



February 12, 2025

Polaris/PARCS Validation

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Brief Polaris Overview

Lead: Matt Jessee



Polaris is a “fast” 2-D LWR lattice physics code, originally deployed in SCALE 6.2 for LWR nodal core simulation

Simple Input

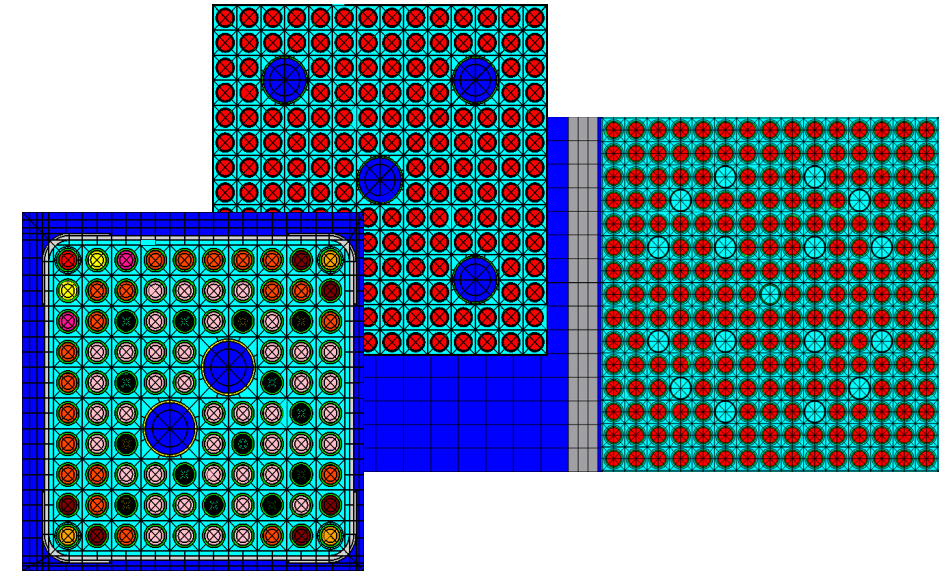
- Assembly geometry
- Material definitions
- Range of system conditions

Output

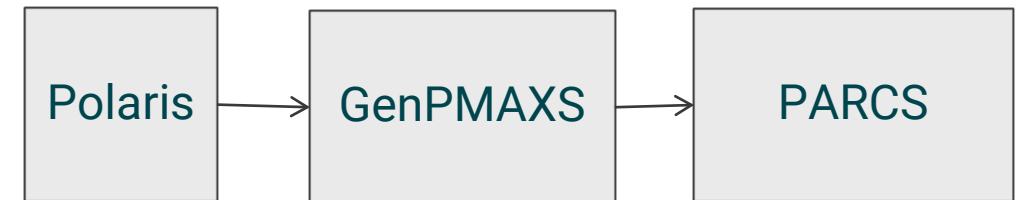
- Assembly-averaged few-group cross sections
 - Used as input for nodal core simulator such as PARCS
- Depletion material isotopics
 - Used for spent fuel characterization

Modeling Requirements

- Accurate prediction of lattice k-eff, pin power distribution, few-group cross-sections, depletion isotopics
- Relatively fast: 1,000s of transport calculations per core analysis



Wide range of LWR geometry support



ORNL has made significant usability and performance improvements to Polaris for ATF/HALEU/HBU investigations.

SCALE 6.3 Enhancements to the Polaris Lattice Physics Code for Light Water Reactor Confirmatory Analysis

Matthew A. Jessee^{1,*}, Ugur Mertyuerek¹, Kang Seog Kim¹, Shane W. D. Hart¹,
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¹Oak Ridge National Laboratory, Oak Ridge, TN, USA; ²OECD Nuclear Energy Agency, Paris, France

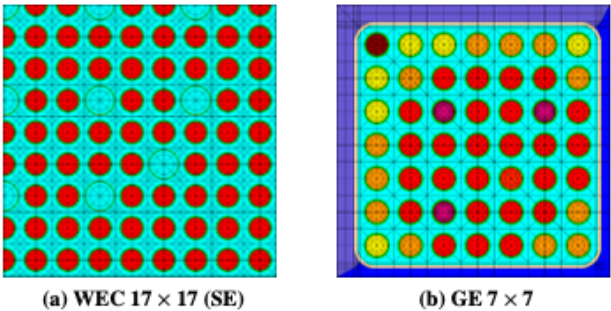


Figure 1. Typical PWR and BWR lattice designs

Table I. Polaris depletion run-time comparisons

Lattice	SCALE 6.2		SCALE 6.3		Speedup
	total (sec)	sec/statepoint	total (sec)	sec/statepoint	
WEC 17 × 17 (SE) 0 IFBA	23048	122	8443	45	2.6
WEC 17 × 17 (SE) 104 IFBA	56760	300	16174	86	3.5
GE 7 × 7	26001	140	10232	55	2.5

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SCALE 6.3 Enhancements:

- Run-time speedups
- F33 file generation and F71 enhancements
- Gamma detector edits
- ATF materials and compositions

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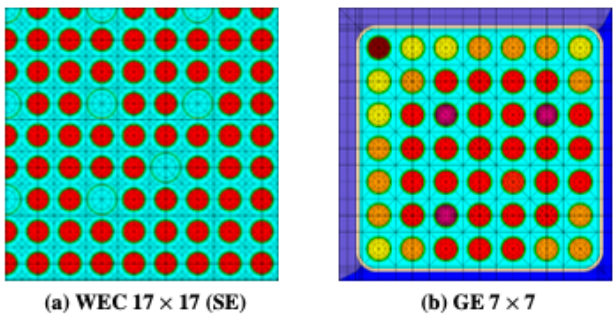


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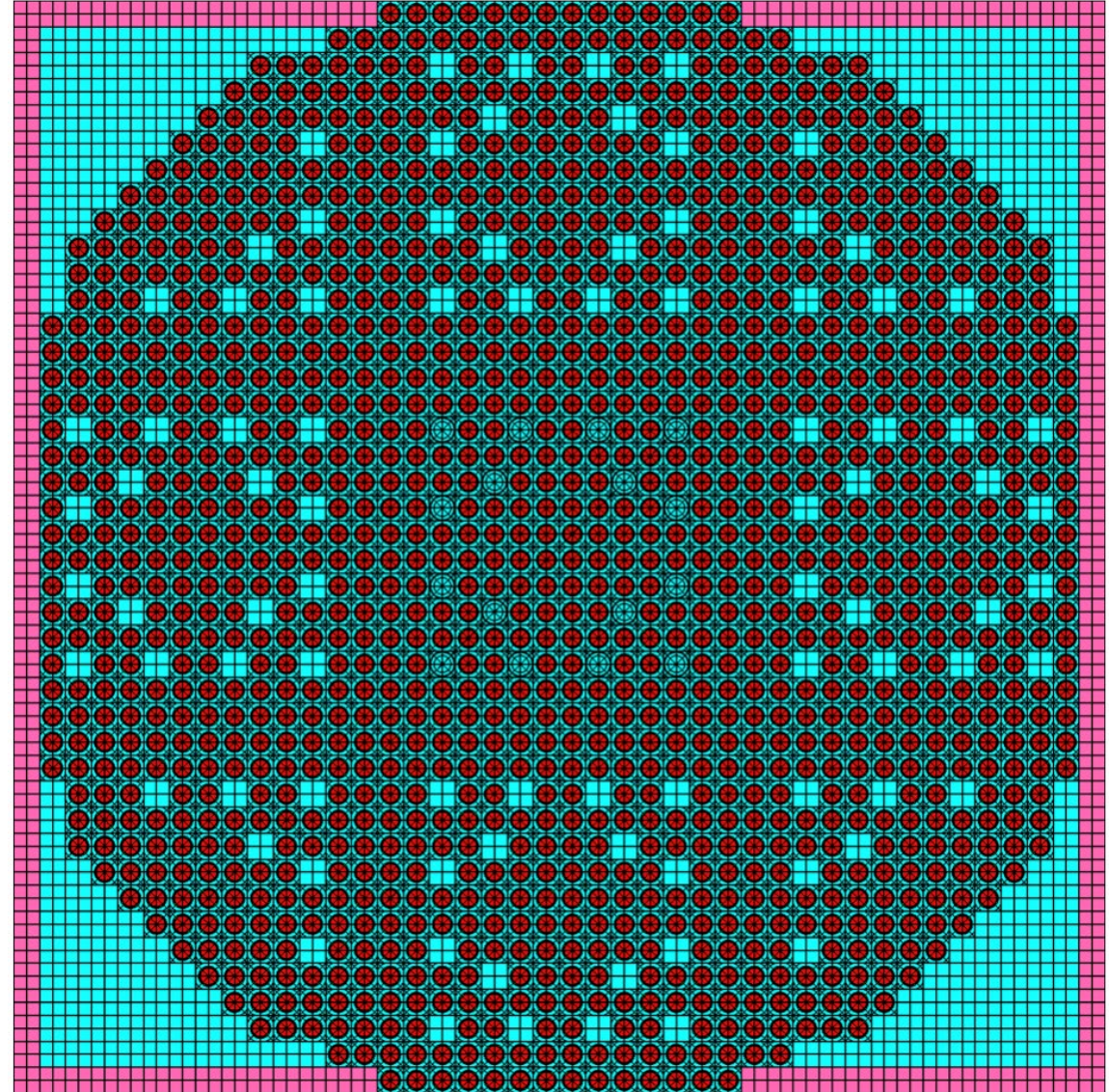
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- F33 file generation and F71 enhancements
- Gamma detector edits
- ATF materials and compositions

SCALE 7.0 Enhancements:

- Geometric buckling search and modular geometry
- On-the-fly energy collapse (still needs rigorous assessment)
- Automatic burnup selection and gad/ifba defaults
- Case matrix optimization
- Gamma smearing



SCALE 6.3 Reactor Physics Validation Report

Lead: Kang Seog Kim



ORNL/TM-2023/3060 outlines several reactor physics validation cases for Polaris-PARCS.

ORNL/TM-2023/3060

SCALE 6.3 Validation: Reactor Physics



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December 2024



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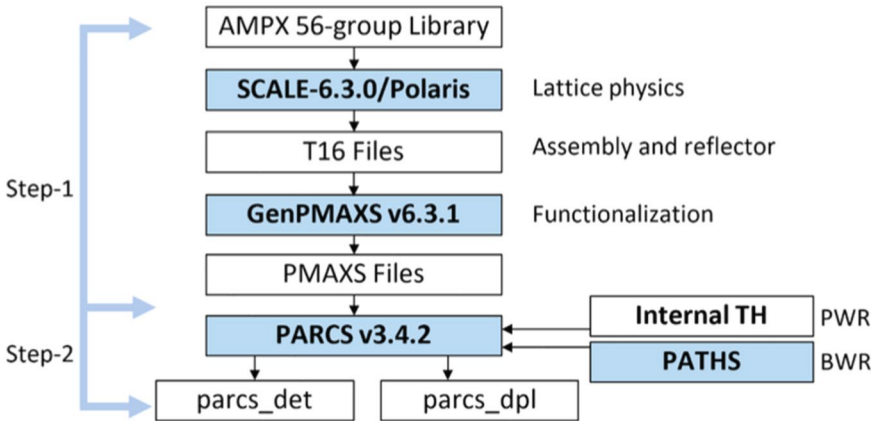


Figure 2.2. Flowchart of the Polaris-GenPMAXS-PARCS procedure.

Table 2.1. Key programs and data used in the benchmark calculations.

Program	File name	Version	md5sum ^a	Reference
SCALE/Polaris	scalerte	6.3.0	c30aa9d4841d51636ea08f2aa71cf1e5	[3]
ENDF/B-VII.1 56-group library	scale.rev00.xn56g19v7.1	6.3.0	2a1ab889c81354758bd85b3c0593db7a	[1]
GenPMAXS	genpmaks-v6.3.1-linux2-intel-x64-release.x	6.3.1	5a0428587c6ba65e2028e6dc98d29488	[10]
PARCS	parcs-v342-linux2-intel-x64-release.x	3.4.2	fd005b709d0b597dd6910129d03fe8f5	[5]

^a A program to ensure file integrity.

ORNL/TM-2023/3060 outlines several reactor physics validation cases for Polaris-PARCS

PWR

- Critical experiments: 5 CE and 6 B&W-1810
- Watts Bar Nuclear Unit 1 (WBN1) cycles 1-3 (WEC 4-loop)
- BEAVRS cycles 1-2 (WEC 4-loop)
- Surry unit 1 (SU1) cycles 1-2 (WEC 3-loop)
- Turkey point unit 3 cycles 1-3 (Wec 3-loop)

Table 3.5. Publicly available PWR plant measured data.

Plant	Type	Measured data					Reference	ORNL report
		Design	HZP	PPM ^a	In-core	Cycles		
Watts Bar Nuclear Unit 1	WEC 4-loop	yes	yes	yes	yes	1, 2, 3	[31, 33]	[20]
BEAVRS	WEC 4-loop	yes	yes	yes	yes	1, 2	[32]	[21]
Surry Unit 1	WEC 3-loop	yes	no	yes	yes	1, 2, 3	[34]	[22]
Turkey Point Unit 3	WEC 3-loop	yes	yes	yes	yes	1, 2, 3	[35]	[23]
TMI Nuclear Unit 1	B&W	yes	yes	yes	partly	1, 2	[36, 37]	—
Arkansas Nuclear One Unit 2	C-E	yes	no	—	yes	1	[38]	—
Zion Unit 2	WEC 4-loop	yes	yes	yes	yes	1, 2	[39]	—
Almaraz Unit 2	WEC 3-loop	yes	yes	yes	partly	1, 2	[40]	—

^a Critical boron concentration.

Table 3.6. Specifications of the PWR plants.

Parameter	Watts Bar Unit 1	BEAVRS	Surry Unit 1	Turkey Point 3
Core power (MW _{th})	3,411	3,411	2,441	2,200
Operating pressure (psia)	2,250	2,250	2,250	2,250
Core flow rate (10 ⁶ kg/h)	59.738	61.5	45.8	44.0
Inlet temperature (°C)	291.85	292.89	293.33	282.22
Number of assemblies	193	193	157	157
Initial core loading (MTU)	88.8	81.8	70.0	70.4
Pin lattice configuration	17 × 17	17 × 17	15 × 15	15 × 15
Active fuel length (cm)	365.76	365.76	366.903	365.76
Number of fuel rods	264	264	204	204
Number of spacer grids	6 Zr-4, 2 Inc-718	6 Zr-4, 2 Inc-718	7 Inc-718	7 Inc-718
Assembly pitch (cm)	21.50	21.50364	21.50364	21.50364
Pin pitch	1.26	1.25984	1.43	1.43
Fuel pellet radius (cm)	0.4096	0.39218	0.46469	0.46469
Cladding inner/outer radius (cm)	0.4180/0.4750	0.40005/0.45720	0.47422/0.53594	0.47422/0.53594
Number of control banks	57	57	53	53
Control rod material	B ₄ C/AgInCd	B ₄ C/AgInCd	AgInCd	AgInCd
Burnable poison material	Pyrex, IFBA ^a , WABA ^b	Pyrex	Pyrex	Pyrex
In-core detector	Fission chamber	Fission chamber	Fission chamber	Fission chamber

^a IFBA = integrated fuel burnable absorber. ^b WABA = wet annular burnable absorber.

BWR

- Peach Bottom Unit 1 (PB1) cycles 1-3
- Hatch Unit 1 (H1) cycles 1-3
- Quad Cities Unit 1 (QC1) cycles 1-3
- Monticello (MC) cycle 1 (not included)

Table 4.1. Publicly available BWR plant measured data.

Plant	Type	Measured data				Reference	ORNL report
		Design	Gamma scan	TIP	Cycles		
Peach Bottom Unit 2	GE type 4	yes	no	yes	1, 2, 3	[47, 48]	[42]
Hatch Unit 1	GE type 4	yes	yes	yes	1, 2, 3	[49, 50]	[43]
Quad Cities Unit 1	GE type 3	yes	partly	yes	1, 2, 3	[51, 52]	[44]
Monticello	GE type 3	yes	no	no	1, 2, 3	[53]	—

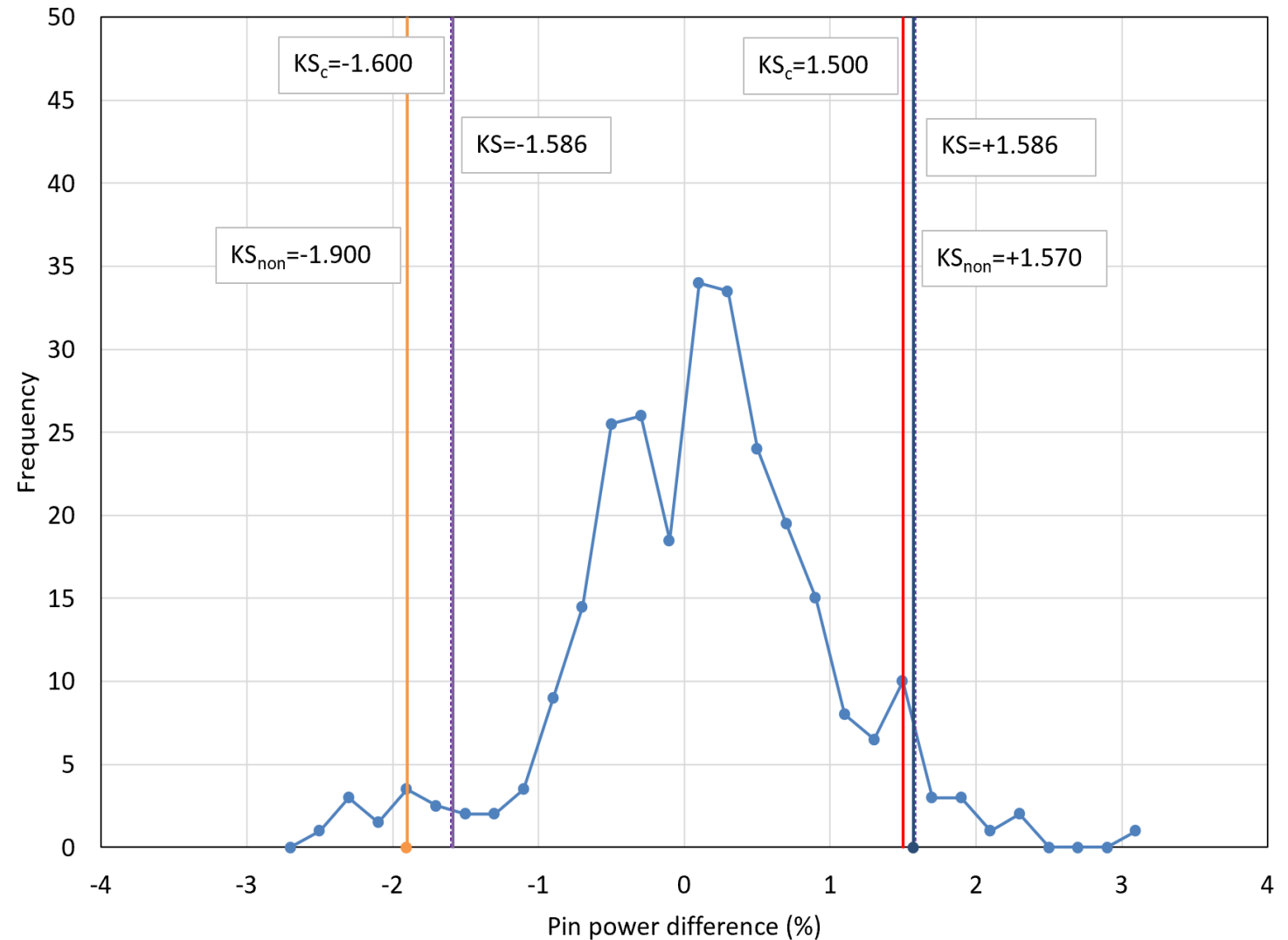
Table 4.2. Specifications of the selected BWR plants.

Parameter	Peach Bottom 2	Hatch 1	Quad Cities 1	Monticello
Core power (MW _{th})	3293	2436	2511	1670
Core pressure (psia)	1035	1035	1035	1035
Core flow rate (Mlb/h)	102.5	78.5	94.12	57.6
Core inlet enthalpy (Btu/lb)	521.3	523.7	521.3	523.0
Number of assemblies	764	560	724	484
Initial core loading (MTU)	144.4	104.7	140.3	93.7
Pin lattice configuration	7×7 / 8×8	7×7 / 8×8	7×7 / 8×8	7×7 / 8×8
Active fuel length (cm)	365.76	365.76	365.76	365.76
Number of fuel rods	47/64	47/64	47/64	47/64
Assembly pitch (cm)	30.48	30.48	30.48	30.48
Pin pitch (cm)	1.875/1.6256	1.875/1.6256	1.87452/1.6256	1.875/1.6256
Fuel pellet radius (cm)	0.60579/0.5207	0.607/0.521	0.61976/0.52832	0.61849/0.52832
Cladding inner radius (cm)	0.62103/0.53976	0.622/0.540	0.63373/0.53975	0.63373/0.53975
Cladding outer radius (cm)	0.71501/0.62611	0.716/0.626	0.71501/0.62611	0.71501/0.62611
Number of control banks	185	136	177	121
Number of TIP instruments	43	31	41	24
Control rod material	B ₄ C	B ₄ C	B ₄ C	B ₄ C
Burnable poison material	Gadolinia	Gadolinia	Gadolinia	Gadolinia
In-core detector	Fission TIP	Fission/gamma TIP	Fission TIP	Fission TIP

PWR Pin Peaking Factor Uncertainty

Polaris calculation for critical experiments

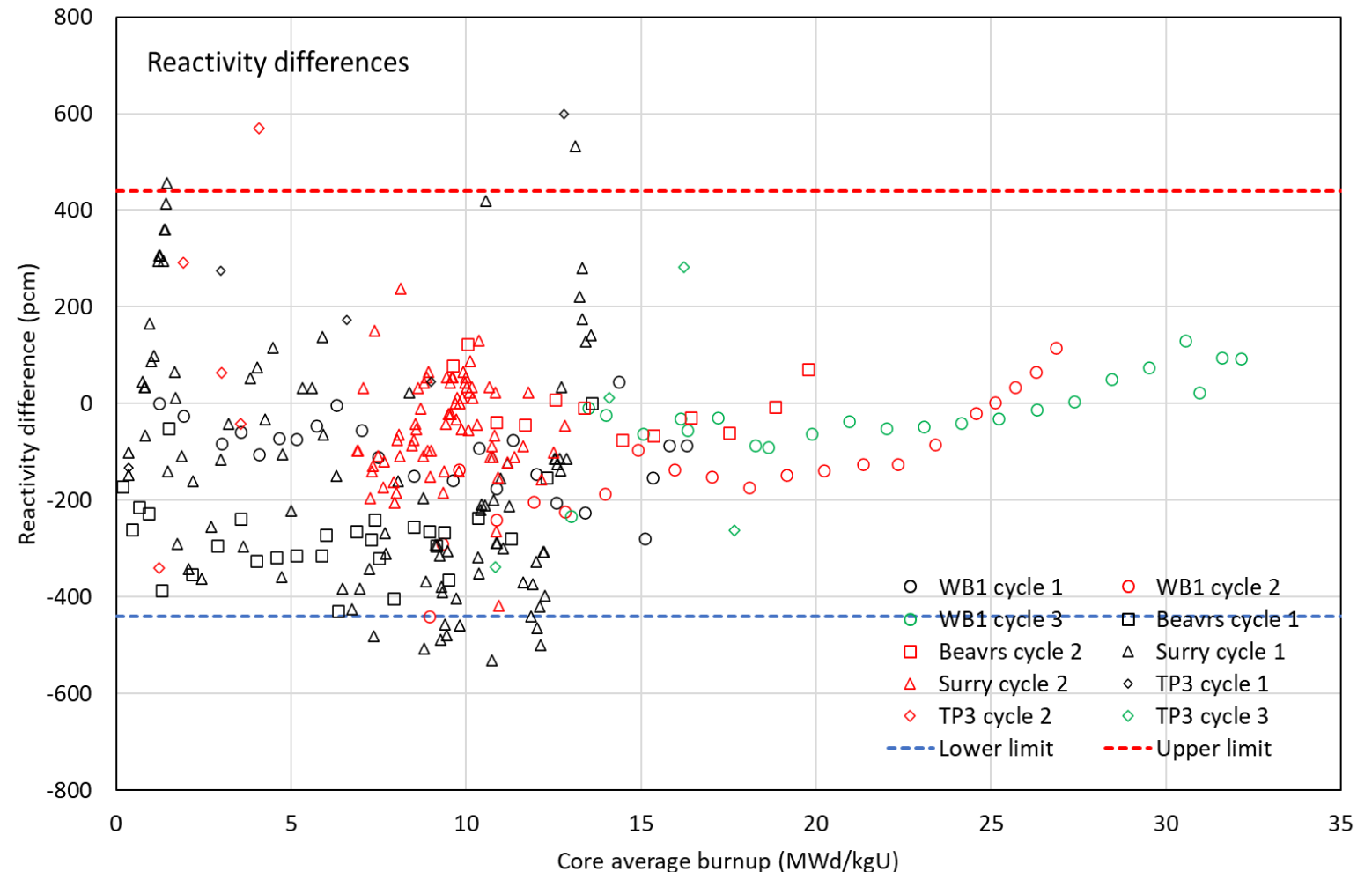
- 5 CE critical experiments
- 6 B&W-1810 critical experiments
- Statistical analysis to obtain uncertainty for pin power distribution
- Pin peaking factor uncertainty: $\pm 1.90\%$



PWR Uncertainties for Key Nuclear Parameters

Uncertainties

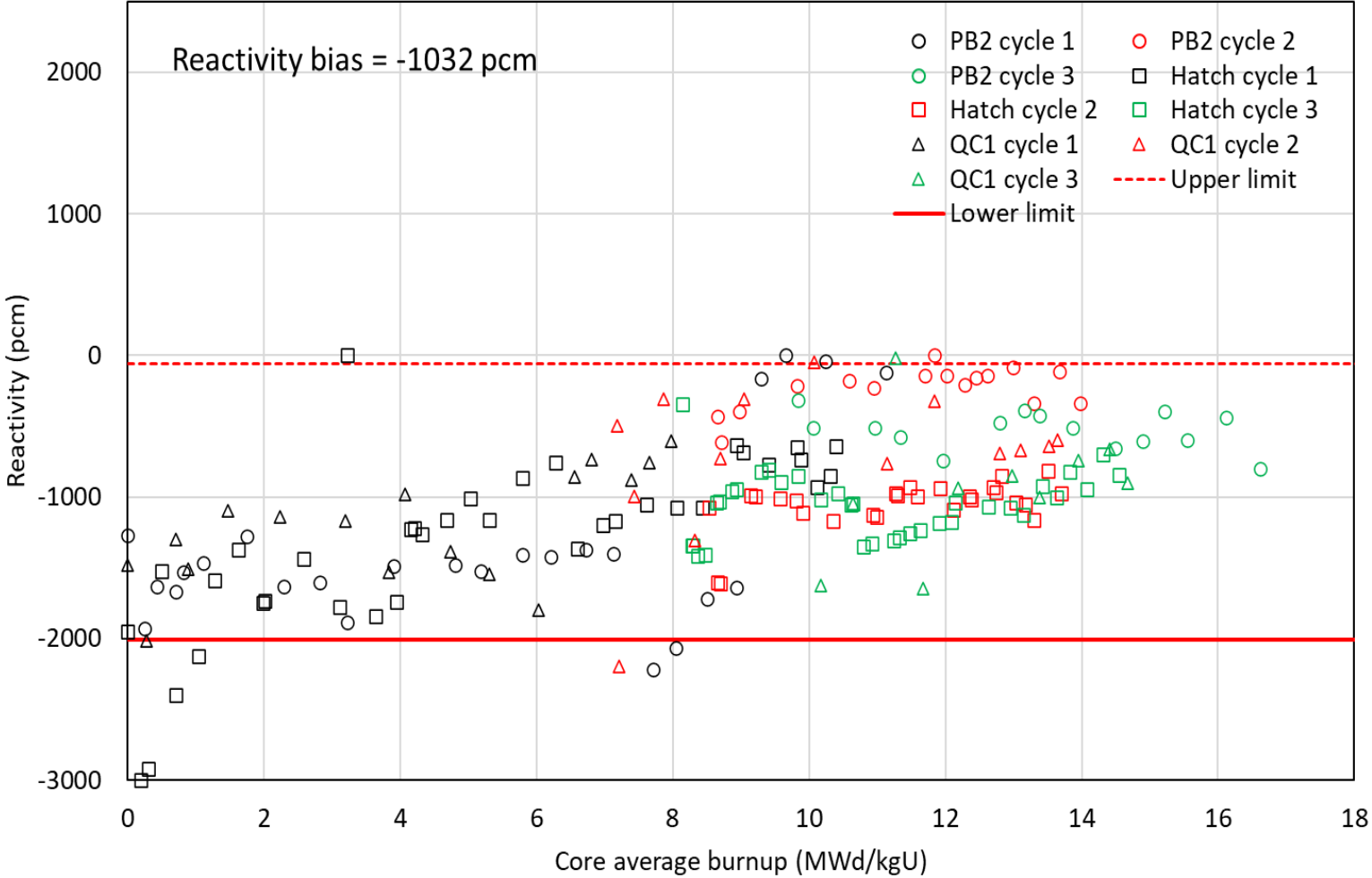
Parameter	Uncertainty
Critical boron concentration	± 42 ppm
Core reactivity	± 440 pcm
Boron worth	$\pm 19.1\%$
Temperature coefficient - Isothermal	± 1.22 pcm/ $^{\circ}\text{F}$
Control rod worth - Individual and total	$\pm 18.0\%$
Pin peaking factor in assembly	$\pm 1.90\%$
Assembly peaking in core - F_q - F_{xy} - F_r	$\pm 8.1\%$ $\pm 7.1\%$ $\pm 3.7\%$
Pin peaking in core - F_q - F_{xy} - $F_r, F_{\Delta H}$	$\pm 8.3\%$ $\pm 7.3\%$ $\pm 4.2\%$



BWR Uncertainties for Key Nuclear Parameters

Uncertainties

Parameter	Uncertainty (bias)
Core reactivity, all (bias)	± 975 pcm (-1032 pcm)
Core reactivity, reload (bias)	± 773 pcm (-834 pcm)
TIP (%)	
- 3D	$\pm 15.6\%$
- 2D axially integrated	$\pm 6.2\%$
- 1D radially integrated	$\pm 14.5\%$



Multigroup Library Enhancements

Lead: Kang Seog Kim



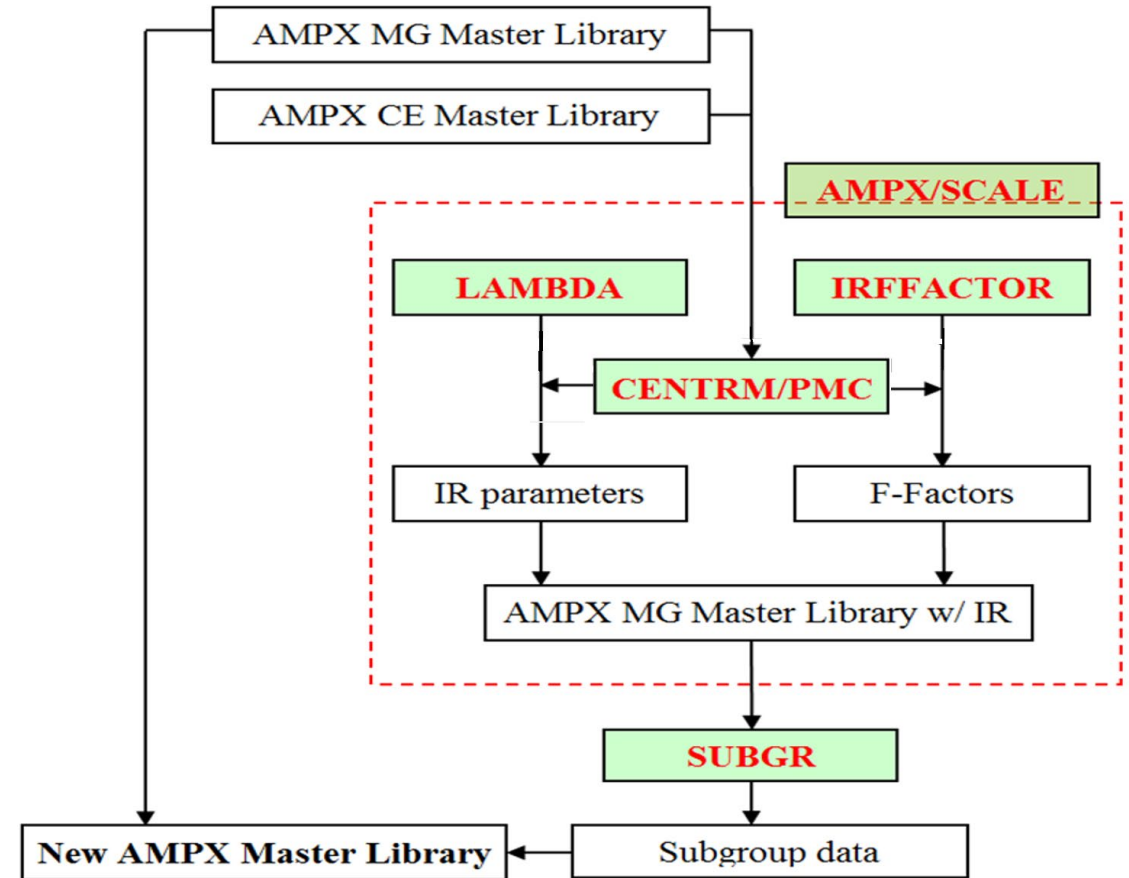
List of Accomplishments

- **Reduce multi-group biases for LWRs and nonLWRs**
 - New 258-group thermal system group structure
 - SCALE 6.1 had 238-group ~400 pcm
 - RR analysis led to 6.2 252-group ~150 pcm
 - SCALE 7.0 258-group reduces bias for any thermal system
 - +6 groups needed to reduce error in S-wave approximation at epithermal energy
 - Companion 61-group, a subset of 258
 - Addresses reactivity biases for depletion, ATF, and high voids
 - Greatly reduces the 56-group bias
 - 5 eV → 10 eV thermal cutoff energy improves results in graphite-moderated systems
 - Epithermal up-scattering resonance (DBRC)
 - Introduced a ESSM material grouping capability and SPH factors
- **Produce ENDF/B-VIII.0 libraries**
 - SCALE 6.3 has 56-, 252-, 302- (fast), 1597- (any)
 - For both E7.1 and E8.0 for comparison purposes
 - 56-group E8.0 not generated for 6.3.0 release due to lost recipes—added later
- **Address legacy issues affecting quality of broad group (56-group) commonly used with Polaris**
 - Even Lethargy widths
 - Old 56-group had some very small energy groups which was difficult to use in VERA-MPACT TCP₀ calculations
 - New 61-group has evenly distributed lethargy widths and can be used by VERA-MPACT—i.e. Polaris and MPACT can use the same libraries
 - Special F-factors
 - Old 56-group contained special F-factors for Zr-91 and Zr-96 making it difficult to reproduce
 - New relies on new ESSM material grouping and SPH factors and does not need the special F-Factors—much easier to generate new libraries, e.g. **ENDF/B-VIII.1**
 - Lower biases for depletion, ATF, and high voids

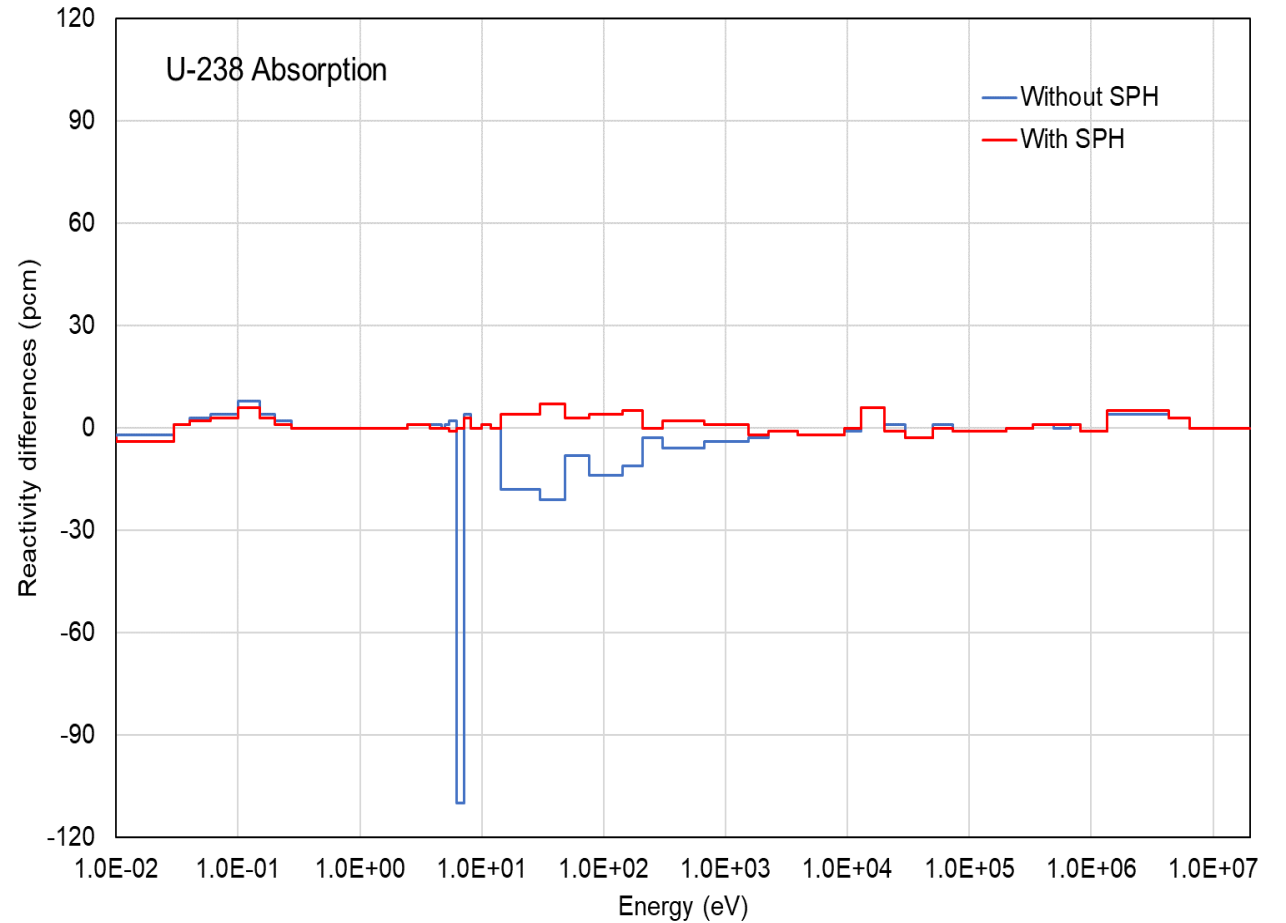
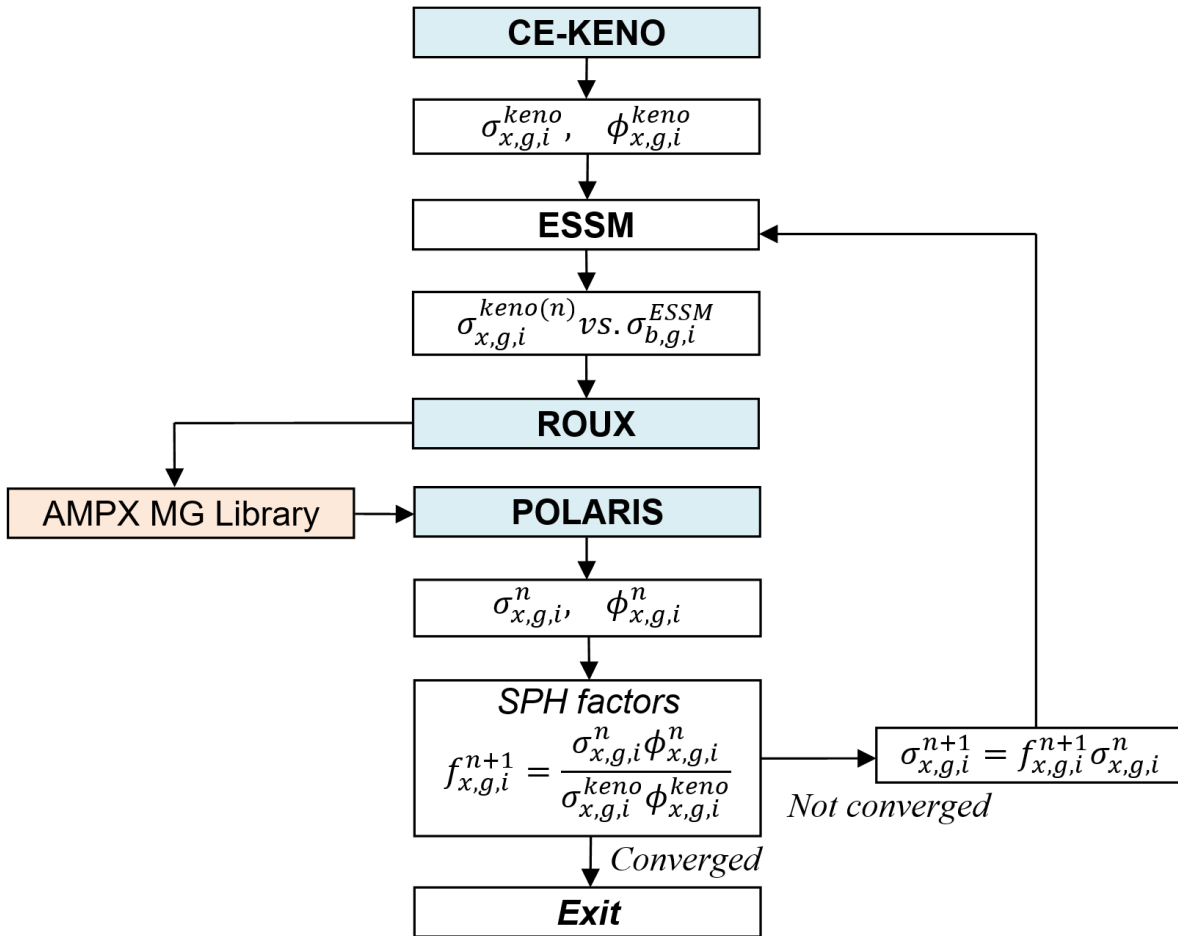
New SCALE 7.0 61- and 258-Energy Group Libraries

- ENDF/B-VII.1 and VIII.0
- No special F-factors (resonance data)
- Based on material-grouping ESSM
- SPH factor adjusted ^{238}U resonance data
- Epithermal upscattering resonance data for ^{238}U
- NLC based ^1H transport cross sections
- 10 eV thermal cutoff
- Extended heterogeneous F-factors

^{107}Ag , ^{109}Ag , ^{113}Cd , ^{113}In , ^{115}In , ^{133}Cs , ^{150}Sm , ^{155}Eu , ^{155}Gd , ^{156}Gd , ^{157}Gd , ^{158}Gd , ^{167}Er , ^{232}Th , ^{233}U , ^{235}U , ^{236}U , ^{238}U , ^{237}Np , ^{238}Pu , ^{239}Pu , ^{240}Pu , ^{241}Pu , ^{242}Pu , and ^{241}Am



New Super-homogenization (SPH) Procedure



Benchmark Suite For Verification

Table 4.1. Summary of the benchmark problems.

Reactor	No	Description	Cases	Variations	Power plants	Ref.
PWR	1	VERA progression 1 and 2	21	T_F, B_P, C_R	WBN1	[17, 18]
	2	VERA snapshot burnups	9	B_U	WBN1	[19]
	3	VERA depletion	27	T_F, B_P, B_U, C_R	WBN1	[20]
	4	VERA extensive pins	600	E_U, T_F, T_M, S_B	BEAVRS, Krsko, Surry, WBN1	[21]
	5	VERA extensive assemblies	2100	E_U, T_F, T_M, B_P, S_B	BEAVRS, Krsko, Surry, TMI1, TMI2, WBN1	[22]
	6	SNU nonuniform	14	T_F, P_O	PWR	[23]
	7	Mosteller	48	T_F, E_U	PWR	[24]
	8	ATF extensive pin	150	E_U, T_F, B_P, C_R, S_B	UN, UNUB ₂ , UO ₂ , US, USUB ₂	-
	9	ATF extensive assembly	150	E_U, T_F, B_P, C_R, S_B	UN, UNUB ₂ , UO ₂ , US, USUB ₂	-
BWR	10	BWR extensive pin	220	E_U, T_F, T_M, V_O	GE09, GE14, PB02, PBT6	[25]
	11	BWR extensive assembly	204	T_F, T_M, V_O	AT10, GE09, GE13, GE14, GE14 LEU+	[26, 27, 28]
	12	BWR depletion	12	V_O	AT10, GE09, GE13, GE14	[26, 27]
		Total	3555			

Benchmark Calculations :: (1) VERA Progression problems

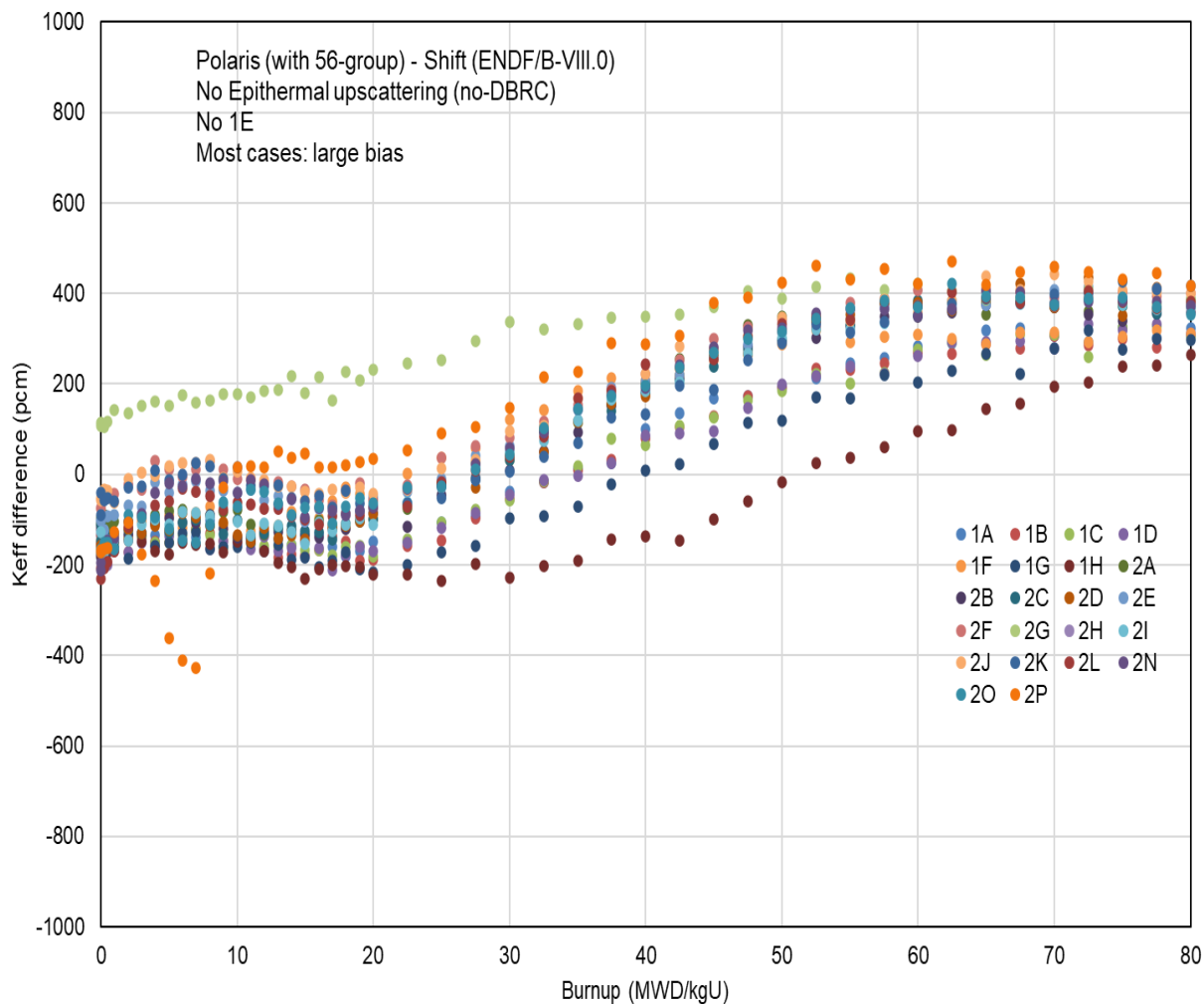
- Refined ray options (right) for IFBA and Gd: 1E, 2L, 2M, 2N, 2O, 2P

Case	KENO	Shift	SCALE 6.3						SCALE 7.0					
			56-group			252-group			61-group			258-group		
			Δk pcm	Pin power %		Δk pcm	Pin power %		Δk pcm	Pin power %		Δk pcm	Pin power %	
				S.D.	Max.		S.D.	Max.		S.D.	Max.		S.D.	Max.
1A	1.18638	4	-135			-57			-78			-92		
1B	1.18139	3	-155			-53			-91			-106		
1C	1.17102	-5	-170			-73			-97			-102		
1D	1.16216	-2	-187			-97			-81			-95		
1E	0.77452	-8	65			26			12			-39		
2A	1.18183	4	-98	0.12	-0.37	-42	0.12	-0.36	9	0.12	0.36	-70	0.12	-0.36
2B	1.18291	-3	-125	0.13	-0.32	-45	0.12	-0.33	7	0.12	-0.33	-87	0.12	-0.33
2C	1.17361	14	-155	0.13	0.33	-80	0.13	0.32	-11	0.13	0.33	-99	0.13	0.32
2D	1.16530	9	-152	0.10	0.32	-83	0.10	0.31	29	0.10	0.32	-74	0.10	0.31
2E	1.07006	-11	-82	0.13	-0.34	-32	0.12	-0.32	44	0.12	-0.30	-80	0.12	-0.32
2F	0.97684	-6	-49	0.16	-0.42	-11	0.14	-0.39	78	0.14	-0.41	-76	0.14	-0.39
2G	0.84924	-11	78	0.15	-0.39	22	0.14	-0.43	106	0.18	-0.54	-164	0.14	-0.43
2H	0.78890	12	-95	0.23	0.80	-53	0.18	0.62	51	0.18	0.58	-154	0.18	0.62
2I	1.17980	-19	-113	0.12	0.38	-53	0.12	0.37	1	0.12	0.39	-80	0.12	0.37
2J	0.97620	-28	-58	0.17	0.36	-21	0.14	0.32	67	0.14	-0.31	-86	0.14	0.32
2K	1.02041	-3	-46	0.15	0.32	-2	0.13	0.28	114	0.13	0.31	-61	0.13	0.28
2L	1.02026	7	-82	0.13	-0.32	-65	0.14	-0.35	-24	0.15	-0.35	-106	0.14	-0.35
2M	0.94084	0	-60	0.12	-0.36	-64	0.12	-0.33	-28	0.14	-0.31	-110	0.12	-0.33
2N	0.87148	-3	-80	0.15	-0.39	-60	0.13	-0.34	7	0.13	-0.34	-123	0.13	-0.34
2O	1.04830	-1	-122	0.16	-0.33	-47	0.14	-0.32	22	0.15	-0.35	-69	0.14	-0.32
2P	0.92854	-7	-118	0.15	0.41	-46	0.13	0.39	68	0.16	0.43	-74	0.13	0.39

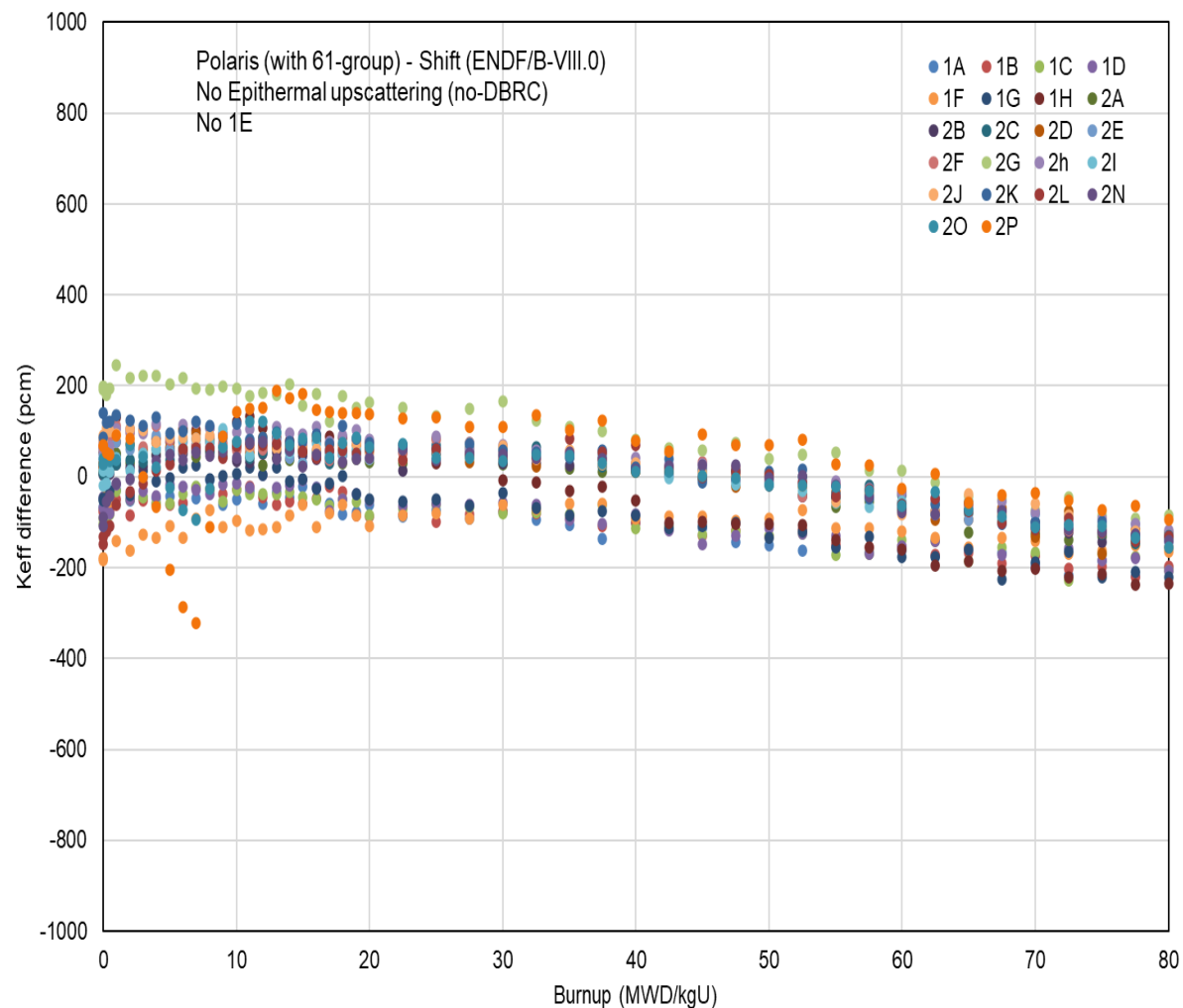
^a S.D.: Standard Deviation

Benchmark Calculations :: VERA Depletion I

SCALE 6.3 56-group

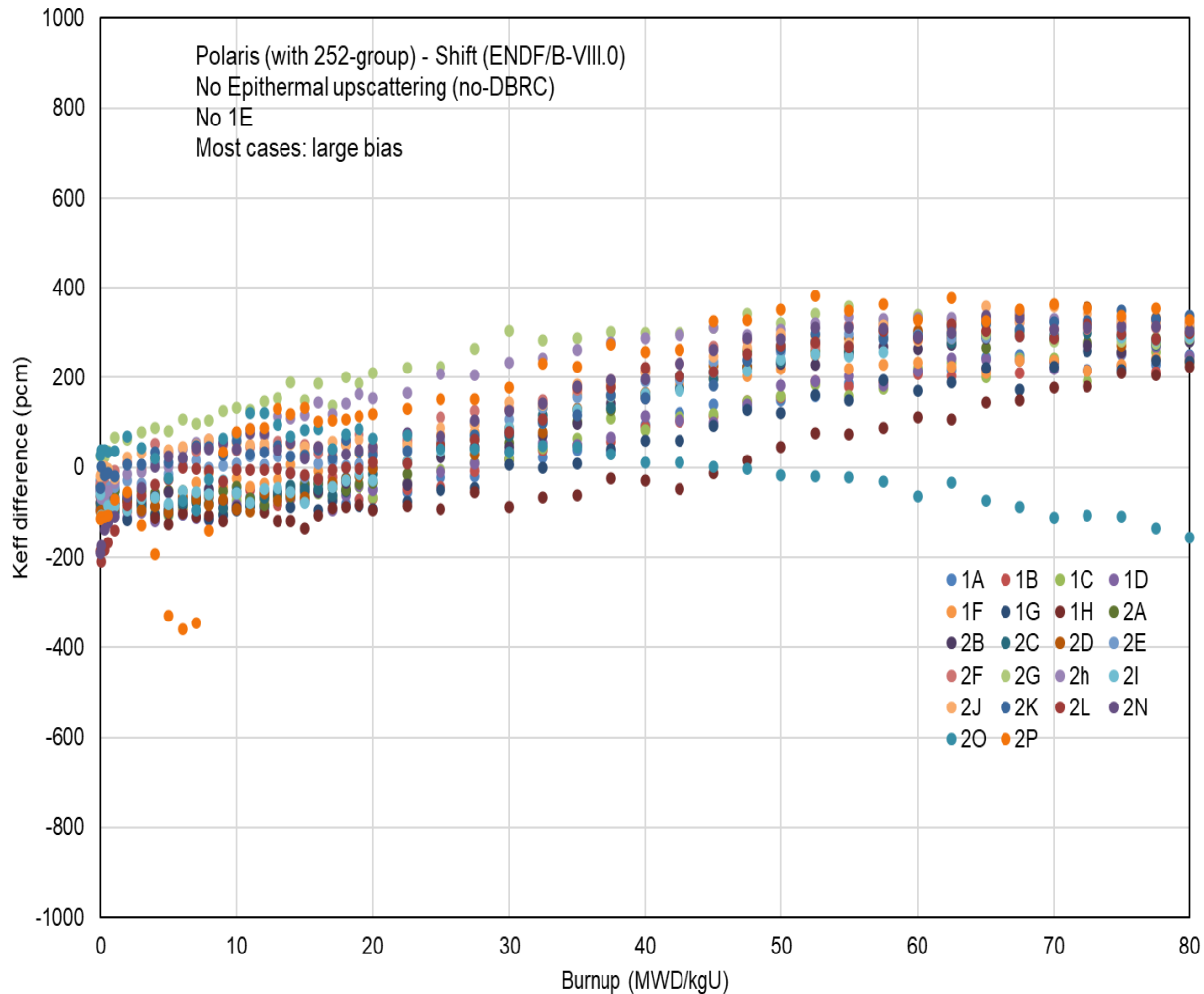


SCALE 7.0 61-group

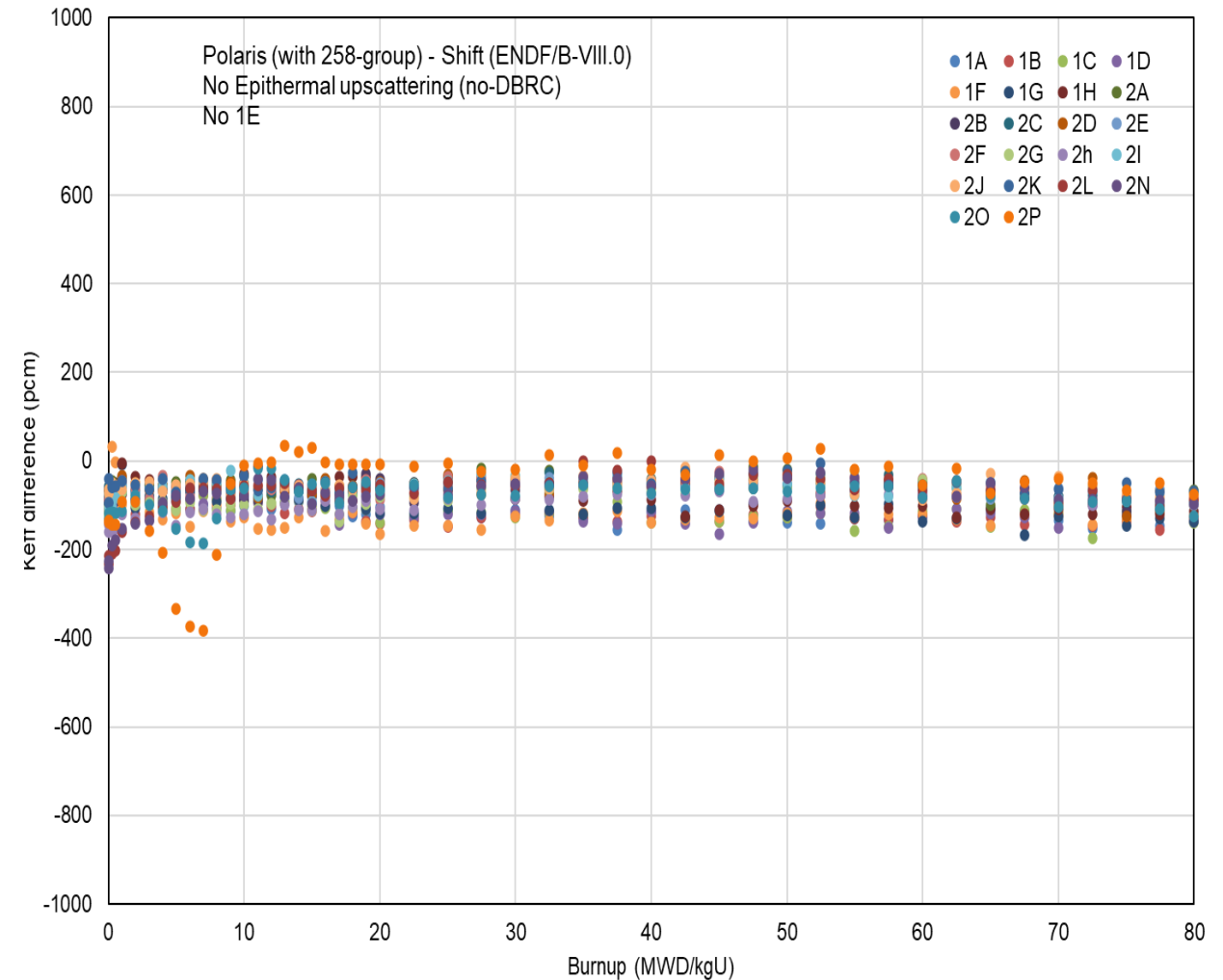


Benchmark Calculations :: VERA Depletion II

SCALE 6.3 252-group

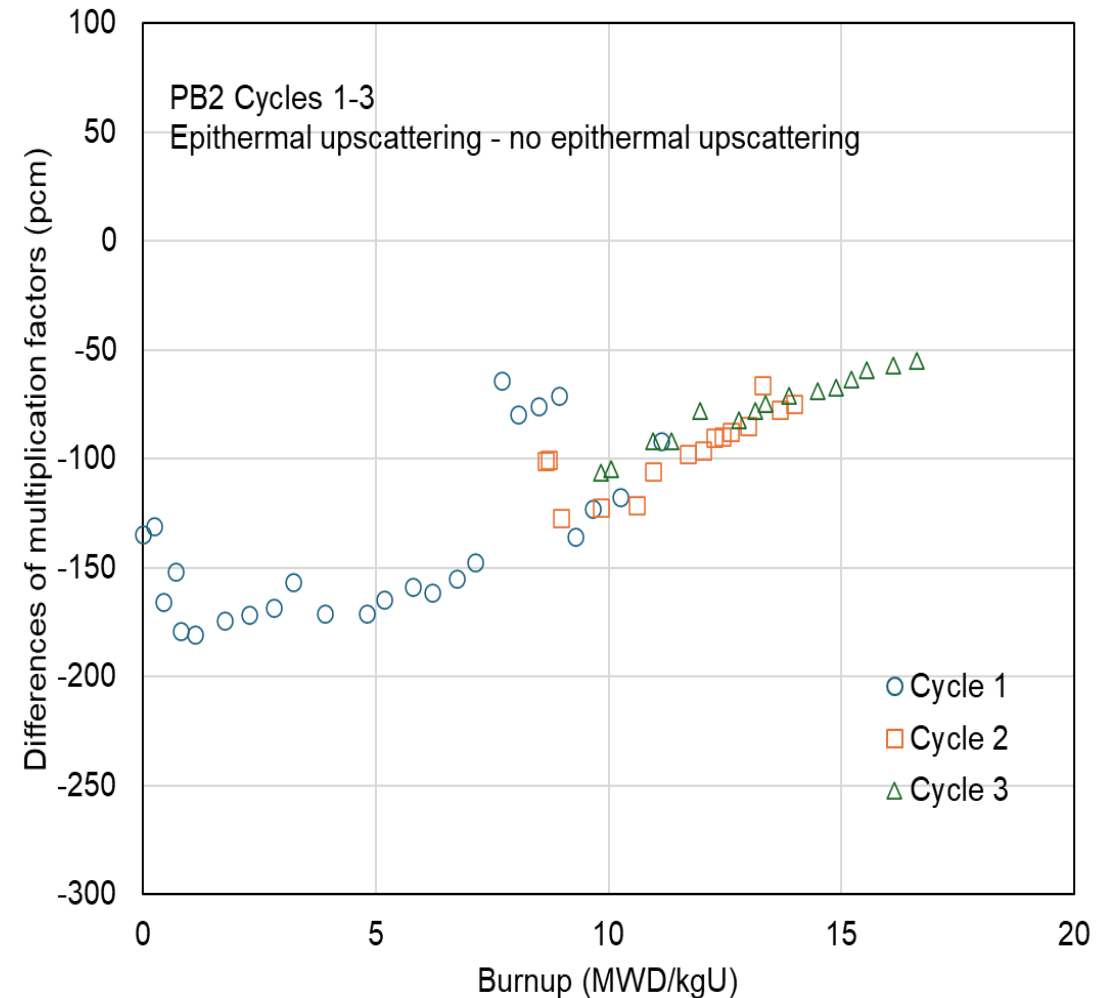
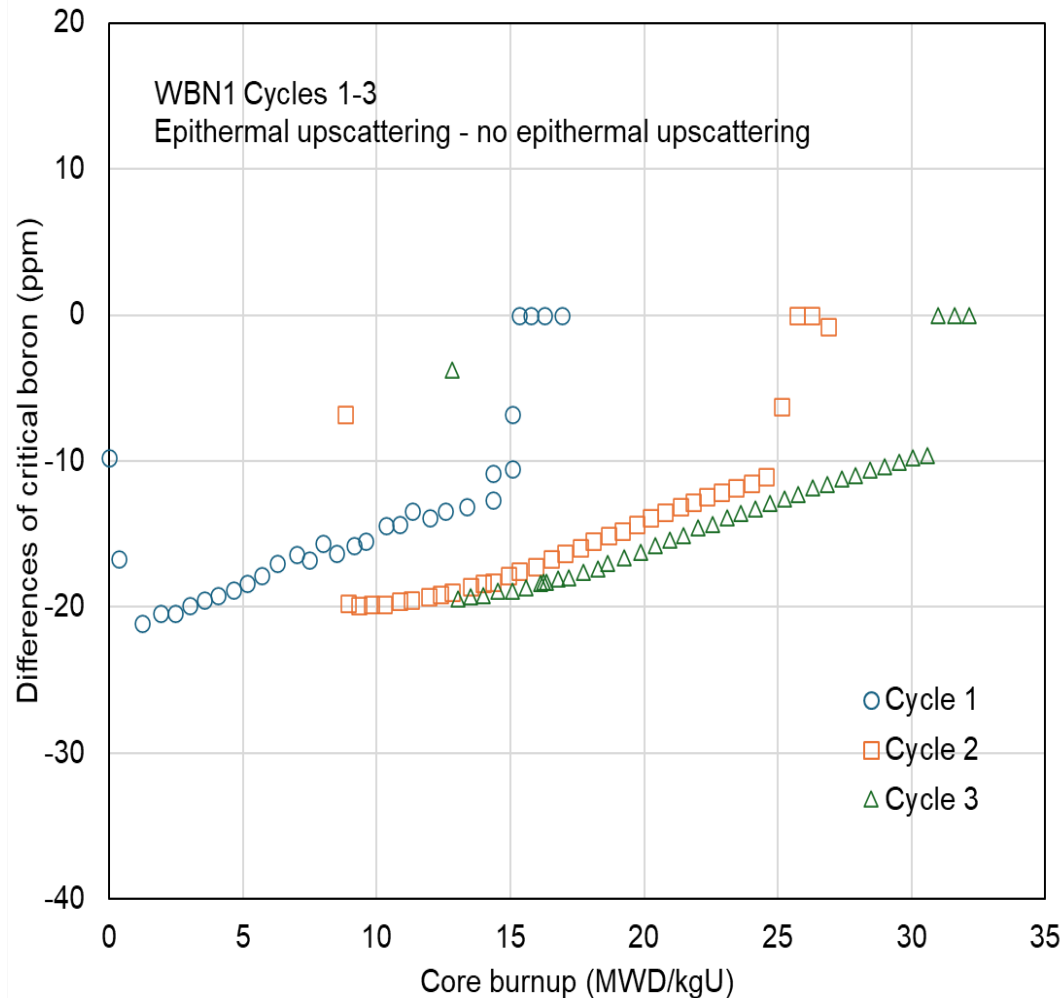


SCALE 7.0 258-group



Benchmark Calculations :: WBN1 and PB2

- 61-group with and without Epithermal upscattering



Conclusions

■ Validation Accomplishments

- Setup a standard analysis procedure of the SCALE/Polaris-PARCS procedure for LWR analysis
- First complete validation of the SCALE/Polaris-PARCS procedure for the LWR physics analysis
- Uncertainties for the key nuclear parameters for the PWR and BWR confirmatory analysis
- Publicly open repository including all the analysis related documents and input/output files

■ Polaris Enhancements

- SCALE 6.3 version is 2x to 3x faster than SCALE 7.0
- Generation of reactor libraries for ORIGEN source term assessment is a key new feature
- ATF input cards available

■ Significant improvements implemented in MG libraries for SCALE 7.0

- Better performance for depletion
- Epithermal up-scattering resonance data
- No special resonance data for Zr-91 and 96 cladding material
- 10 eV thermal cutoff for better results for graphite moderator cases
- Transport corrected scattering matrices for H-1 based NLC method