Verification of the Hexagonal Ray Tracing Module and the CMFD Acceleration in nTRACER

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Introductions

☐ Motivations

- **Restricted Hexagonal core calculation applicability in nTRACER[a)]**
  - Restricted to 2D calculation
  - Triangle based hexagonal CMFD kernel
- **Expanded hexagonal core calculation applicability**

☐ Purposes

- **Verification of effectiveness of hexagonal CMFD acceleration**
- **Verification of accuracy of hexagonal MOC calculation**

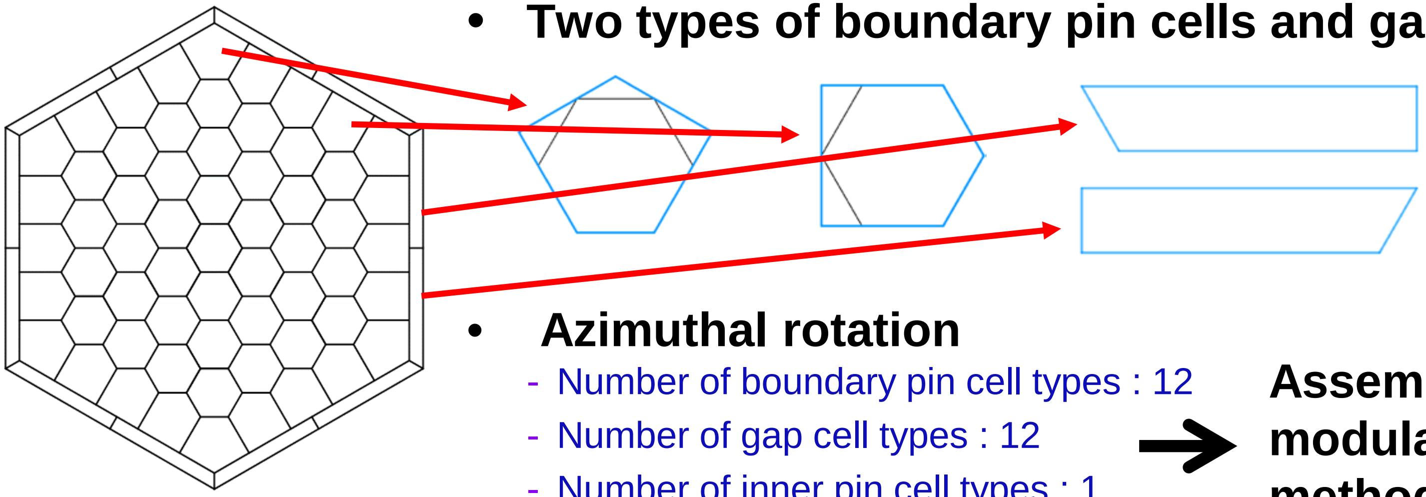
☐ Objectives

- **Verify the hexagonal MOC calculation for various geometries**
- **Asses the effectiveness of hexagonal CMFD acceleration**
- **Asses the accuracy of hexagonal MOC calculation**

a) Y.S. Jung and *et al.*, "Practical Numerical Reactor Employing Direct Whole Core Neutron Transport and Subchannel thermal/hydraulic solvers," Ann. Nuc. Energy, Vol. 62, 357 (2013)..

Sub-meshing in Hexagonal Assembly

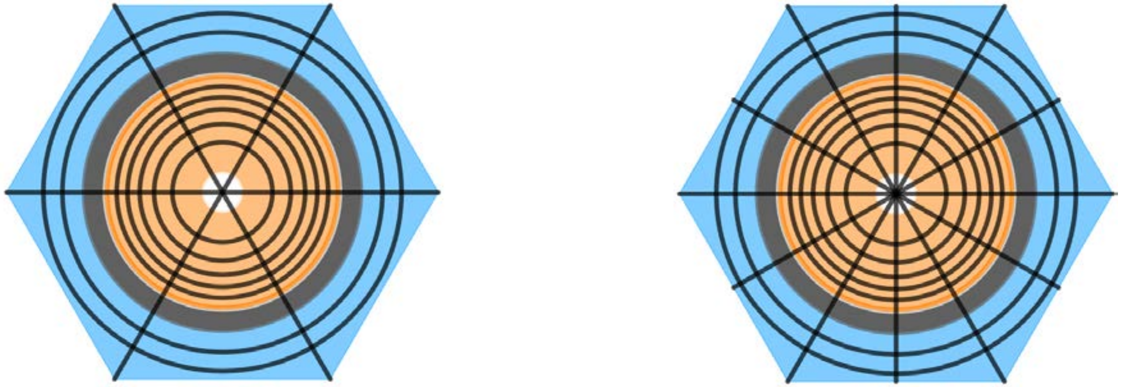
☐ Elongated Boundary Pin Cell and Trapezoidal Gap Cell



- **Two types of boundary pin cells and gap cells**
- **Azimuthal rotation**
  - Number of boundary pin cell types : 12
  - Number of gap cell types : 12
  - Number of inner pin cell types : 1

→ **Assembly based modular ray tracing method**

☐ Source Meshes in Pin Cells

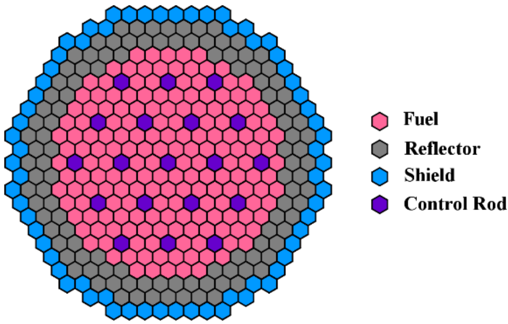


Explicit Geometry Treatment

☐ Flexible Applicability

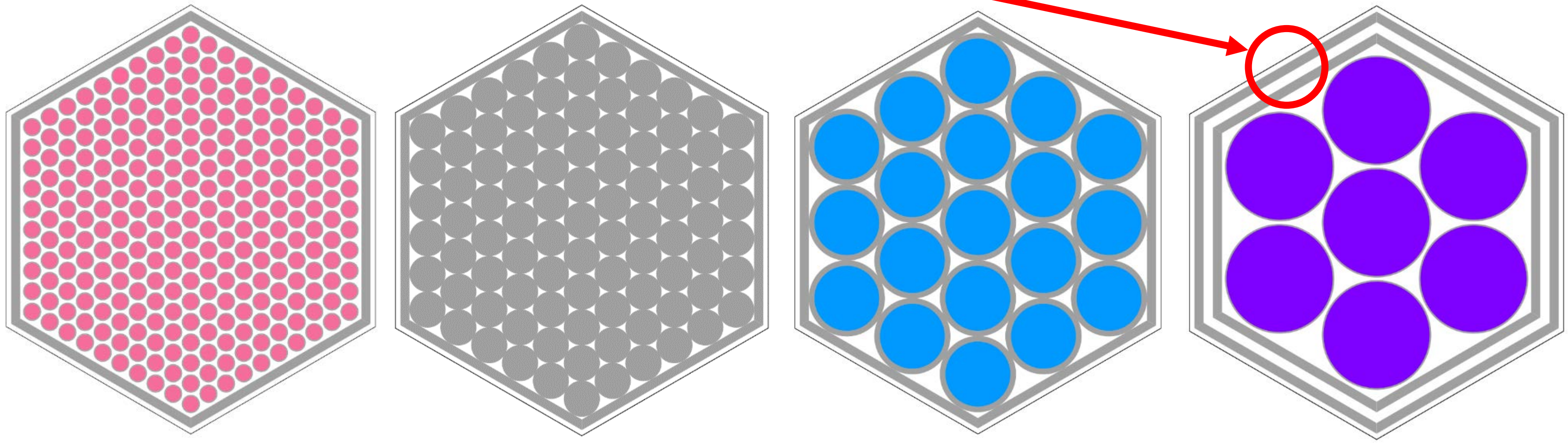
ex) ABR metallic benchmark[a] (Fast reactor)

- **Assemblies with various different pin pitches**
- **Multiple duct layers in assemblies**



ABR Core

→ Applicable without any assumption or approximation



Fuel Assembly **Reflector Assembly** **Shield Assembly** **Control Rod Assembly**

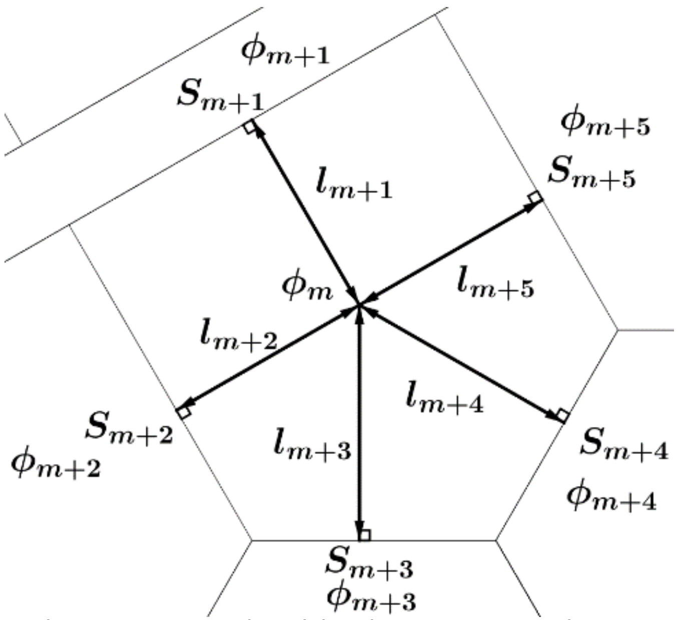
a) T. K. Kim, W. S. Yang, C. Grandy, and R.N. Hill, *Core Design Studies for a 1000MWth Advanced Burner Reactor, Annals of Nuclear Energy*, 36.3: 331-336, 2009

Hexagonal CMFD

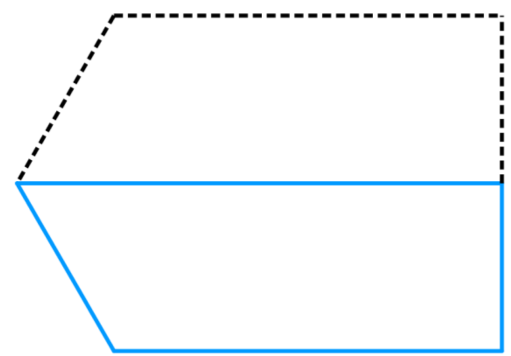
☐ Finite Difference Formula

$$\sum_i \left(\tilde{D}_m^i - \hat{D}_m^i\right) S_{m+i}\phi_m - \sum_i \left(\tilde{D}_m^i + \hat{D}_m^i\right) S_{m+i}\phi_{m+i} + \Sigma_{t,m}\phi_m V_m = Q_m V_m$$

$$\tilde{D}_m = \frac{D_m D_{m+1}}{D_m l_{m+1} + D_{m+1} l_m} \qquad \hat{D}_m = -\frac{-\hat{J}_m - \tilde{D}_m\left(\phi_{m+1} - \phi_m\right)}{\phi_{m+1} + \phi_m}$$



Various types of CMFD meshes

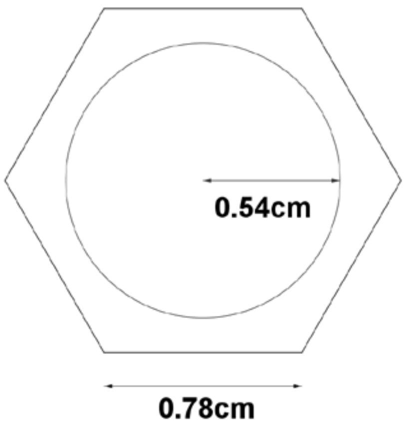


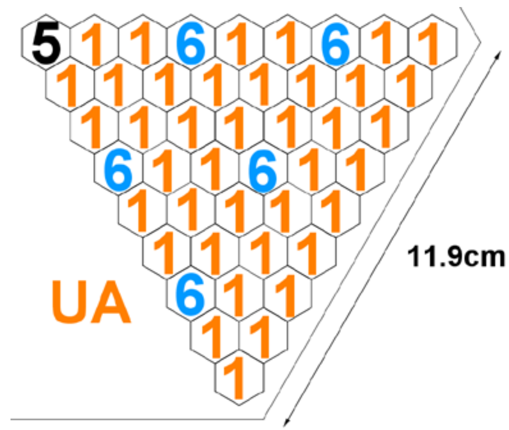
Applicable for general geometries

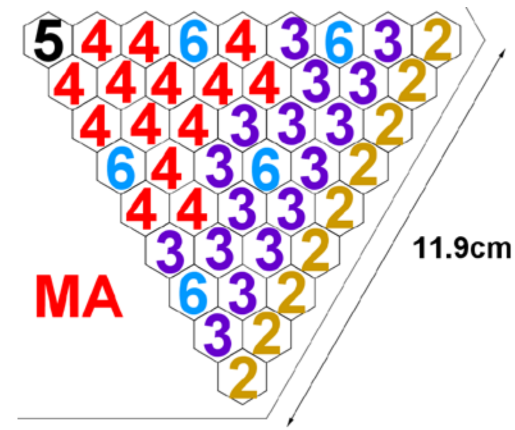
a) K. S. Kim, and M. D. Deheart, Unstructured Partial-and net-current Based Coarse Mesh Finite Difference Acceleration Applied to the Extended Step Characteristics Method in NEWT, Annals of Nuclear Energy, 38.2: 527-534, 2011.

C5G7 Hexagonal Variation Benchmark[a)]

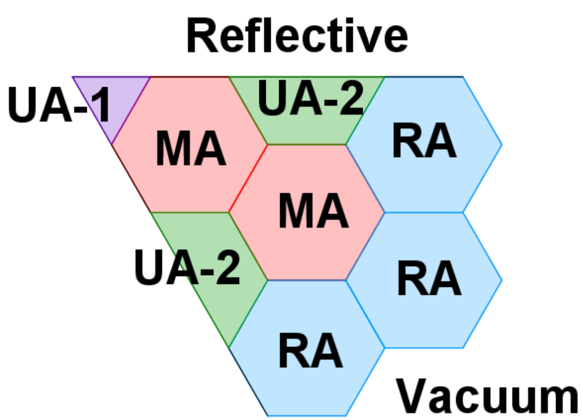
☐ Cell and Assembly







☐ Core



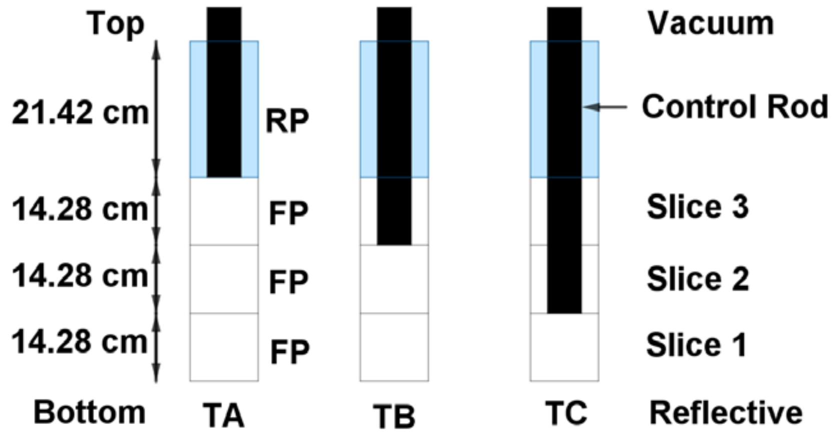
Number : Material in the Pellet
Residual Area : Moderator

1/6 Symmetry
UA-1 vs. UA-2 : 3D cases

a) J. Y. Cho, K. S. Kim, H. J. Shim, J. S. Song, C. C. Lee, and H. G. Joo, Whole Core Transport Calculation Employing Hexagonal Modular Ray Tracing and CMFD Formulation, Journal of nuclear science and technology, 45.8: 740-751, 2008.

Three 3D Cases of C5G7 H Benchmark

☐ Control Rod Insertion Types



☐ 3D Cases

Problems / Assembly	UA-1	UA-2	MA
Unrodded	TA	TA	TA
Rodded A	TB	TA	TA
Rodded B	TC	TB	TA

Calculation Conditions

☐ nTRACER

- **Number of azimuthal angles : 24 in π**
- **Number of polar angles : 4 in π/2**
- **Ray spacing : 0.05 cm**
- **1D SP_3 SENM axial calculation**
- **4 sub-planes per plane**

☐ McCARD[a)]

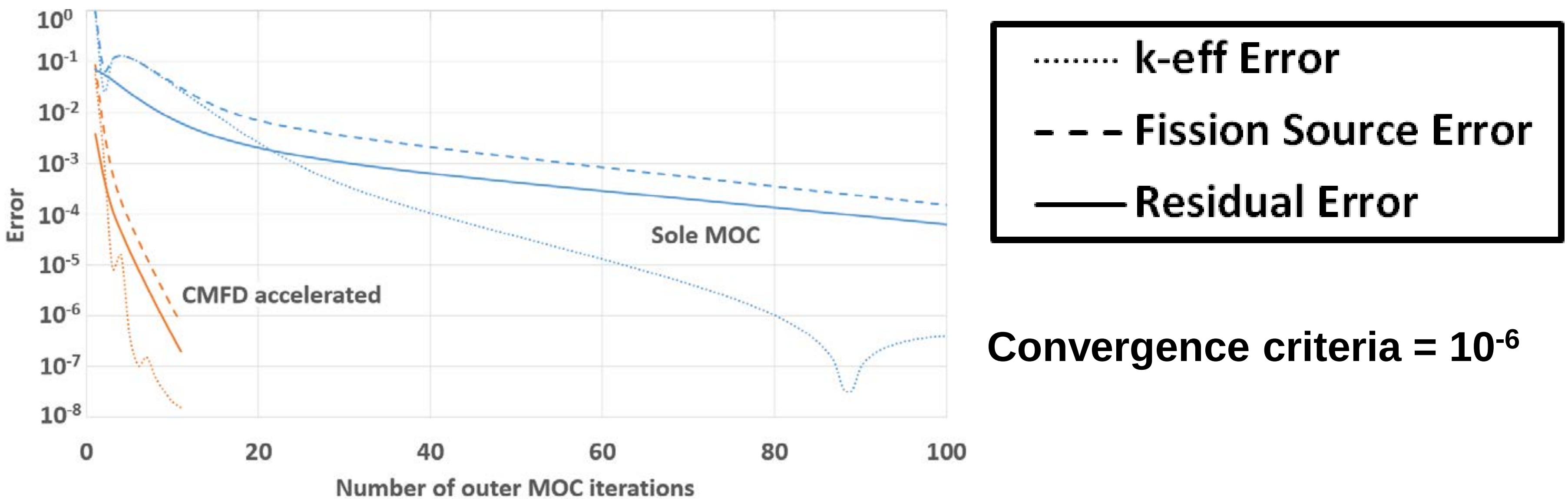
- **Number of inactive cycles (NI) : 500**
- **Number of active cycles (NA) : 1000**
- **Number of particles per cycle (NP) : 1,000,000**

- **Both code utilized 1/6 symmetry**

a) H. J. Shim, B. S. Han, J. S. Jung, H. J. Park, C. H. Kim, McCARD: Monte Carlo Code for Advanced Reactor Design and Analysis, Nucl. Eng. Technol., 44[2], 161, 2012.

Effectiveness of the Hexagonal CMFD Acceleration

☐ 2D Core Calculation[a)]



Convergence criteria = 10^{-6}

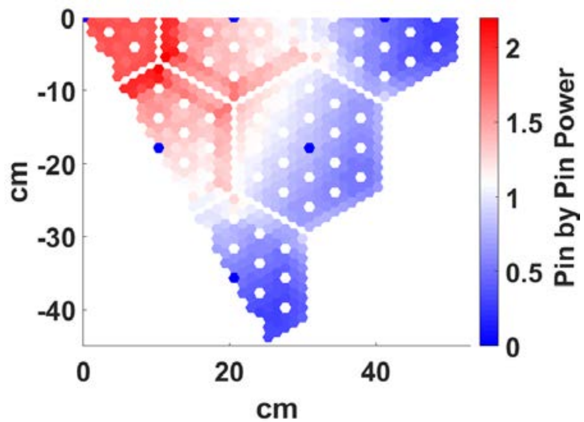
Case	# of outer MOC iterations	Computation Time (s)
Sole MOC	222 ↓ x 1/20	569 ↓ x 1/17
CMFD Accelerated	11	34

CMFD inner iterations = 521

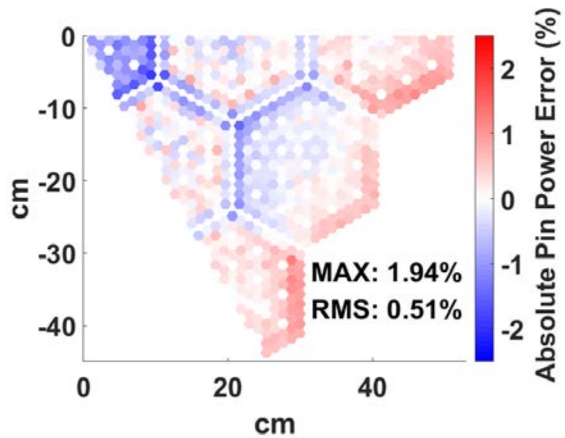
a) Intel® Xeon E5- 2640 2.60 GHz, 128 GB of memory, 16 thread per node

2D Core Calculation

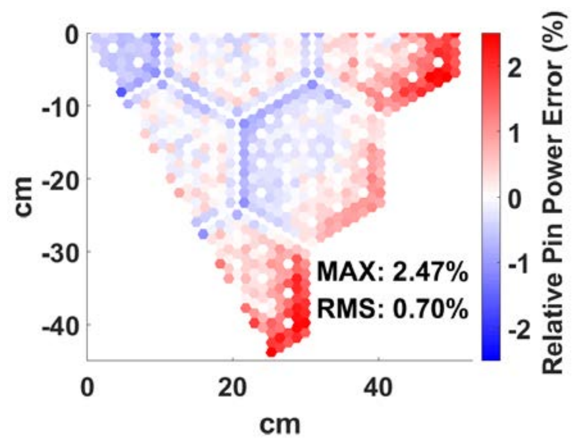
☐ Comparison between nTRACER and McCARD



McCARD
pin by pin power



nTRACER
Absolute Pin Power Error



nTRACER
Relative Pin Power Error

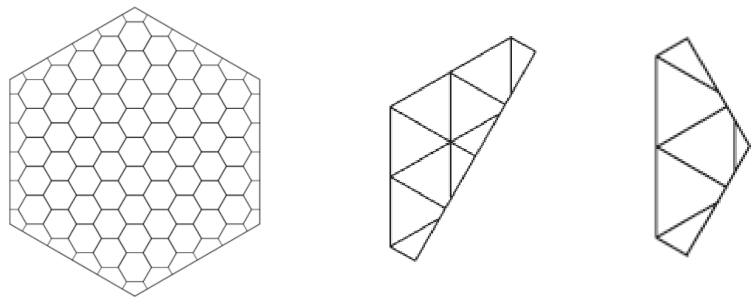
K-eff	McCARD (σ, pcm)	1.16243 (2)
	nTRACER (Δρ, pcm)	1.16231 (-9)
Absolute Pin power error[a], %	Max.	1.94
	RMS	0.50
Relative Pin power error[a], %	Max.	2.47
	RMS	0.70

a) Pin Power σ < 0.69%

Comparison between nTRACER and DeCART[a)]

☐ Calculation Conditions of DeCART

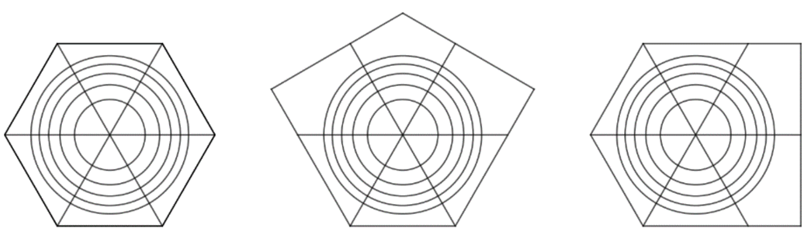
- Number of azimuthal angles : 12 in π
- Number of polar angles : 2 in π/2
- Ray spacing : 0.05 cm
- 1D NEM-SP_3 axial calculation

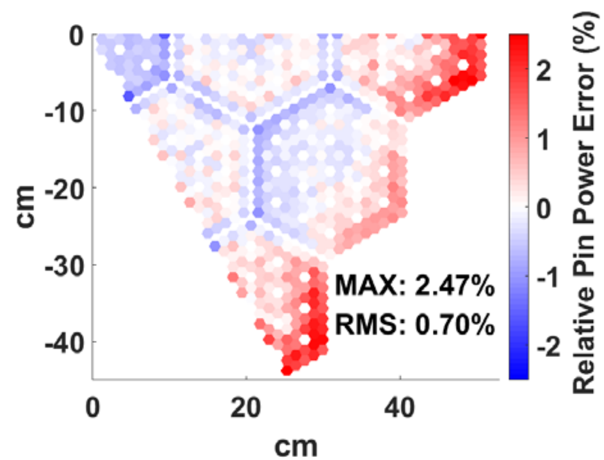


DeCART
Modeling of Hexagonal Assembly

☐ 2D Core Calculation

	nTRACER	DeCART
Δρ, pcm	-9	9
Max. Relative Error	2.47	1.83
RMS Relative Error	0.70	0.50





nTRACER
Relative Pin Power Error
Modeling of Hexagonal Assembly

a) J. Y. Cho, K. S. Kim, H. J. Shim, J. S. Song, C. C. Lee, and H. G. Joo, Whole Core Transport Calculation Employing Hexagonal Modular Ray Tracing and CMFD Formulation, Journal of nuclear science and technology, 45.8: 740-751, 2008.

3D Core Calculations

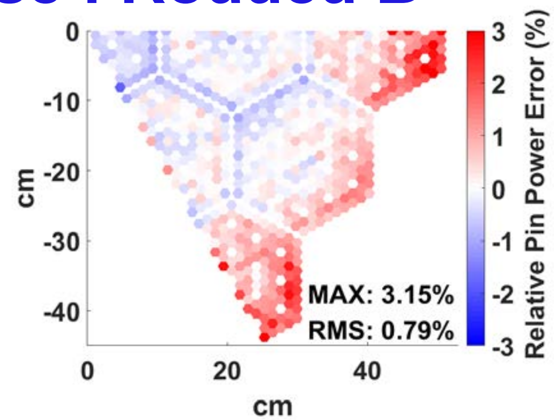
		Unrodded	Rodded A	Rodded B
McCARD[a)b)]	k-eff (σ, pcm)	1.12273 (1)	1.11886 (1)	1.10264 (1)
nTRACER	k-eff (Δρ, pcm)	1.12280 (6)	1.11890 (3)	1.10267 (2)
Slice 1 Pin Power Error, %	Max.	2.73	2.66	3.15
	RMS	0.67	0.68	0.79
Slice 2 Pin Power Error, %	Max.	2.74	2.61	2.99
	RMS	0.69	0.67	0.71
Slice 3 Pin Power Error, %	Max.	2.58	2.33	2.56
	RMS	0.66	0.66	0.75
2D Integrated Pin Power Error, %	Max.	2.56	2.29	2.70
	RMS	0.64	0.63	0.67

a) NI = 500, NA = 1000, NP = 2,000,000
b) Pin Power σ < 0.50%

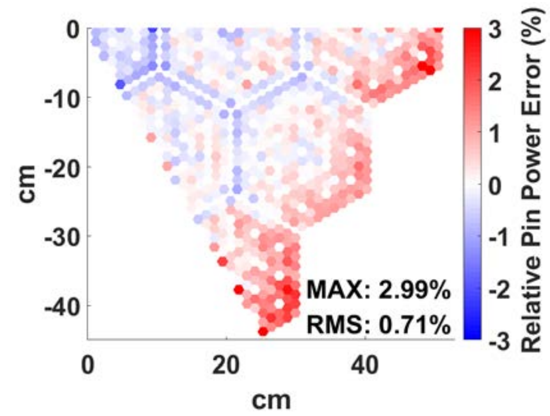
* Normalized to unity for 3D core
* Relative pin power error

Slice by Slice Pin Power Error

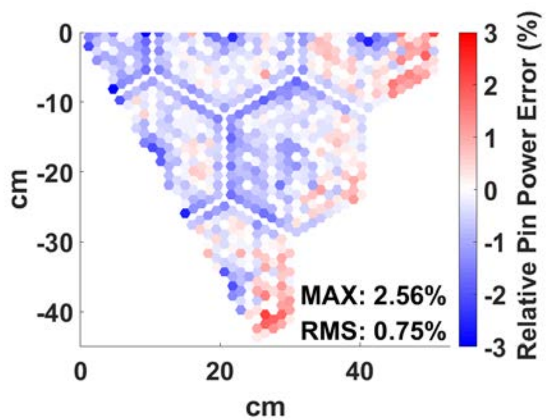
☐ Case : Rodded B



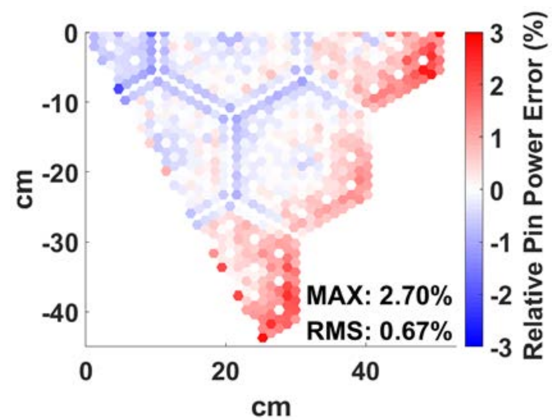
Slice 1



Slice 2



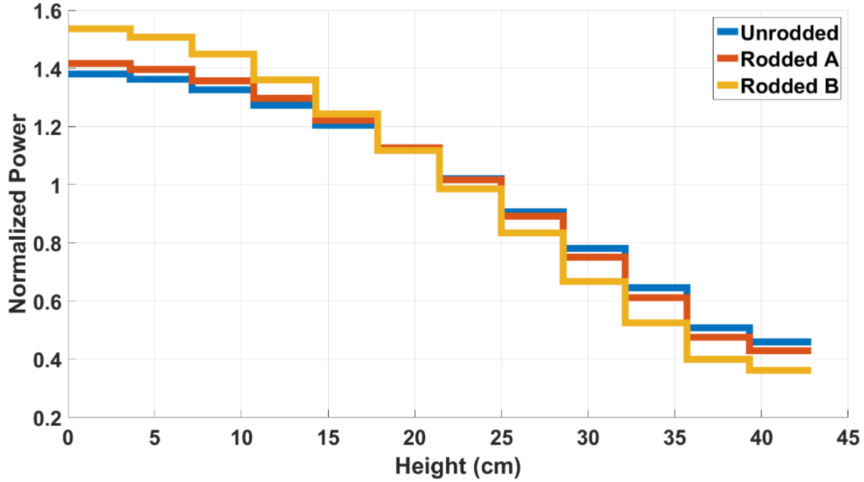
Slice 3



2D Integrated

Radially Integrated Pin Power Error

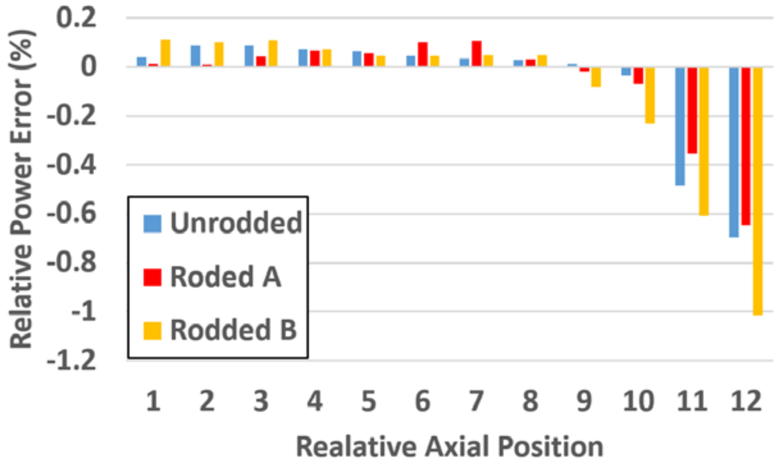
☐ McCARD Results



Each sub-plane : 3.57 cm

Increased control rod insertion
→ Increased axial power slope

☐ nTRACER Errors

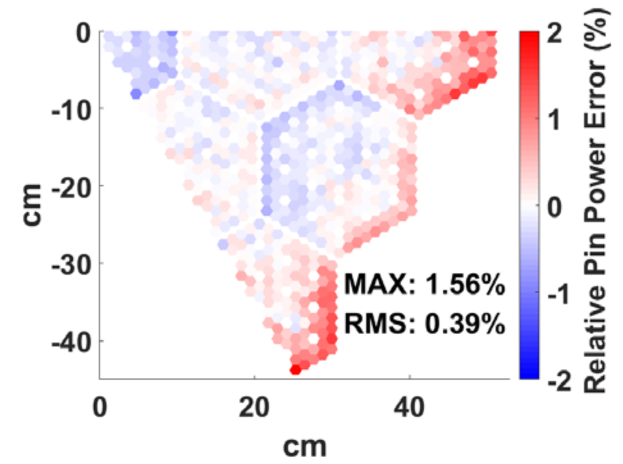


Maximum : 1.01%

12 Azimuthal Divisions in Pin Cells

□ 2D Core Calculation

K-eff	McCARD (σ, pcm)	1.16243 (2)
	nTRACER (Δρ, pcm)	1.16257 (10)
Relative Pin power error[a)], %	Max.	1.56
	RMS	0.39



□ 3D Core Calculations

		Unrodded	Rodded A	Rodded B
McCARD[a)b)]	k-eff (σ, pcm)	1.12273 (1)	1.11886 (1)	1.10264 (1)
nTRACER	k-eff (Δρ, pcm)	1.12288 (12)	1.11908 (18)	1.10286 (16)
Slice 1 Pin Power Error, %	Max.	1.51	1.69	2.25
	RMS	0.36	0.37	0.50
Slice 2 Pin Power Error, %	Max.	1.69	1.65	2.13
	RMS	0.39	0.38	0.45
Slice 3 Pin Power Error, %	Max.	1.88	2.12	2.53
	RMS	0.44	0.43	0.57
2D Integrated Pin Power Error, %	Max.	1.46	1.43	1.85
	RMS	0.33	0.32	0.38

a) NI = 500, NA = 1000, NP = 2,000,000
b) Pin Power σ < 0.50%

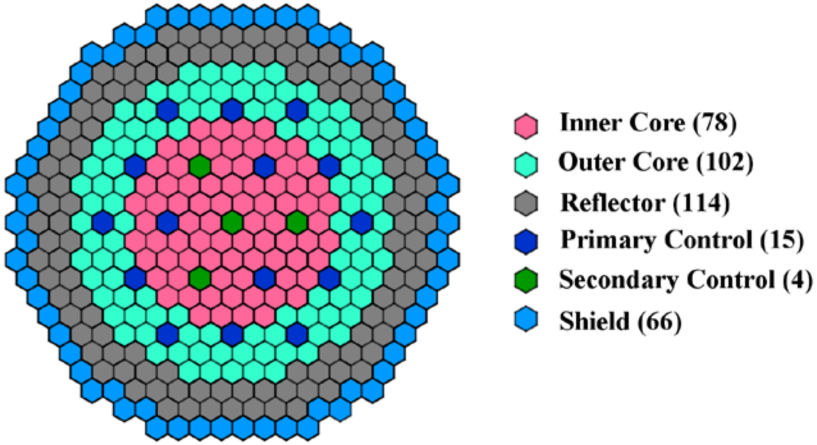
* Normalized to unity for 3D core
* Relative pin power error

2D ABR C5G7 Variation Benchmark

ABR Metallic Benchmark

- ABR (Advanced Burner Reactor)
- Designed for the study of future fast reactor designs
- Fuel Assembly pitch : 16.2471 cm
- Fuel Pin Pitch : 0.8966 / 1.5528 / 4.8578 / 3.3603 cm
- Selected to verify hexagonal calculations for various geometries

Core Configuration

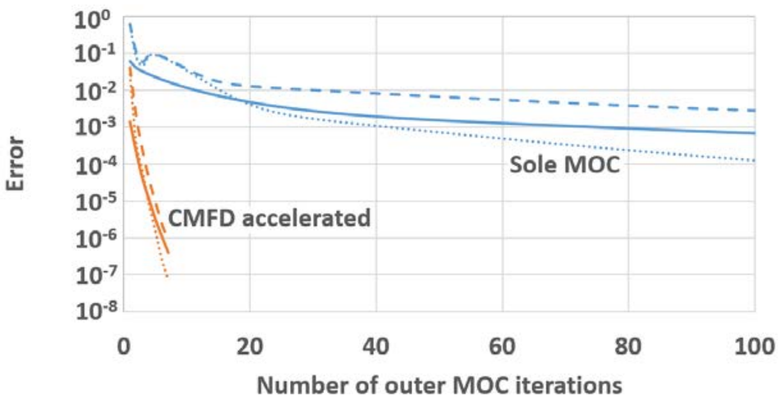


C5G7 Variation

Metallic	C5G7 Variation
Inner Fuel	UO_2-Clad
Outer Fuel	4.3% MOX
Na	Moderator
HT-9	Guide Tube
Natural B_4C	Control Rod

2D ABR C5G7 Variation Benchmark Calculation

☐ Effectiveness of Hexagonal CMFD Acceleration[a)]



Convergence criteria = 10^{-6}

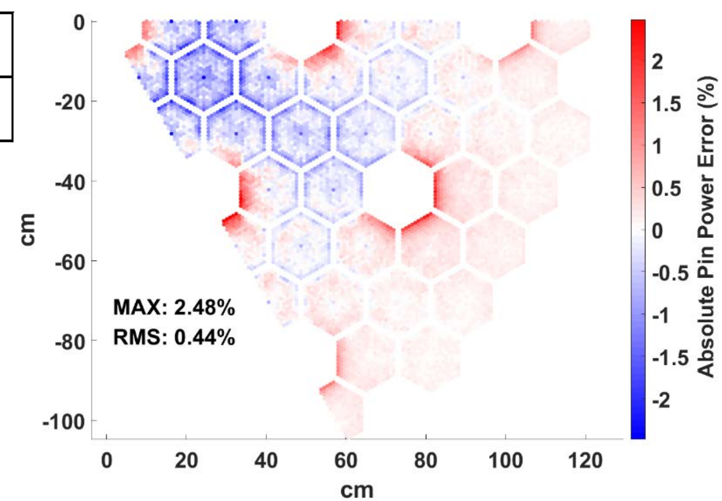
Case	# of outer MOC iterations	Computation Time (s)
Sole MOC	735	35,101
	x 1/105	x 1/102
CMFD Accelerated	7	344

☐ Comparison between nTRACER and McCARD

K-eff	McCARD[b)c)] (σ, pcm)	1.19693 (3)
	nTRACER (Δρ, pcm)	1.19773 (56)

b) NI = 500, NA = 1000, NP = 2,000,000
c) Pin Power σ < 0.27%

1. Underestimation of radial leakage
2. Error along control rod assemblies
   - Relatively large source mesh area

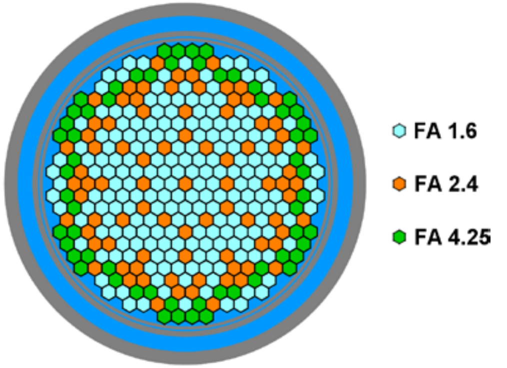


a) Intel® Xeon E5- 2640 2.60 GHz, 128 GB of memory, 16 thread per node

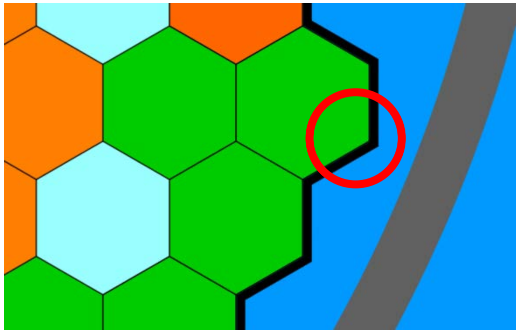
'Full-Core' VVER-440 Benchmark

☐ Details of 'Full-Core' Benchmark

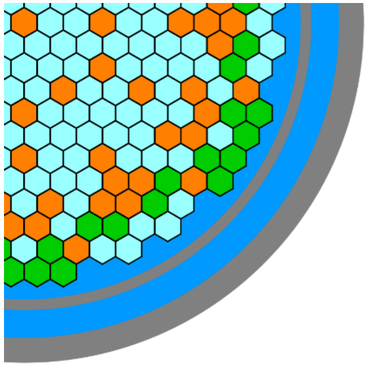
- 2D & vacuum boundary condition on the radial outer boundary
- Explicit radial reflector description
  - 'Vygorodka' : Internal edged metal sheet
  - Core basket (neglected), core barrel, and pressure vessel
- Fuel Pin Pitch : 1.23 cm
- Fuel Assembly (FA) pitch : 14.7 cm
- Pressure vessel outer radius : 191.1 cm
- Temperature of all materials : 543.15 K
- Selected to verify hexagonal calculations based on 47 group XS



☐ Radial Reflectors



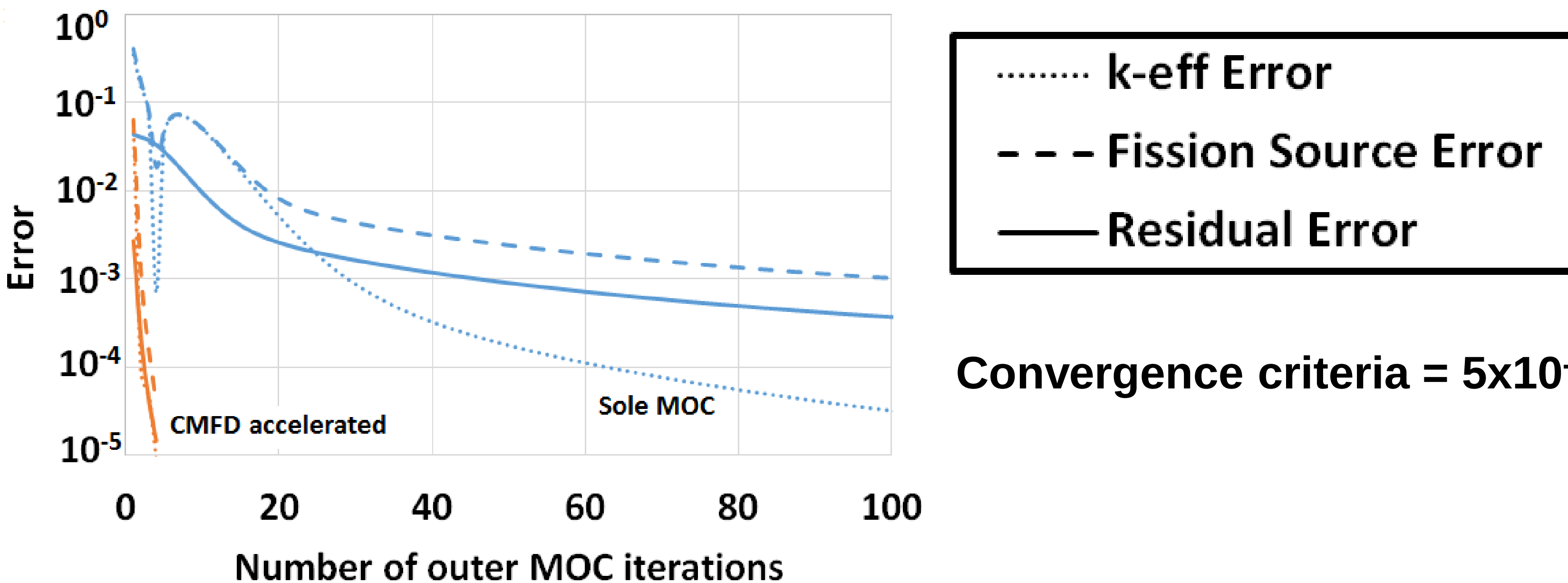
'Vygorodka'



Core Barrel and Pressure Vessel

Effectiveness of the Hexagonal CMFD Acceleration

☐ 2D Core Calculation with P_0 Condition[a)]



Convergence criteria = 5×10^{-5}

☐ # of Outer MOC Iterations

CASE	P_0	P_1	P_2	P_3
Sole MOC	537	537	537	537
CMFD accelerated	4	4	4	4

x 1/134

☐ Computation Time (min.)

CASE	P_0	P_1	P_2	P_3
Sole MOC	4,777	5,356	6,009	9,211
CMFD accelerated	112	122	130	137

x 1/67

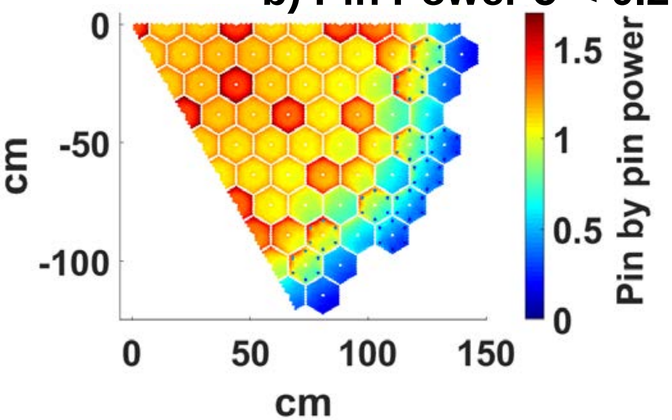
a) Intel® Xeon E5- 2640 2.60 GHz, 128 GB of memory, 16 thread per node

'Full-Core' VVER-440 Benchmark Calculation

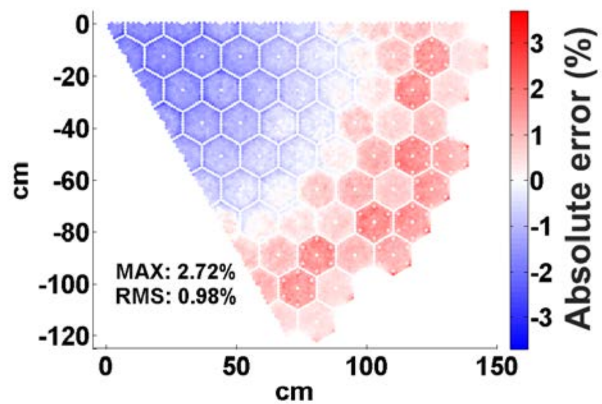
CASE		P_0	P_1	P_2	P_3
K-eff	McCARD[a)b)]	1.08857 (2)			
	nTRACER	1.08724	1.08665	1.08704	1.08701
	Δρ, pcm	-113	-163	-130	-132
ΔP[b)]	Max, %	3.93	2.44	2.78	2.72
	RMS, %	1.62	0.69	1.00	0.98

a) NI = 500, NA = 3000, NP = 500,000

b) Pin Power σ < 0.29%



McCARD
pin by pin power



nTRACER
pin power error : P_3

Power tilt

- Bigger pin power at periphery
- Smaller pin power at center

McCARD reference

k :	1.00204
std :	2 pcm

Renewal of nTRACER XS Library

SGFSP Time

OLD

P_0 – Inflow T.C. (764s)

-2.39	-2.14	-1.14	-1.71	-0.87	-1.07	0.20	0.75	0.96
-2.14	-1.35	-1.76	-0.96	-1.40	-0.40	-0.49	0.62	1.08
-1.14	-1.76	-0.81	-1.40	-0.45	-0.89	0.30	0.54	0.88
-1.71	-0.95	-1.40	-0.52	-0.93	-0.02	-0.39	0.55	1.16
-0.87	-1.38	-0.45	-0.93	0.09	-0.39	0.42	0.82	
-1.06	-0.40	-0.88	-0.01	-0.39	0.59	0.88	1.23	
0.21	-0.48	0.31	-0.39	0.42	0.88	1.28		
0.77	0.62	0.54	0.55	0.83	1.23			
0.97	1.09	0.88	1.16					

k :	1.00118
Δρ :	-86

Abs.		Rel.	
RMS	Max	RMS	Max
0.85	1.50	0.95	2.39

P_3 (800s)

-3.90	-3.70	-2.88	-2.84	-1.81	-1.42	-0.11	0.95	1.80
-3.70	-3.15	-3.16	-2.31	-2.07	-0.93	-0.44	0.92	1.90
-2.86	-3.15	-2.34	-2.38	-1.35	-1.08	0.19	0.98	1.81
-2.84	-2.31	-2.36	-1.51	-1.34	-0.28	0.11	1.20	2.07
-1.80	-2.06	-1.35	-1.34	-0.30	-0.10	0.97	1.74	
-1.41	-0.92	-1.08	-0.28	-0.10	0.90	1.56	2.23	
-0.10	-0.43	0.20	0.11	0.97	1.56	2.16		
0.96	0.92	0.99	1.21	1.74	2.23			
1.81	1.90	1.81	2.07					

k :	1.00095
Δρ :	-109

Abs.		Rel.	
RMS	Max	RMS	Max
1.56	2.45	1.73	3.90

NEW

P_0 (421s)

-0.49	-0.34	0.36	-0.36	0.08	-0.42	0.18	0.21	-0.11
-0.34	0.25	-0.21	0.22	-0.38	0.12	-0.38	0.08	0.00
0.36	-0.21	0.48	-0.22	0.31	-0.36	0.24	0.02	-0.19
-0.36	0.22	-0.22	0.32	-0.24	0.19	-0.43	-0.04	-0.11
0.09	-0.38	0.31	-0.24	0.41	-0.27	0.11	0.06	
-0.42	0.12	-0.36	0.19	-0.27	0.27	0.27	0.03	
0.18	-0.38	0.24	-0.43	0.11	0.27	0.18		
0.21	0.08	0.03	-0.04	0.06	0.03			
-0.11	0.01	-0.19	-0.11					

k :	1.00167
Δρ :	-37

Abs.		Rel.	
RMS	Max	RMS	Max
0.24	0.45	0.25	0.49

P_3 (435s)

-1.04	-0.99	-0.58	-0.84	-0.40	-0.51	-0.11	0.13	0.29
-0.99	-0.66	-0.84	-0.49	-0.62	-0.18	-0.34	0.11	0.39
-0.58	-0.84	-0.36	-0.64	-0.20	-0.39	0.08	0.17	0.31
-0.84	-0.49	-0.64	-0.21	-0.37	0.04	-0.07	0.30	0.44
-0.39	-0.62	-0.20	-0.37	0.15	-0.03	0.38	0.55	
-0.51	-0.18	-0.39	0.04	-0.03	0.38	0.54	0.63	
-0.11	-0.34	0.08	-0.07	0.38	0.54	0.67		
0.13	0.11	0.17	0.30	0.55	0.63			
0.29	0.39	0.31	0.44					

k :	1.00173
Δρ :	-31

Abs.		Rel.	
RMS	Max	RMS	Max
0.40	0.69	0.44	1.04

Conclusion

☐ Hexagonal CMFD Acceleration

- **2D C5G7 H benchmark : factor of 20 in # of MOC, factor of 17 in time**
- **2D ABR C5G7 variation benchmark : 105 / 103**
- **2D 'Full-Core' VVER-440 benchmark : 134 / 67**
- **Hexagonal CMFD kernel is confirmed to efficiently accelerate calculations**

☐ Hexagonal MOC Calculation

- **-9 pcm reactivity error, 0.70 % RMS pin power error in for 2D C5G7 H**
- **6 pcm / 0.79 % for 3D C5G7 H benchmark**
- **56 pcm / 0.56 % for 2D ABR C5G7 variation benchmark**
- **-132 pcm / 0.98 % for 'Full-Core' VVER-440 benchmark**
- **Hexagonal MOC module is confirmed to accurately simulate the core**

☐ Future Work

- **Simulate gap cells with high accuracy**
- **Update nTRACER XS Library for hexagonal core calculation**