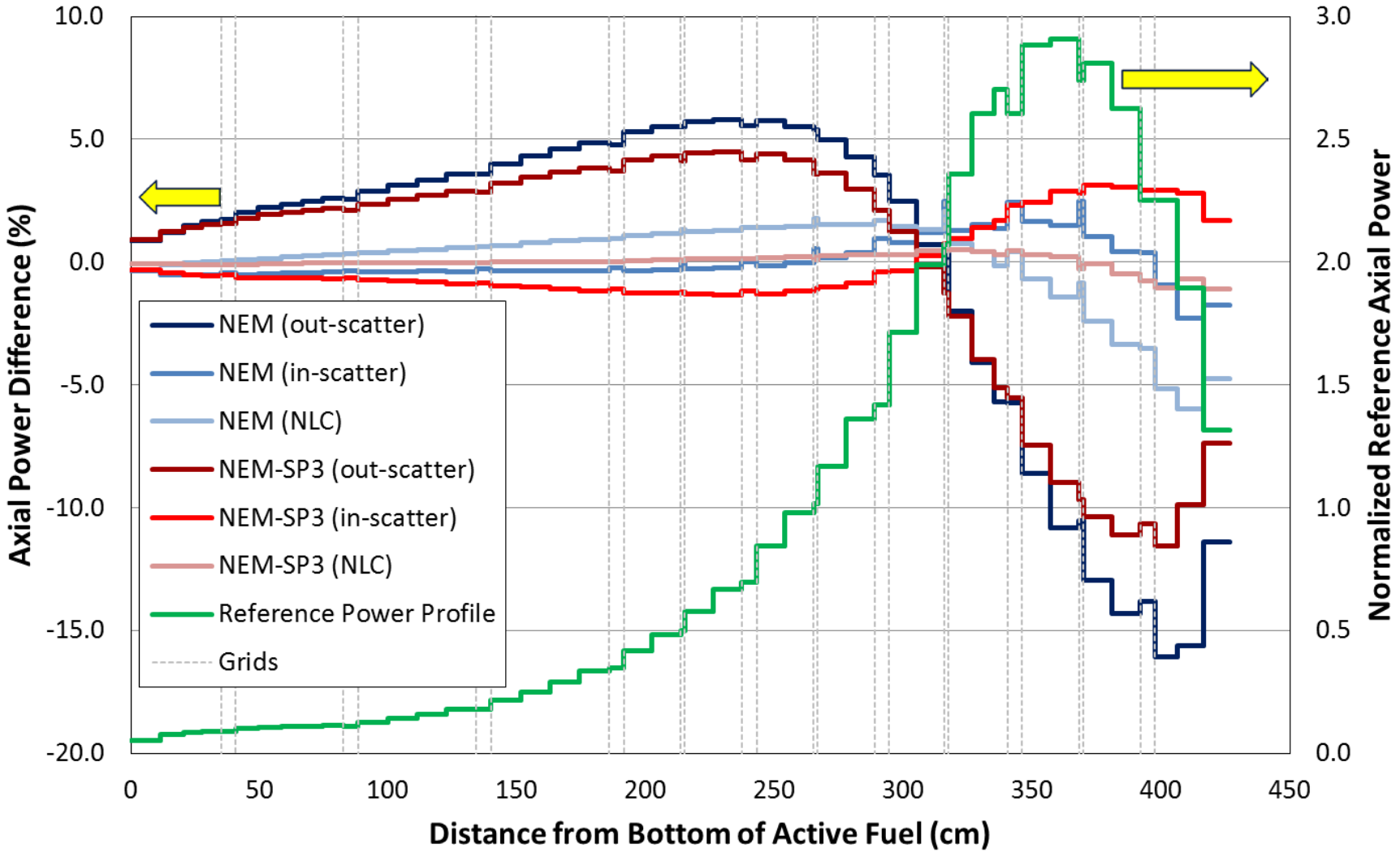
Assembly 4 Results – Axial Profile



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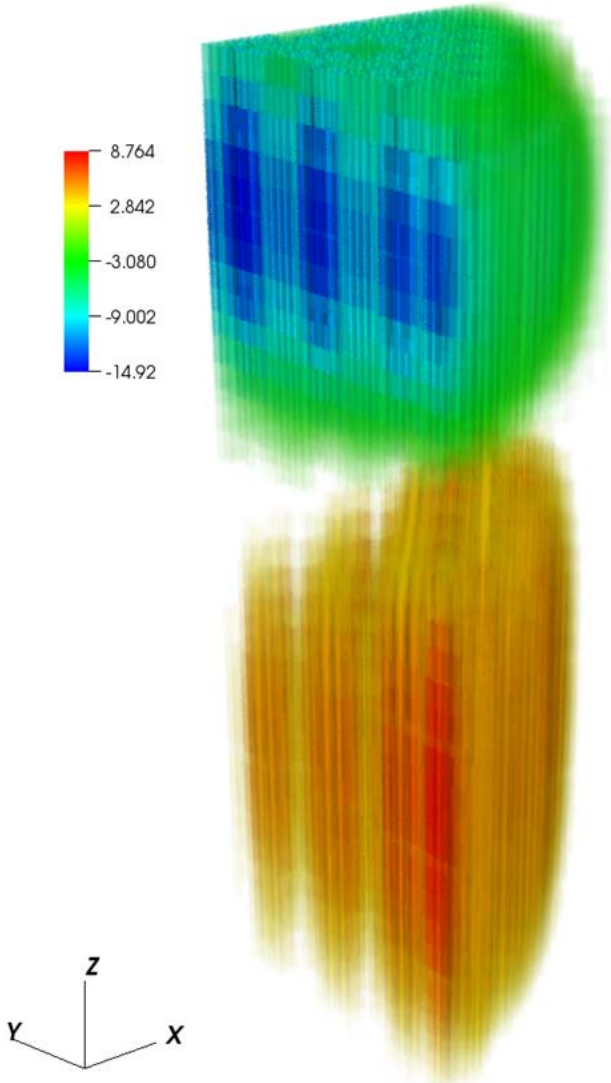
All-Rods-Out (ARO) – Results

- All materials at 565 K
- Only NEM-SP_3 was used
- Eigenvalue and difference in fission rate distribution:

Axial Trans. Corr.	Δk (pcm)	ΔF RMS (%)	ΔF MAX (%)	ΔAO (%)
Out-Scat.	-242	5.45	14.92	-3.69
In-Scat.	-200	1.05	4.28	0.37
NLC	-210	1.34	5.21	-0.56

- Unlike with assembly cases, in-scatter approximation outperforms NLC
- Shift (Monte Carlo) used as reference



Out-Scatter

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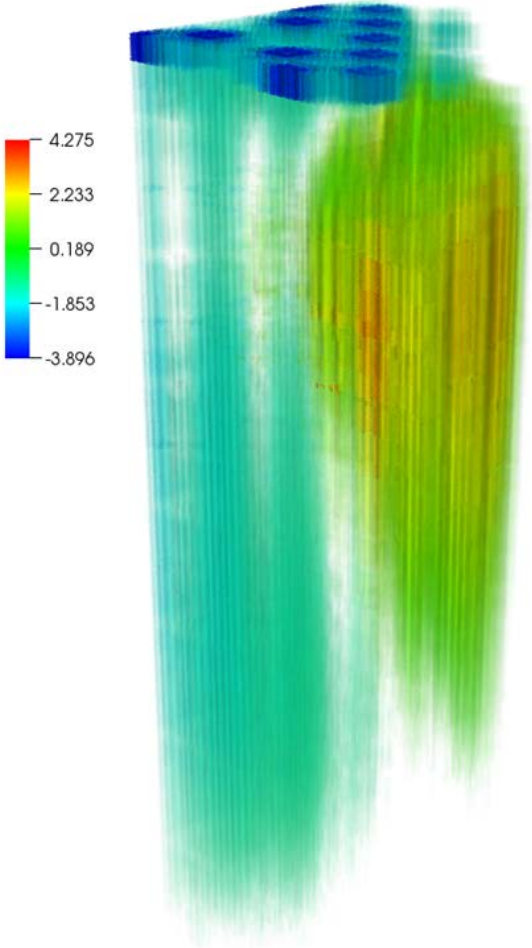
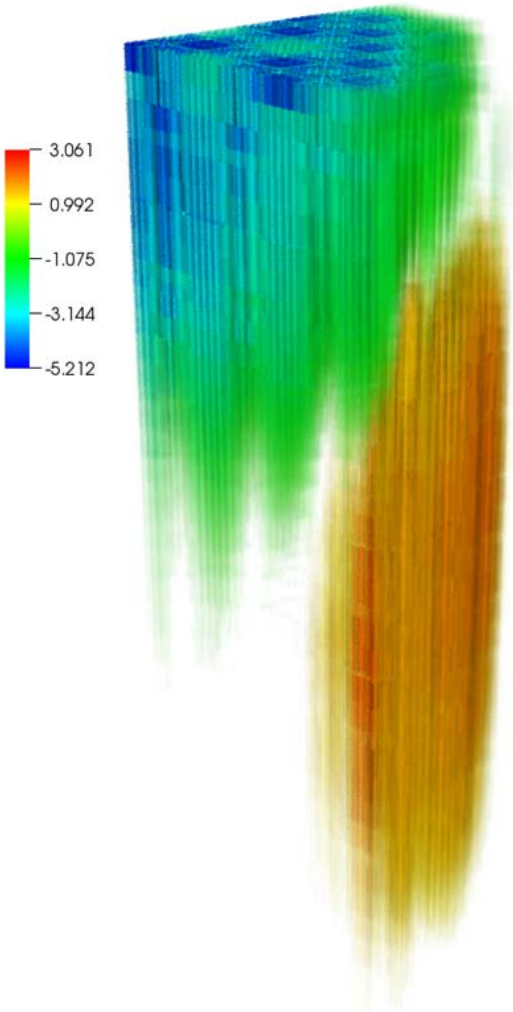
All-Rods-Out (ARO) – Results



In-Scatter



NLC

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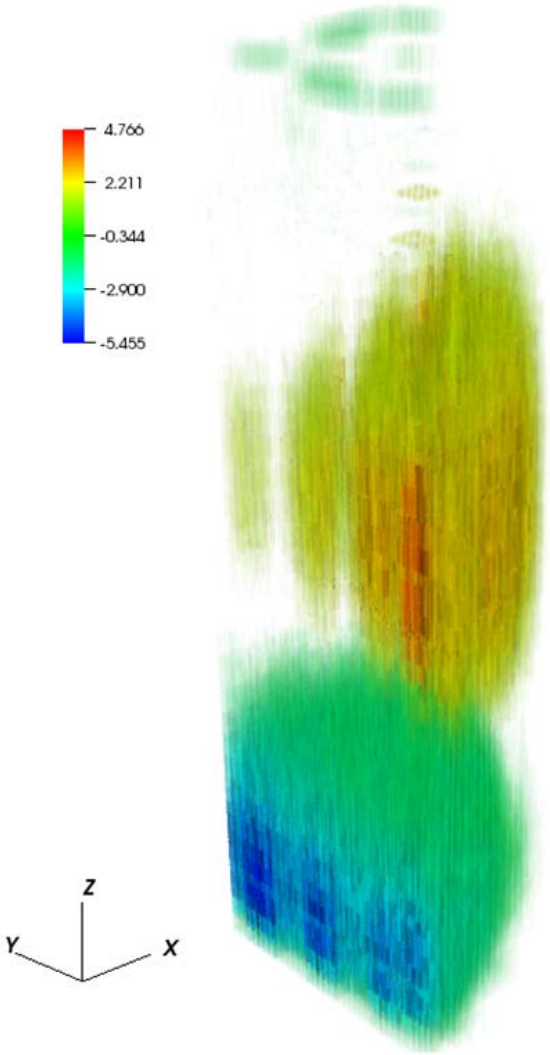
Multirodded – Results

- Moderator at 600 K, fuel at 900 K
- Eigenvalue and difference in fission rate distribution:

Axial Trans. Corr.	Δk (pcm)	ΔF RMS (%)	ΔF MAX (%)	ΔAO (%)
Out-Scat.	-155	1.62	5.46	0.83
In-Scat.	-133	0.49	2.29	-0.03
NLC	-138	0.62	2.74	0.23

- As with the ARO case, in-scatter approximation performs the best



Out-Scatter

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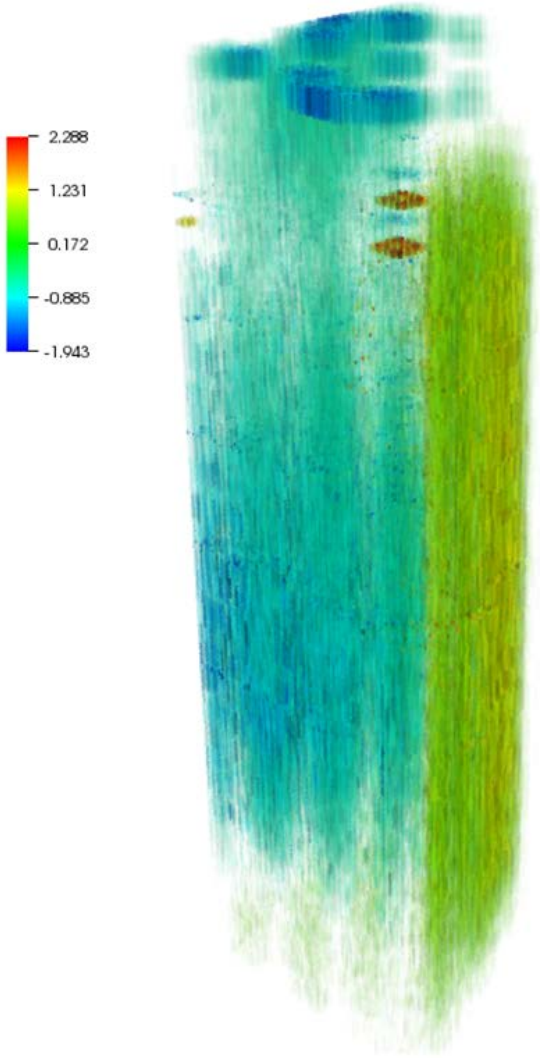
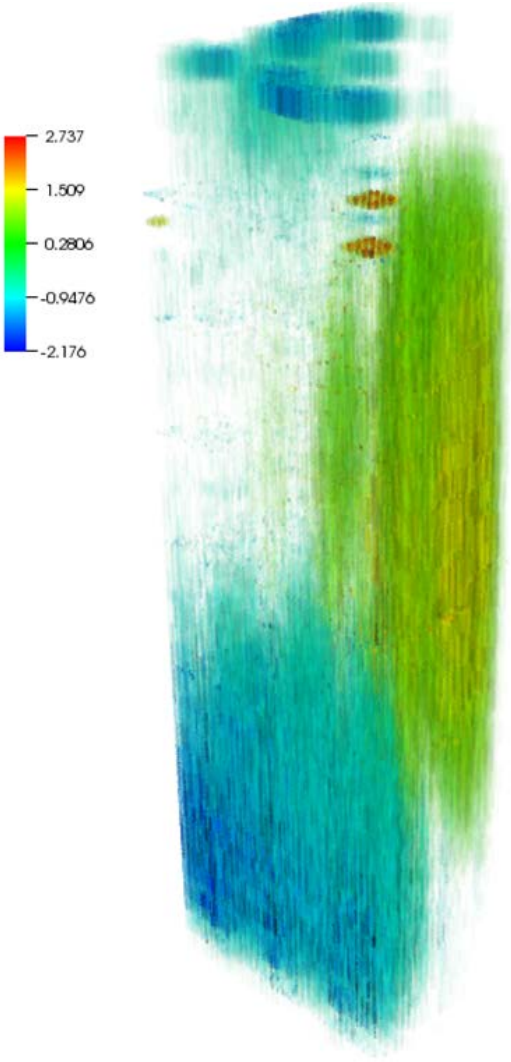
Hot, Multirodded – Results



In-Scatter



NLC

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Summary/Conclusions

- Severe accuracy issues when using the out-scatter approximation to formulate diffusion coefficients in cases with partial length burnable absorbers
- Using in-scatter and NLC approximations significantly improves accuracy
  - Runtime difference is negligible
- Single assembly cases showed accurate results with NLC, though in-scatter outperformed on quarter-core cases
- Radial tilts currently observed in MPACT cases using P_N scattering, which could be the source of inconsistent trends

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Acknowledgments

- The authors wish to express gratitude to the developers of KENO and Shift, which were used to generate reference solutions in this work.
- This research was supported by the Consortium for Advanced Simulation of Light Water Reactors (www.casl.gov), an Energy Innovation Hub (http://www.energy.gov/hubs) for Modeling and Simulation of Nuclear Reactors under US Department of Energy Contract No. DE-AC05-00OR22725.
- This research also made use of resources of the Oak Ridge Leadership Computing Facility at the Oak Ridge National Laboratory, which is supported by the Office of Science of the US Department of Energy under Contract No. DE-AC05-00OR22725.

Thank you for your time!
Questions?

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