



VERA Solutions by UNIST MC Code MCS

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1. Introduction

- **The Monte Carlo (MC) method is to solve complicated 3D problems, especially which cannot be simulated explicitly by using deterministic code systems.**
- **To improve the accuracy of reactor analysis tools for neutron-physics simulation, Ulsan National Institute of Science and Technology (UNIST) has been developing the MC code named MCS.**
- **V&V works on MCS to ensure the accuracy and reliability.**
- **To verify and validate MCS using the VERA Core Physics Benchmark problems including the results of 3D multi-assembly and whole-core simulations.**

2. Monte Carlo Codes (1/2)

▪ Monte Carlo Code MCS [1]

- **Language: Fortran 2003**
- **Purpose**
 - **Large Scale Reactor Analysis** with accelerated Monte Carlo simulation
 - University research: MC methodology development, advanced reactor design
- **General 3-D geometry (CSG)**
- **Nuclear Data**
 - ENDF-B/VII.0 and ENDF-B/VII.1
 - Continuous energy and multi-group
 - Double indexing method
- **Physics**
 - Resonance upscattering (DBRC, FESK)
 - Probability table method
 - $S(\alpha, \beta)$
 - On the fly Doppler broadening
 - Cobra-TF/FRAPCON coupling
 - Photon transport
- **Acceleration**
 - MOC and MC Hybrid solver
 - Modified power iteration
 - Wielandt method
 - CMFD
- **Parallelism**
 - Parallel fission bank
- **Depletion**
 - CRAM, MEM, Krylov Subspace
 - Hybrid depletion

2. Monte Carlo Codes (2/2)

▪ KENO-VI [1]

- 3D Monte Carlo criticality computer code, one of the primary criticality safety analysis tools in SCALE (Standardized Computer Analysis for Licensing Evaluation) [12], developed and maintained by the Oak Ridge National Laboratory (ORNL).
- Used by the U.S. Nuclear Regulatory Commission (NRC) to enable standardized analyses and evaluation of nuclear facilities.

▪ VERA-CS [2]

- MPACT for reactor physics and neutron transport;
- COBRA-TF (CTF) for thermal-hydraulics; and
- ORIGEN-S for isotopic depletion.

[1] M.E. Dunn, C.L. Bentley, S. Goluoglu, L.S. Paschal, L.M. Petrie and H.L. Dodds, Development of a Continuous Energy Version of KENO Va. Nuclear Technology, Vol.119(3), p.306-313, 1997.

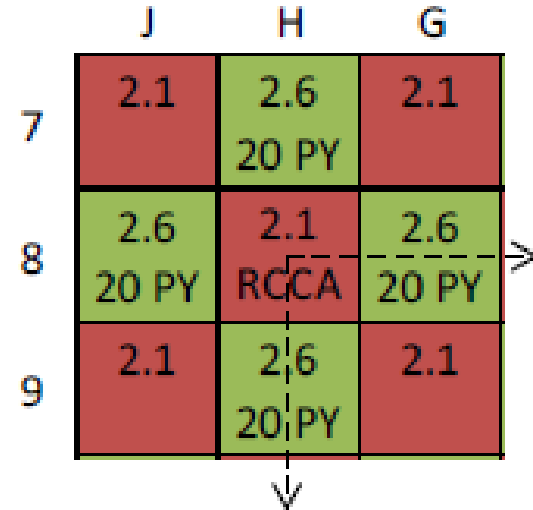
[2] J.A. Turner, K. Clarno, M. Sieger, et al., "The virtual environment for reactor applications (VERA): design and architecture," *Journal of Computational Physics*, Vol. 326, 2016, pp. 544-568.

3. Benchmark Solutions (1/20)

3.1. 3D HZP 3x3 Assembly Control Rod Worth

Specifications:

- 9 Westinghouse 17x17-type fuel assemblies arranged in a 3x3 pattern;
- Simulated condition: BOC, HZP isothermal conditions.
- Two fuel enrichment region:
 - 2.11% enrichment with center RCCA;
 - 2.619% enriched region with 20 Pyrex rods.



Input	Value
Fuel Density	10.257 g/cc
Fuel Enrichment – Region 1	2.11%
Fuel Enrichment – Region 2	2.619%
Power	0% FP
Inlet Coolant Temperature	565 K
Inlet Coolant Density	0.743 g/cc
Reactor Pressure	2250 psia
Boron Concentration	1360 ppm

3. Benchmark Solutions (2/20)

3.1. 3D HZP 3x3 Assembly Control Rod Worth

Problem 4 Solution Results

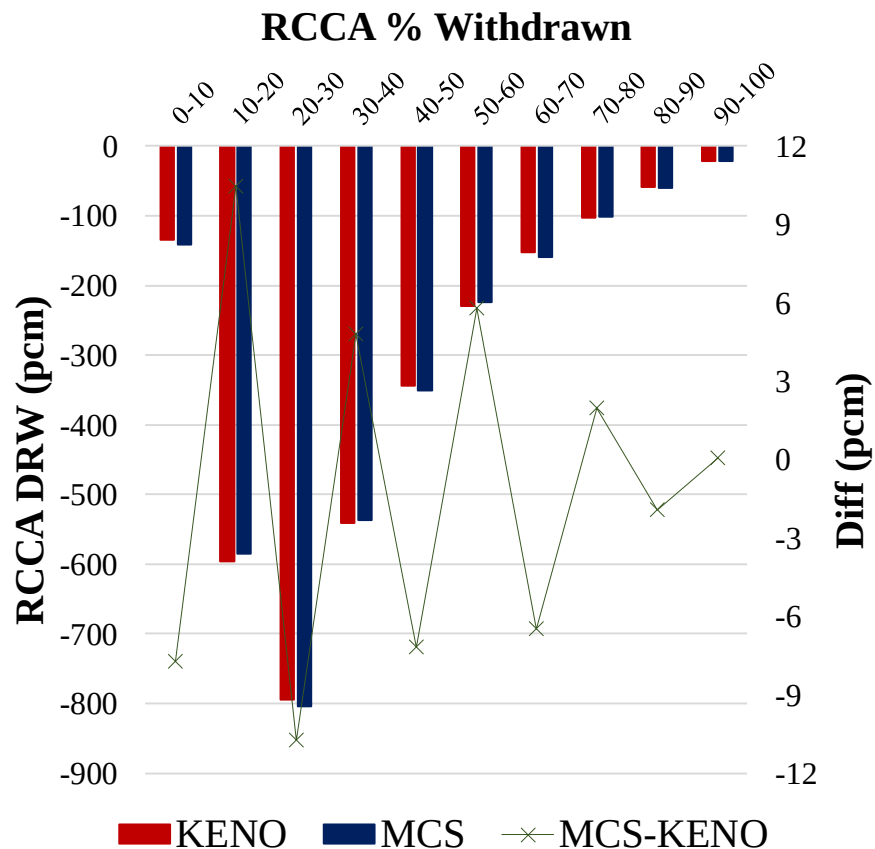
Code	Library	No. of histories	No. of processors	Exec. time (min)
KENO-VI	ENDF/B-VII.0	5.0E+09	300	1560
MCS	ENDF/B-VII.0	3.0E+08	40	120

% WD*	KENO	MCS	Diff. (± 3 pcm)	DRW		Diff. (pcm)	IRW		Diff. (pcm)
	k-eff (± 1 pcm)	k-eff (± 3 pcm)		KENO (± 2 pcm)	MCS (± 4 pcm)		KENO (± 2 pcm)	MCS (± 4 pcm)	
257.9cm	0.99898	0.99875	-23	--	--	--	-240	-238	2
0	0.97241	0.97207	-34	-134	-142	-8	-2975	-2986	-11
10	0.97368	0.97341	-27	-596	-586	10	-2842	-2844	-2
20	0.97936	0.97899	-37	-794	-805	-11	-2245	-2259	-14
30	0.98704	0.98677	-28	-541	-536	5	-1451	-1454	-3
40	0.99234	0.99202	-33	-344	-351	-7	-910	-918	-8
50	0.99575	0.99548	-26	-230	-224	6	-566	-567	-1
60	0.99803	0.99771	-32	-153	-159	-6	-336	-342	-6
70	0.99955	0.99930	-25	-103	-101	2	-183	-183	0
80	1.00058	1.00031	-27	-58	-60	-2	-80	-82	-2
90	1.00117	1.00091	-26	-22	-22	0	-22	-22	0
100	1.00139	1.00113	-25	--	--	--	0	0	0

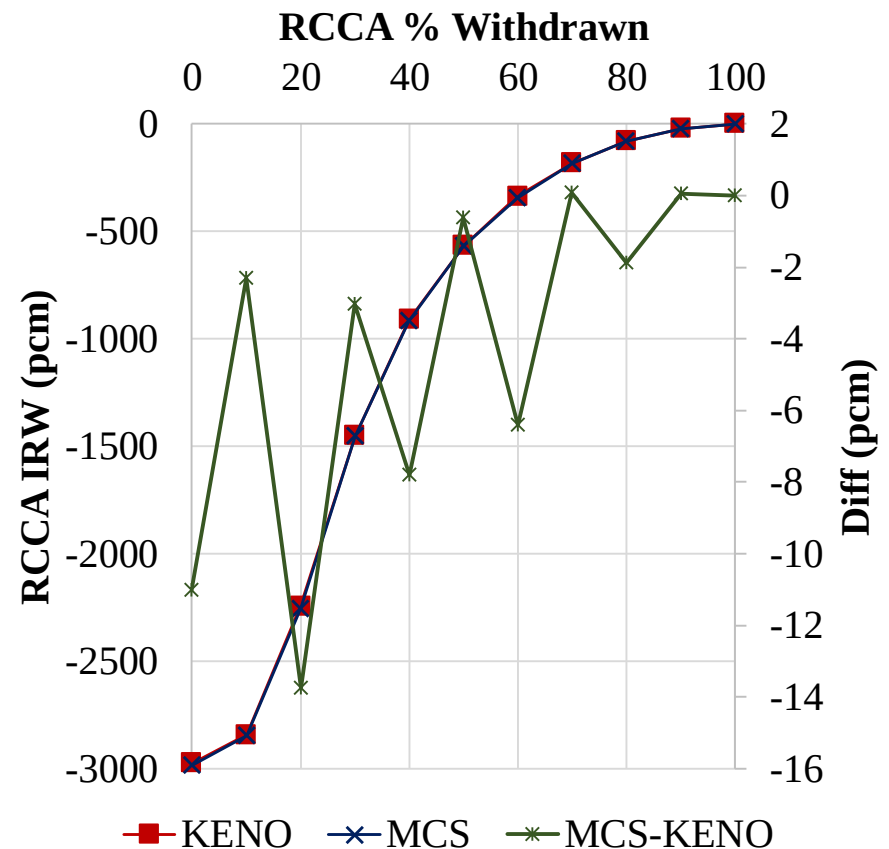
3. Benchmark Solutions (3/20)

3.1. 3D HZP 3x3 Assembly Control Rod Worth

Differential Control Rod Worth



Integral Control Rod Worth Curve

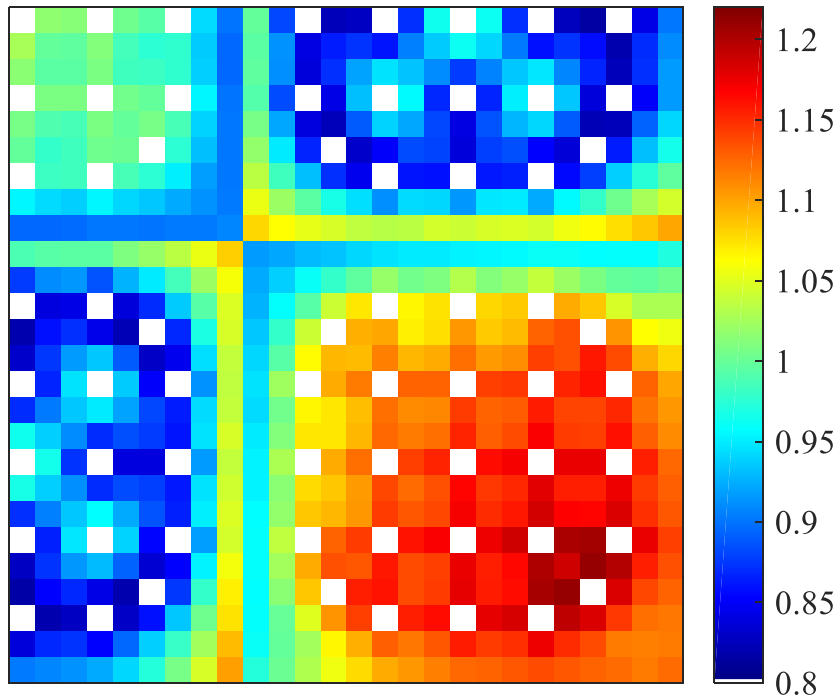


3. Benchmark Solutions (4/20)

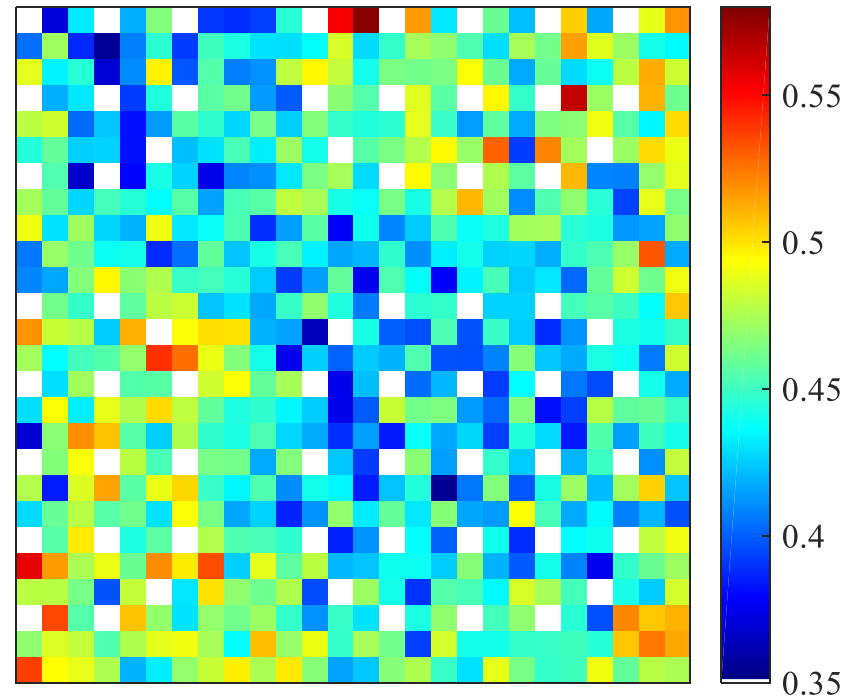
3.1. 3D HZP 3x3 Assembly Control Rod Worth

Radial Power Distribution

Normlized radial pin-wise power distribution



Statistical uncertainty (%)



0.9553
0.9557
-0.0454
0.9246
0.9249
-0.0313

1.0866
1.0862
0.0369

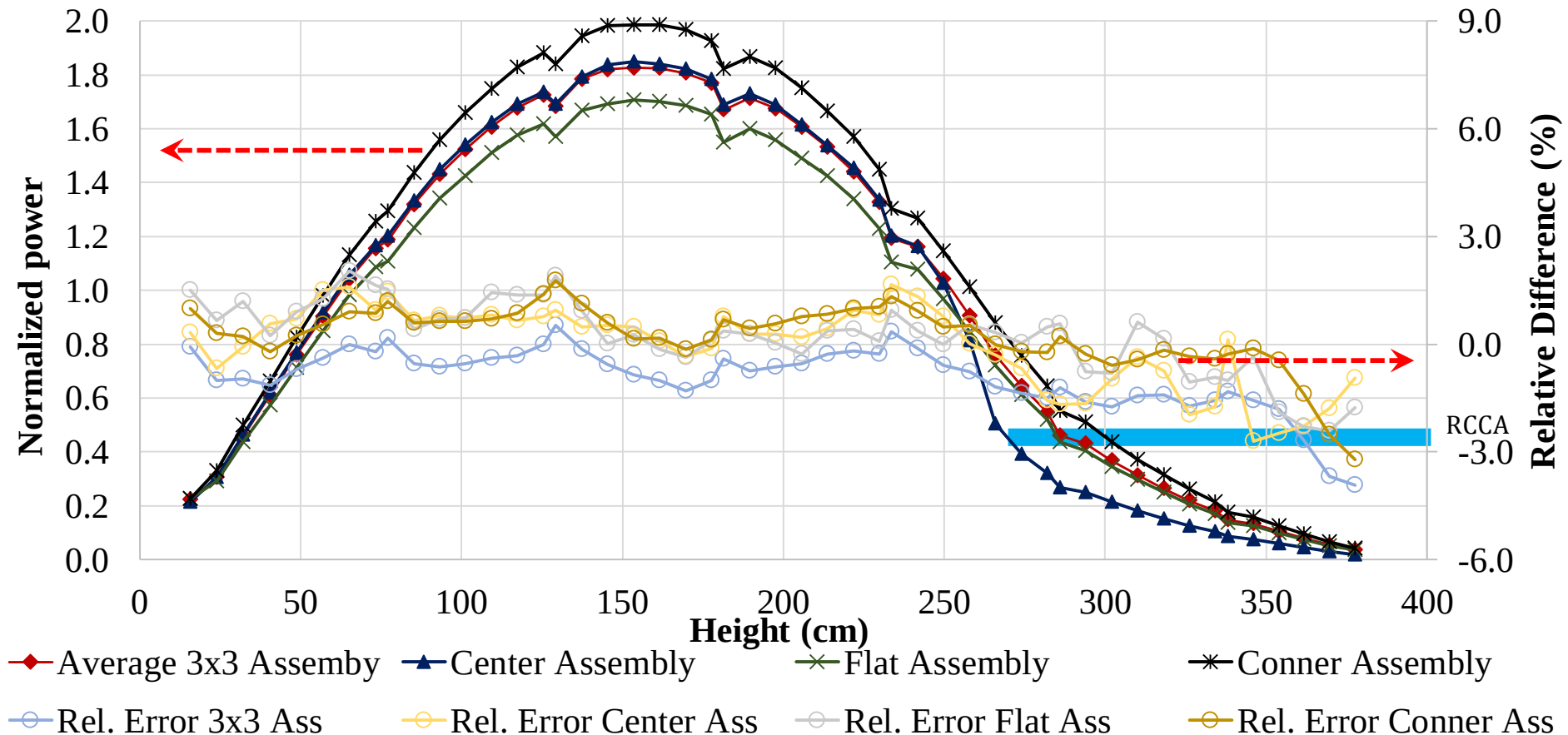
MCS
KENO
Rel. Error (%)

Rel. Error (%)	
RMS	0.0383

3. Benchmark Solutions (5/20)

3.1. 3D HZP 3x3 Assembly Control Rod Worth

Axial Power Distribution Comparison



3. Benchmark Solutions (6/20)

3.2. Physical Reactor Zero Power Physics Test (ZPPT)

Specification

- A full core of Westinghouse 17x17-type fuel assemblies in the WBN1 initial loading pattern.

Input	Value
Fuel Density	10.257 g/cc
Fuel Enrichment – Region 1	2.11%
Fuel Enrichment – Region 2	2.619%
Fuel Enrichment – Region 3	3.10%
Power	0% FP
Inlet Coolant Temperature	565 K
Inlet Coolant Density	0.743 g/cc
Reactor Pressure	2250 psia
Initial Boron Concentration	1285 ppm
Initial Critical Bank D Position	167 steps

	H	G	F	E	D	C	B	A
8	2.1 20	2.6 20	2.1 20	2.6 20	2.1 20	2.6 20	2.1 20	3.1 12
9	2.6 20	2.1 24	2.6 24	2.1 20	2.6 20	2.1 24	3.1 24	3.1
10	2.1 24	2.6 24	2.1 20	2.6 20	2.1 16	2.6 16	2.1 8	3.1
11	2.6 20	2.1 20	2.6 20	2.1 20	2.6 20	2.1 16	3.1 16	3.1
12	2.1 20	2.6 20	2.1 16	2.6 24	2.6 24	2.6 12	3.1 12	
13	2.6 20	2.1 16	2.6 24	2.1 12	2.6 12	3.1 12	3.1	
14	2.1 24	3.1 24	2.1 16	3.1 16	3.1 12	3.1 12		
15	3.1 12	3.1 8	3.1 8	3.1 8	Enrichment Number of Pyrex Rods			

3. Benchmark Solutions (7/20)

3.2. Physical Reactor Zero Power Physics Test (ZPPT)

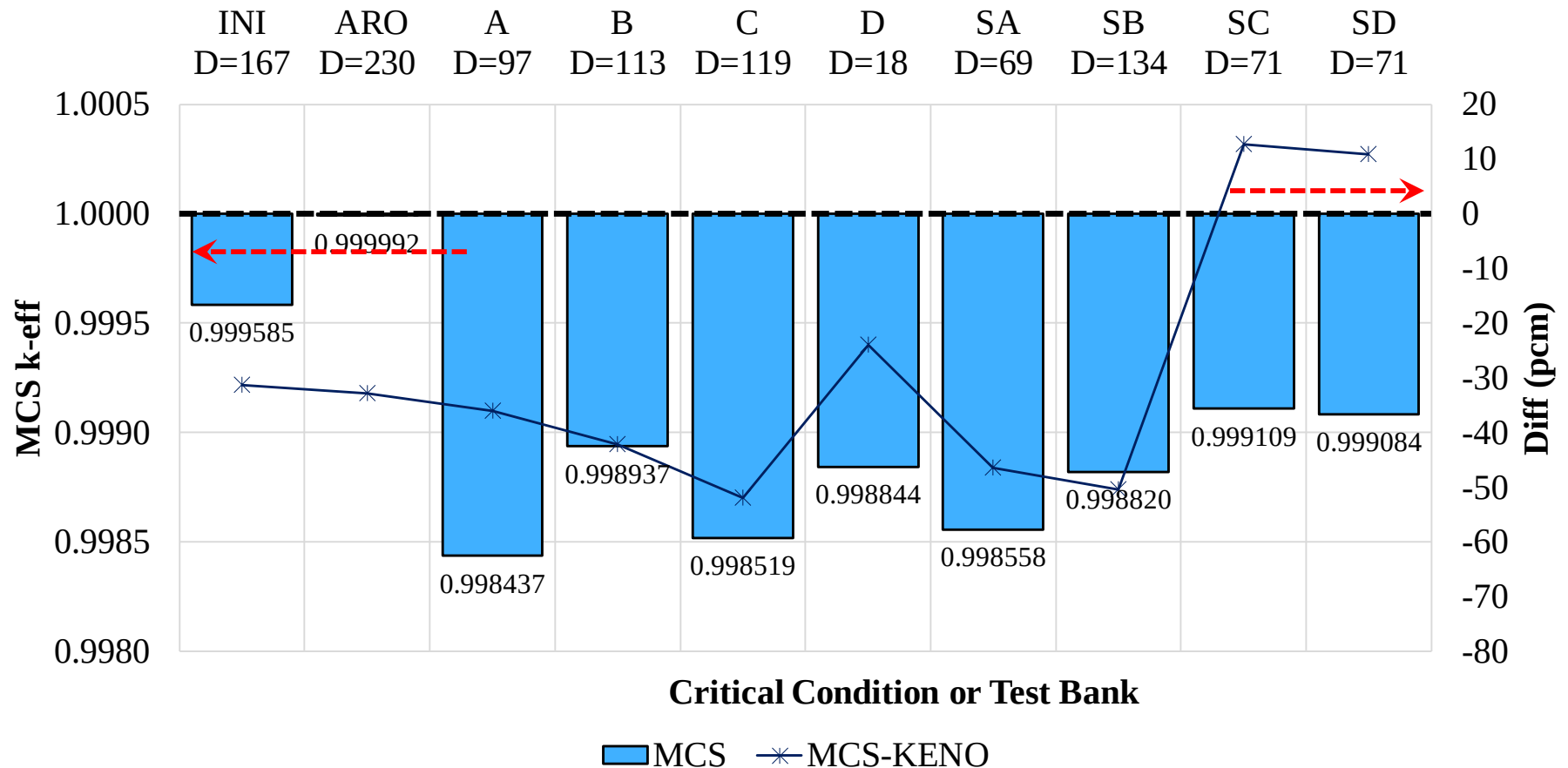
Problem 5 Solution Results

Code		Library		No. of histories		No. of processors		Exec. time (min)			
KENO-VI		ENDF/B-VII.0		7.5E+09		240		2700			
MCS		ENDF/B-VII.0		3.0E+08		48		65			
Case	Boron (ppm)	Bank Withdrawn Steps								k-eff (± 4pcm)	Diff vs KENO (± 4pcm)
		A	B	C	D	SA	SB	SC	SD		
1	1285	-	-	-	167	-	-	-	-	0.99959	-31
2	1291	-	-	-	-	-	-	-	-	0.99999	-33
3	1170	0	-	-	97	-	-	-	-	0.99844	-36
4	↓	-	0	-	113	-	-	-	-	0.99894	-42
5	↓	-	-	0	119	-	-	-	-	0.99852	-52
6	↓	-	-	-	18	-	-	-	-	0.99884	-24
7	↓	-	-	-	69	0	-	-	-	0.99856	-46
8	↓	-	-	-	134	-	0	-	-	0.99882	-50
9	↓	-	-	-	71	-	-	0	-	0.99911	13
10	↓	-	-	-	71	-	-	-	0	0.99908	11

3. Benchmark Solutions (8/20)

3.2. Physical Reactor Zero Power Physics Test (ZPPT)

Problem 5 MCS Solution Criticality



3. Benchmark Solutions (9/20)

3.2. Physical Reactor Zero Power Physics Test (ZPPT)

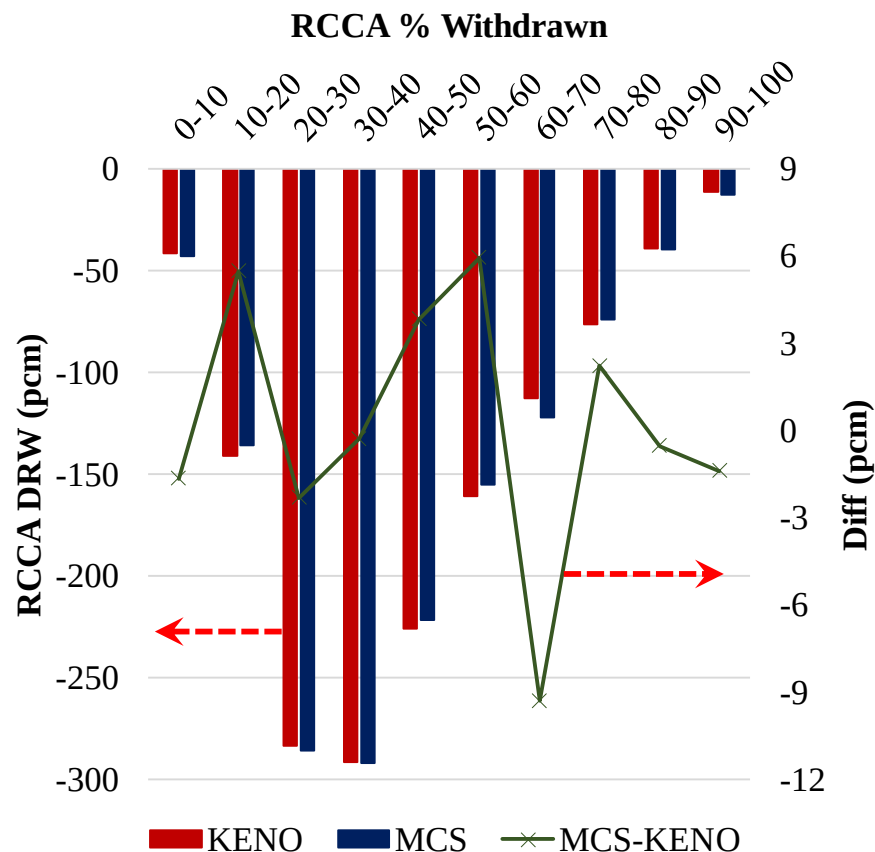
Measured and Solution ZPPT Results

Test Result	Measured	KENO	MCS	Rel. Diff. vs. Measured data (%)	Rel. Diff. Vs. KENO (%)
Initial Criticality	1	0.999899 ± 0.000010	0.999585 ± 0.000044		
Bank A Worth (pcm)	843	898 ± 2	894 ± 4	6.0 ± 0.4	-0.5 ± 0.5
Bank B Worth	879	875 ± 2	878 ± 4	-0.1 ± 0.5	0.3 ± 0.6
Bank C Worth	951	984 ± 2	987 ± 4	3.8 ± 0.4	0.3 ± 0.5
Bank D Worth	1342	1386 ± 2	1390 ± 4	3.6 ± 0.3	0.3 ± 0.4
Bank SA Worth	435	447 ± 2	454 ± 4	4.3 ± 0.9	1.5 ± 1.1
Bank SB Worth	1056	1066 ± 2	1063 ± 4	0.7 ± 0.4	-0.3 ± 0.5
Bank SC Worth	480	499 ± 2	460 ± 4	-4.2 ± 0.9	-7.9 ± 1.0
Bank SD Worth	480	499 ± 2	460 ± 4	-4.2 ± 0.9	-7.9 ± 1.0
Total Bank Worths	6467	6654 ± 4	6585 ± 11	1.8 ± 0.2	-1.0 ± 0.2
DBW (pcm/ppm)	-10.77	-10.21 ± 0.02	-10.19 ± 0.03	0.58	0.02
ITC (pcm/F)	-2.17	-3.18 ± 0.04	-3.25 ± 0.11	-1.08	-0.07

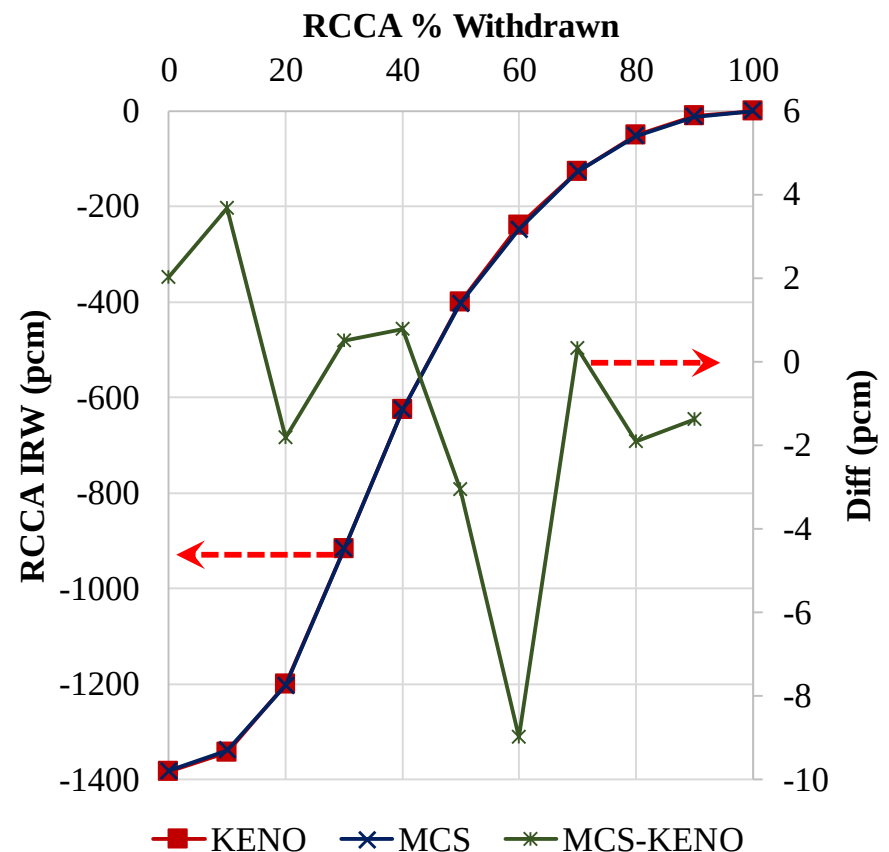
3. Benchmark Solutions (10/20)

3.2. Physical Reactor Zero Power Physics Test (ZPPT)

Differential Control Rod Worth



Integral Control Rod Worth Curve



3.2. Physical Reactor Zero Power Physics Test (ZPPT)

Average Axial Power Distribution

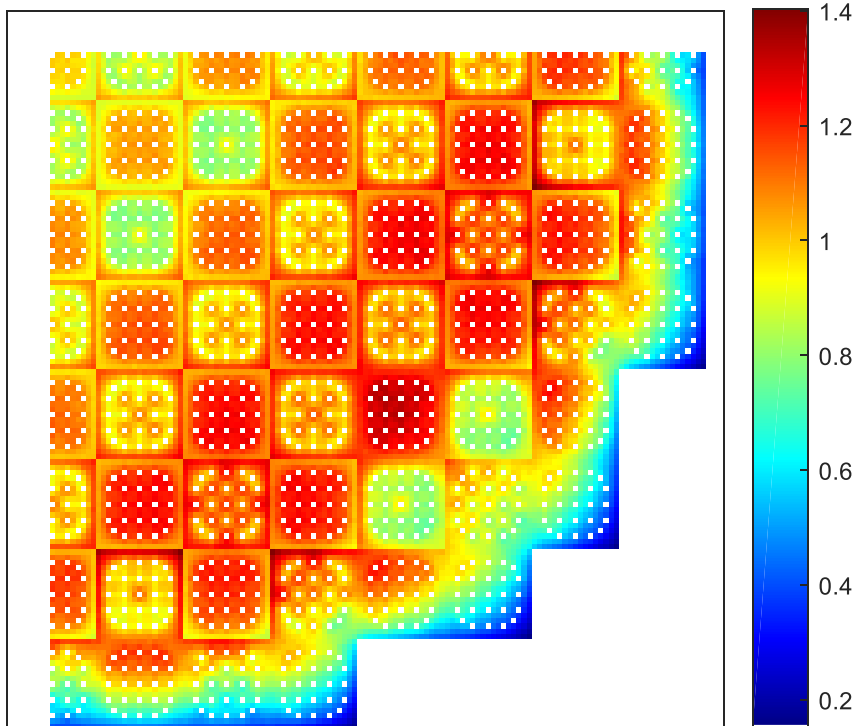
KENO MCS <i>Rel. Diff. (%)</i>	
<i>Rel. Diff. (%)</i>	
Min	-0.796
Max	0.740
RMS	0.504



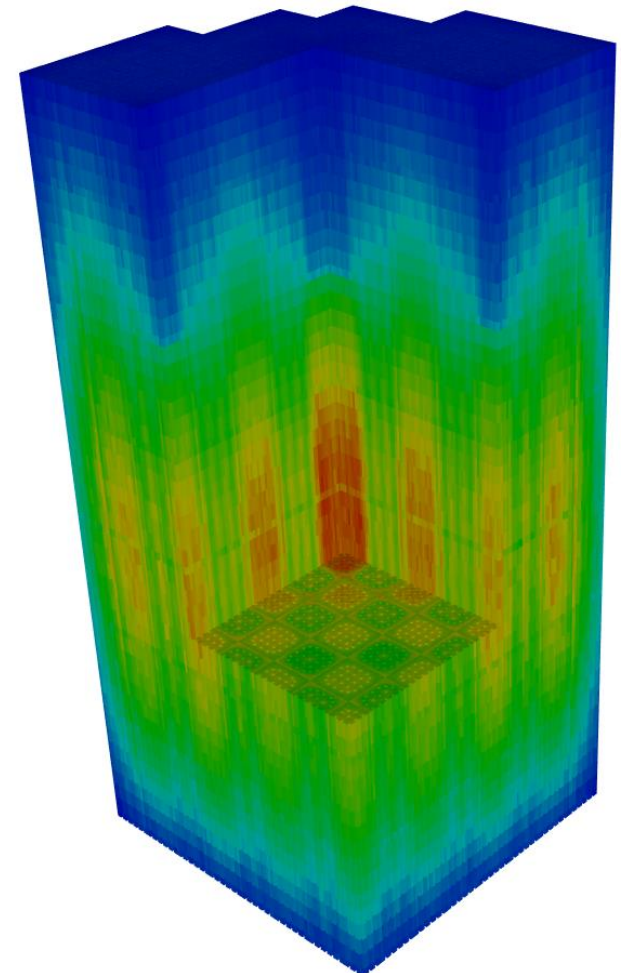
3. Benchmark Solutions (12/20)

3.2. Physical Reactor Zero Power Physics Test (ZPPT)

Normalized Pin-wise Radial Power Distribution



3D Average Power Distribution



3. Benchmark Solutions (13/20)

3.3. Physical Reactor Depletion

Specification

- **Library: ENDF/B-VII.1;**
- **Fuel pin: 1 radial ring and 10 axial meshes;**
- **Inactive cycles/Active cycles/Sub-cycle/Histories: 4/40/300/15,000;**
- **T/H feedback (on)**
- **DBRC + OTF + OpenW**
- **The total simulation time: 99 hours with 216 processes.**

Input	Value
Fuel Density	10.257 g/cc
Fuel Enrichment	2.1/2.6/3.1%
Rated Power (100%)	3411 MW
Inlet Coolant Temperature	565 K
Inlet Coolant Density	0.743 g/cc
RCCA Bank D Position (steps withdrawn)	215
Rated Coolant Mass Flow (100%)	131.7 Mlbs/hr
Cycle Length	441.0 EFPDs
EOC Exposure	16.939 GWd/MT

3. Benchmark Solutions (14/20)

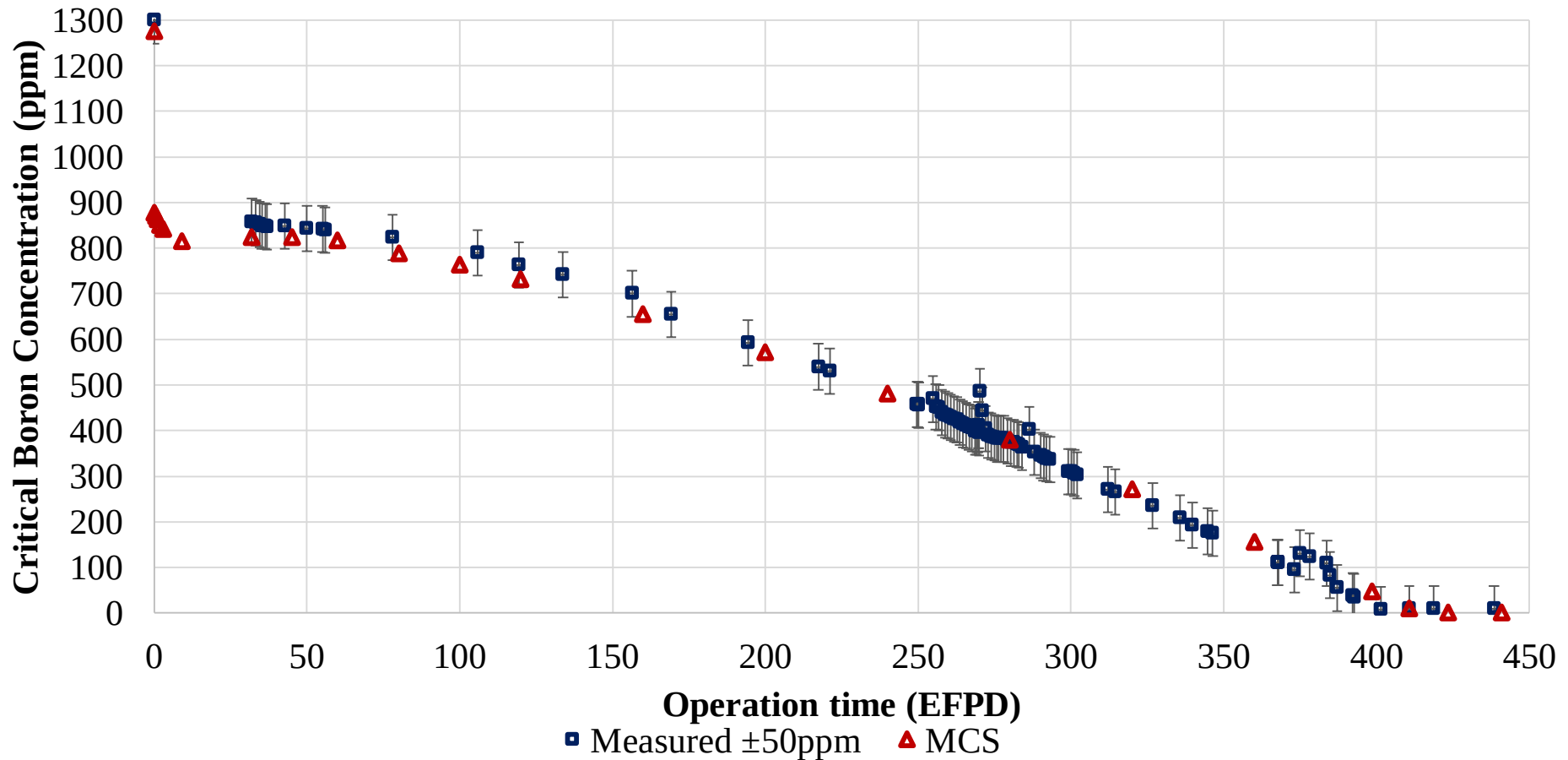
3.3. Physical Reactor Depletion

Measured				MCS			
Exposure (EFPD)	Power (%)	Bank D	Boron (ppm)	Exposure (EFPD)	Power (%)	Bank D	Boron (± 1 ppm)
0	0	186	1299	0	0	219	1275.00
32	99.7	219	858	32	100	219	822.99
42.8	100	215	848	45	100	219	823.63
55.9	99.9	214	839	60	100	219	815.69
78	99.9	208	823	80	100	219	788.63
105.8	99.8	217	790	100	100	219	763.06
119.4	99.8	212	763	120	100	219	731.05
156.4	99.9	218	700	160	100	219	655.07
194.3	98.9	215	592	200	100	219	571.19
249.6	99.9	216	458	240	100	219	480.96
284	99.9	218	363	280	100	219	378.96
314.5	99.5	214	266	320	100	219	270.77
367.7	100	216	111	360	100	219	155.80
401.4	99.6	217	7	398.6	100	219	46.27
410.7	89.9	216	9	410.7	100	219	8.59
418.8	83.4	228	9	423.6	100	219	0.02
439.5	65.3	227	9	441	100	219	0.00

3. Benchmark Solutions (15/20)

3.3. Physical Reactor Depletion

Boron Letdown Curve for WBN1 Cycle 1

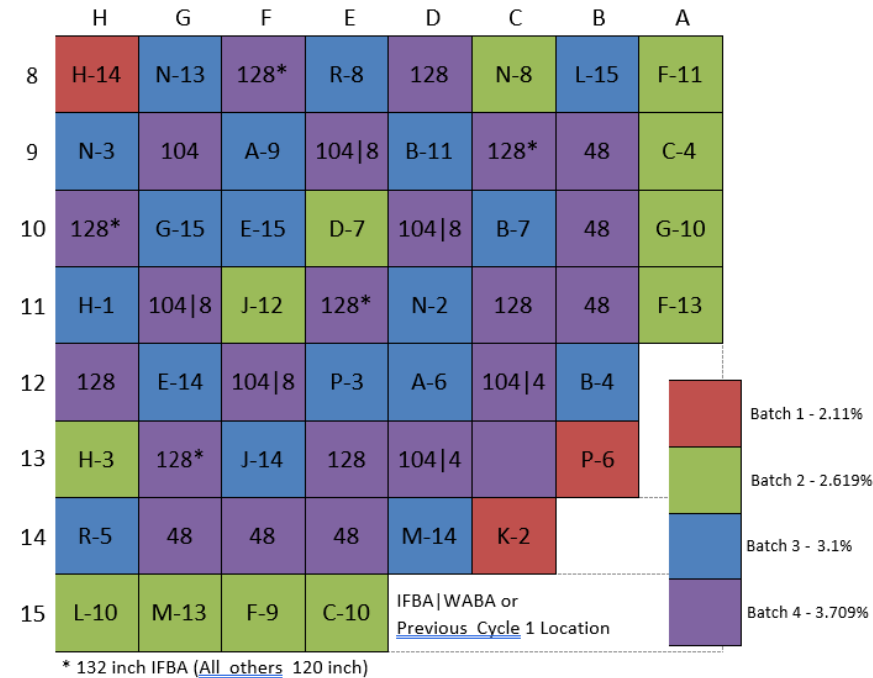


3. Benchmark Solutions (16/20)

3.4. Physical Reactor Refueling

Specification

Input	3A
Fuel Density	10.257 g/cc
Fuel Enrichment - Burned fuel - Fresh fuel (84 Ass.)	2.1/2.6/3.1% 2.613/3.709%
Rated Power (100%)	3411 MW
Inlet Coolant Temperature	565 K
Inlet Coolant Density	0.743 g/cc
Reactor Pressure	2250 psia
RCCA Bank D Position (steps with drawn)	215
Rated Coolant Mass Flow (100%)	131.7 Mlbs/hr
Burnable poison	IFBA and WABA

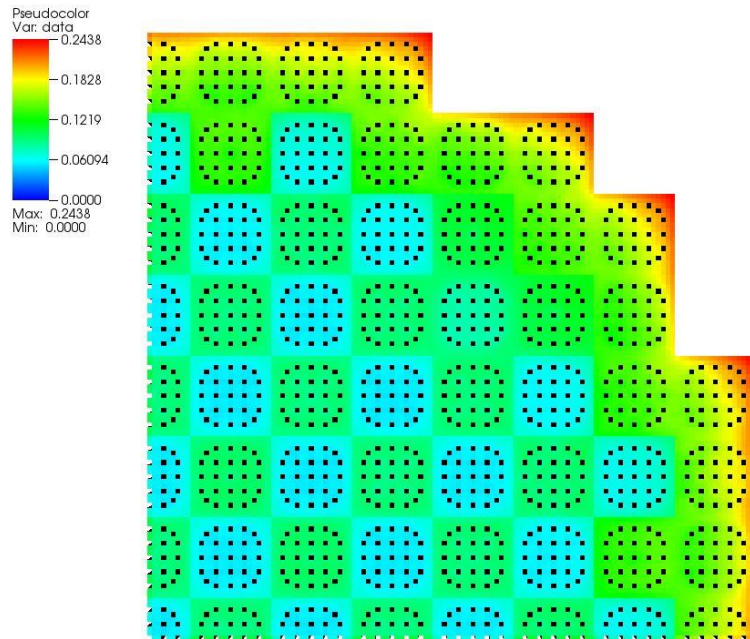


3. Benchmark Solutions (17/20)

3.4. Physical Reactor Refueling

U-235 density at EOC Cycle 1

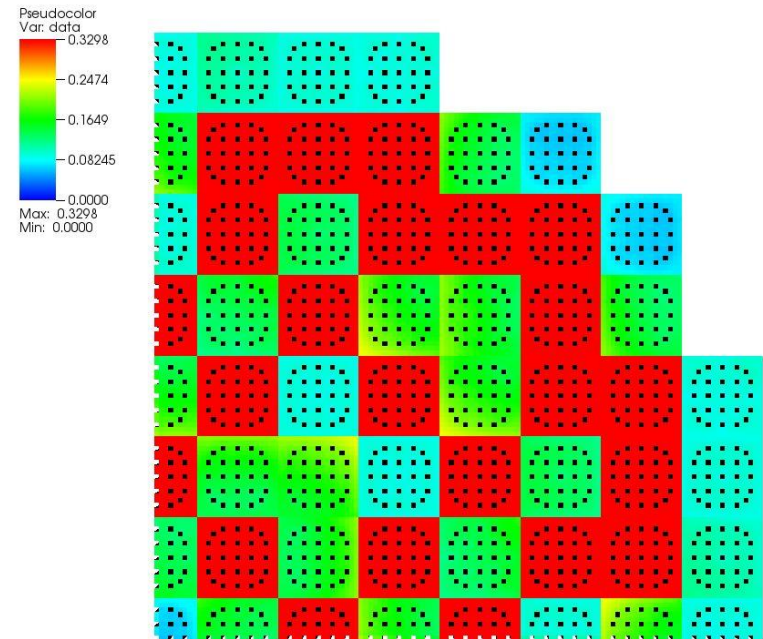
DB: vera_1stcycle_img.xml_mt3.vtk
Cycle: 3 Time:3



user: user
Tue Mar 27 11:51:52 2018

U-235 density at BOC Cycle 2

DB: vera_2ndcycle_img.xml_mt3.vtk
Cycle: 3 Time:3



user: user
Tue Mar 27 11:53:46 2018

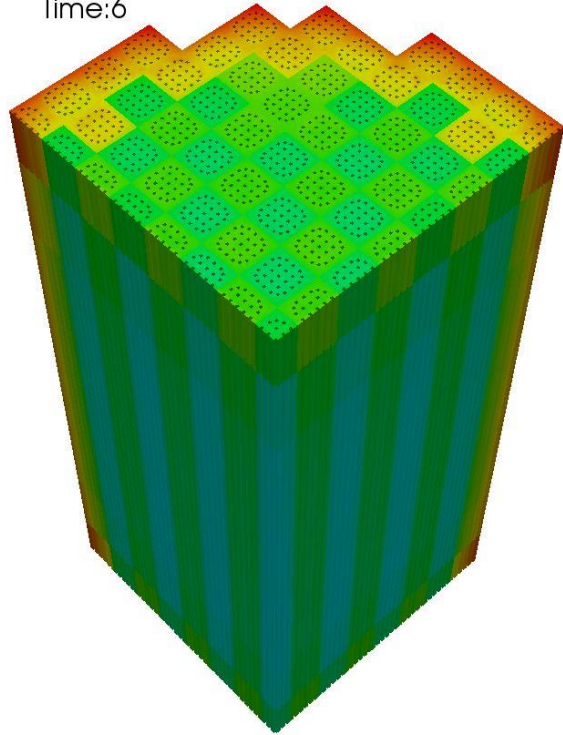
3. Benchmark Solutions (18/20)

3.4. Physical Reactor Refueling

U-235 density at EOC Cycle 1

DB: vera_1stcycle_img.xml_mt6.vtk
Cycle: 6 Time:6

Pseudocolor
Var: data
0.2592
0.1944
0.1296
0.06481
0.0000
Max: 0.2592
Min: 0.0000

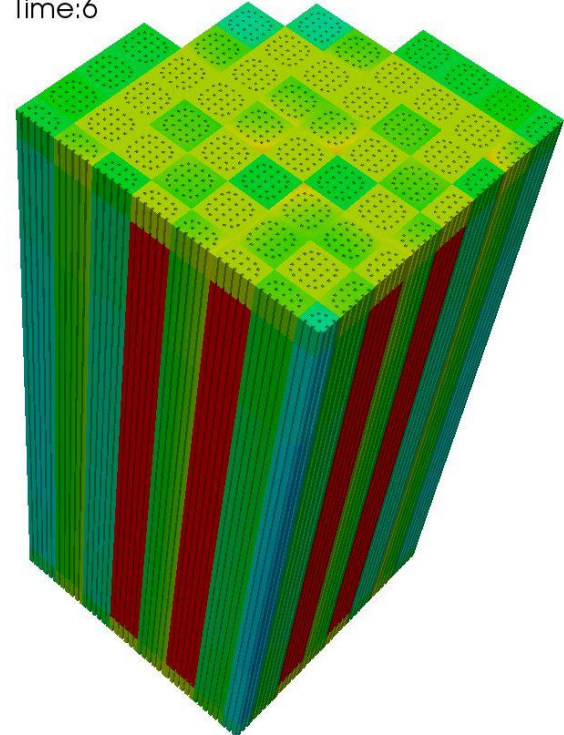


user: user
Tue Mar 27 11:52:55 2018

U-235 density at BOC Cycle 2

DB: vera_2ndcycle_img.xml_mt6.vtk
Cycle: 6 Time:6

Pseudocolor
Var: data
0.3298
0.2474
0.1649
0.08245
0.0000
Max: 0.3298
Min: 0.0000



user: user
Tue Mar 27 11:50:23 2018

3. Benchmark Solutions (19/20)

3.4. Physical Reactor Refueling

Problem 10 Solution Results – CBC [ppm] in compared to MPACT/CTF [1]

- **LIB: ENDF/B-VII.1;**
- **Active/inactive/histories/sub-cycle: 20/5/10,000/300**

Code System	MPACT/CTF	MCS (± 1ppm)	Difference (ppm)
HZP	1427.43	1439.10	11.67
HFP	1251.22	1260.34	9.12

[1] Kochunas, B., Jabaay, D. and Downar, T., 2015. Restart and Shuffling in MPACT Revision 1 February 26, 2015.

3. Benchmark Solutions (20/20)

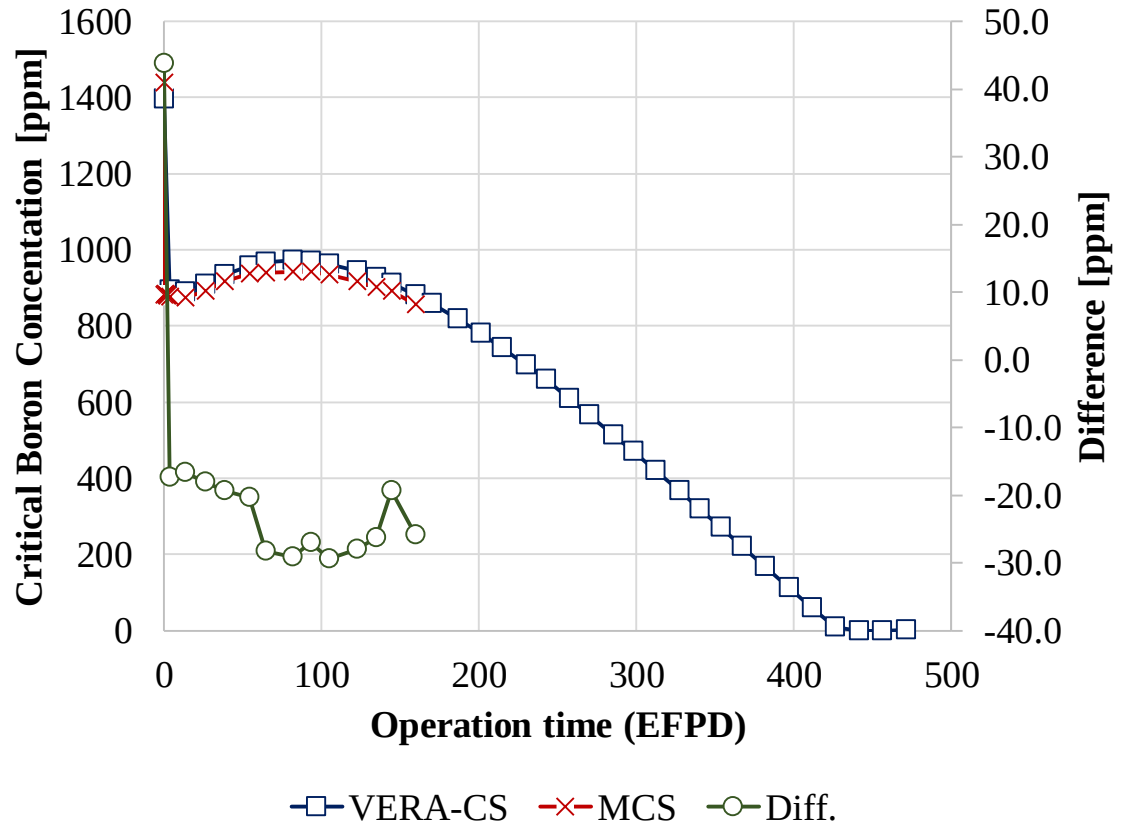
3.4. Physical Reactor Refueling

Reference Solution:

- VERA-CS [1]: within 20ppm in compared to measured data.

Options	VERA-CS	MCS
Lib. END/B	VII.0	VII.1
Equilibrium xenon	On	On
DBRC	-	On

Boron Letdown Curve for WBN1 Cycle 2



[1] Godfrey, A.T., Collins, B.S., Kim, K.S., Montgomery, R., Powers, J.J., Salko, R.K., Stimpson, S.G., Wieselquist, W.A., Clarno, K.T., Gehin, J.C. and Palmtag, S., 2016. VERA Benchmarking Results for Watts Bar Nuclear Plant Unit 1 Cycles 1-12. Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States).

4. Conclusions

- **The benchmark solutions of VERA problems obtained using UNIST MC code MCS:**
 - 3D 3x3 mini-core, whole-core BOC and depletion simulations,
 - Good agreements with the reference results including cycle 1 depletion.
- ➔ MCS could be a simulation tool for whole-core analysis in predicting the eigenvalue, pin power distribution, control rod worth, and depletion calculation.
- **Future work:**
 - Whole-core depletion calculation of WBN1 cycle 2 with thermal-hydraulic feedback coupled with the geometry thermal expansion.

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