Whole Core Transport Calculation for the VHTR Hexagonal Core

2007. 6. 5

Jin-Young Cho, Kang-Seog Kim, Chung-Chan Lee
Korea Atomic Energy Research Institute
Han-Gyu Joo
Seoul National University

Introduction

☐ The DeCART Code

- Direct Multigroup 3-D Whole-Core Transport Calculation Code at Power Generating Conditions in PWRs
- Generates Core Reactivity, 3-D Pinwise Power and Temperature Distributions Directly using a multi Group Cross Section Library
- No Homogenization nor Group Condensation Needed

☐ Primary Methods

- Planar Method Of Characteristics within the 3-D CMFD Framework
  - 2-D MOC calculation with an approximated axial leakage source to generate dynamically homogenized cell Xsec and radial coupling coeff.
  - Pin cell-based 3D CMFD (Coarse Mesh Finite Difference) calculation with axial SP3-NEM kernel and Sub-Plane Scheme
- Temperature Dep. Subgroup Method for Resonance Treatment

☐ Primary Capability

- Sub-pin Level Fuel Temperature Calculation for Each Pin
- MPI based Parallel Computation on LINUX Clusters
- P1 Anisotropic Scattering Treatment
- Transient Calculation for a Given XS
- Sub-Pin Level Depletion Calculation
- Rectangular and Hexagonal Core Calculation

Introduction

☐ Implementation of the Whole Core Transport Kernel for Hexagonal Core

- **Modular Ray Tracing Module based on Hexagonal Assembly**
  - **Modular Rays Using Similar Scheme to the Rectangular Geom.**
- **Multi-Group CMFD Module for an Efficient Transport Calculation**

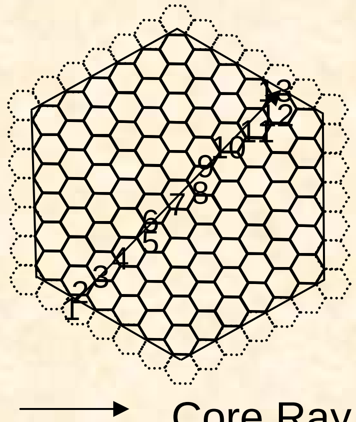
☐ Benchmark Calculation

- **C5G7MOX Hexagonal Variation Problem**
- **Three Types of NGNP BLOCKs**
- **2-D Realistic NGNP Core**
- **Comparison with HELIOS and Monte Carlo Solutions**

Modular Rays for Hexagonal Assembly

□ Requirements for Modular Ray

- **Path Linking Capability: to Construct a Core Ray by Linking the Modular Rays and can be Met by Adjusting the Azimuthal Angles and Ray Spacings**
- **Complete Reflection Capability: Can be Met by Using Reflective Angles to Core Boundary Angles**



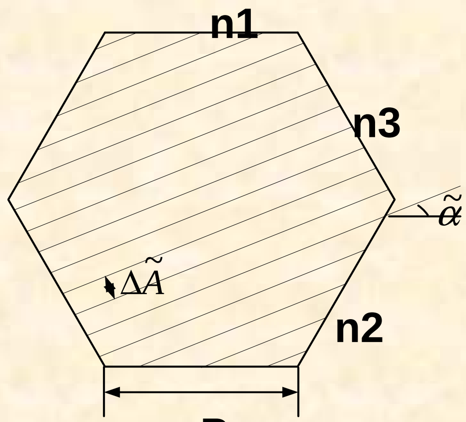
□ Modular Ray Angle and Ray Spacing

$$\tan\alpha = \frac{\sqrt{3}}{2(n2/n1)+1} \qquad \Delta A = \frac{P\sin\alpha}{n1}$$

where

$$n1 = \text{int}\left[\sin(\tilde{\alpha})\frac{P}{\Delta\tilde{A}}\right] \qquad n2 = \text{int}\left[\sin(60^\circ - \tilde{\alpha})\frac{P}{\Delta\tilde{A}}\right]$$

$\tilde{\alpha}$, $\Delta\tilde{A}$**: User Input,** $\tilde{\alpha}$ **< 60**



□ Relation between n1, n2 and n3

$$n3 = n1 + n2$$

KAERI

Symmetric Angles for Hexagonal Assembly

- **If a ray angle α which meets the first requirement is given for $0 < \alpha < 30$, the following angles are generated to meet the 2nd requirement of complete reflection capability**

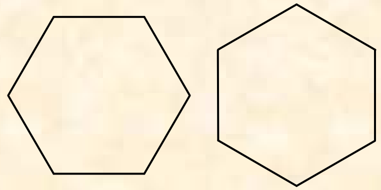
$$\alpha_2 = \frac{\pi}{3} - \alpha \qquad \alpha_3 = \frac{\pi}{3} + \alpha$$

$$\alpha_4 = \frac{2\pi}{3} - \alpha \qquad \alpha_5 = \frac{2\pi}{3} + \alpha$$

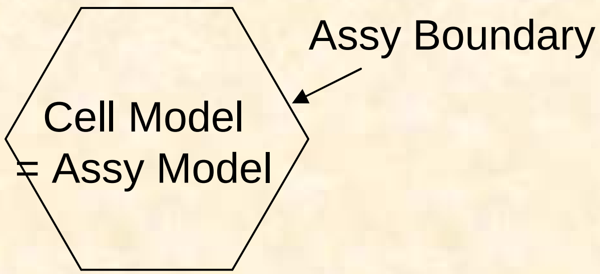
$$\alpha_6 = \pi - \alpha$$

Hexagonal Geometry Model

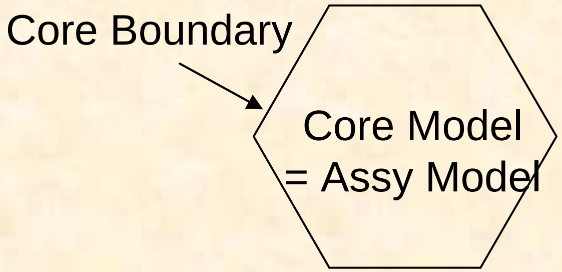
- In hexagonal core, two types of hexagons exist
- Assembly geometry is fixed
- Pin and core geometry is flexible depending on the problem type



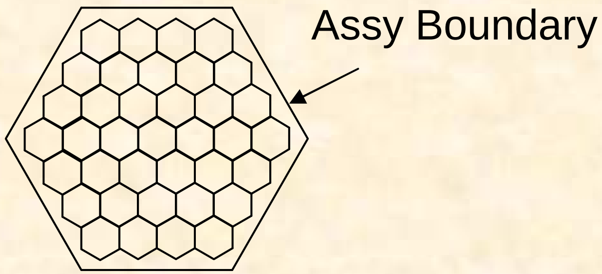
Hexagon Types



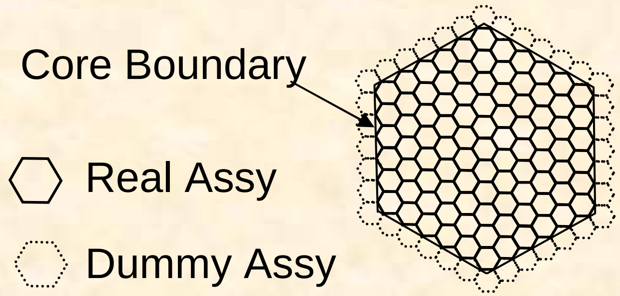
1 Cell per Assembly



Single Assembly Problem



Multi-Cell per Assembly



Multi-Assembly Problem

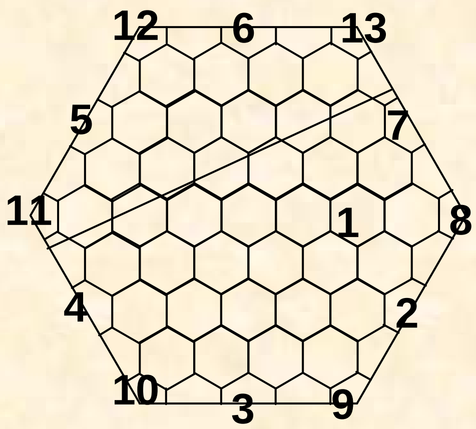
Other Features

☐ Ray Analysis based on Structure Unit

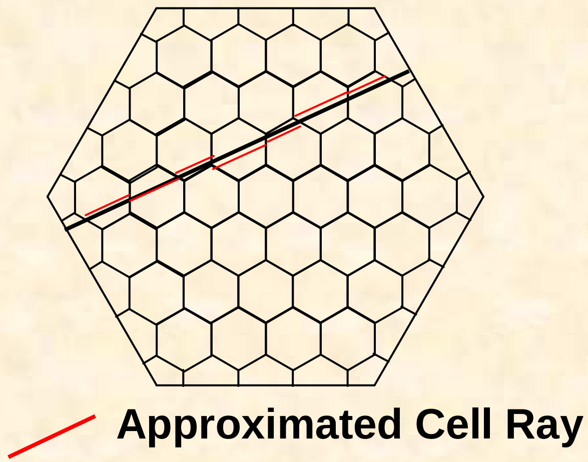
- Gather All Beginning Points for Each Structure Unit
- Easy to Reduce Memory Requirement by Cell Ray Approximation
- Gap between Approximated Ray and Original Ray Less than 0.025 mm

☐ Modified Cycle Ray Scheme

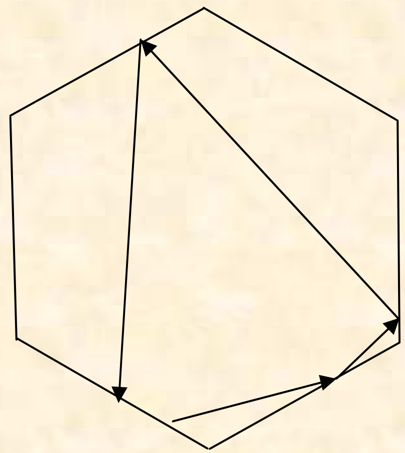
- Reduce Memory Requirement for Angular Flux at the Core Boundary
- All the Rays Start and Finish at a Given Surface



Structure Unit



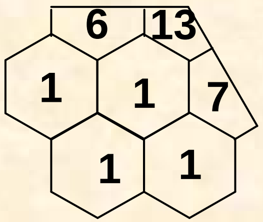
Cell Ray Approximation

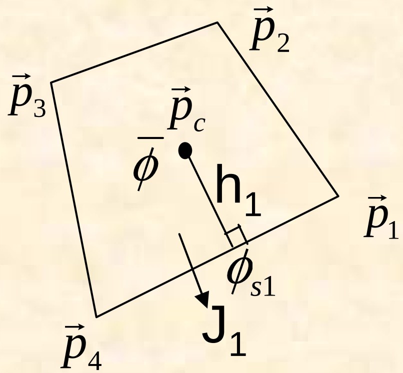


Modified Cycle Ray

CMFD Module

- CMFD Module is Designed based on Structure Unit
- Structure Unit 1 is Regular but the Others are Irregular
- FDM Module to Treat the Unstructured Geometry





- Net Current Approximation for FDM

$$\vec{P}_c = \frac{1}{N}\sum_{i=1}^{N}\vec{P}_i \qquad J_1 = -D\frac{\phi_{s1} - \bar{\phi}}{h_1}$$

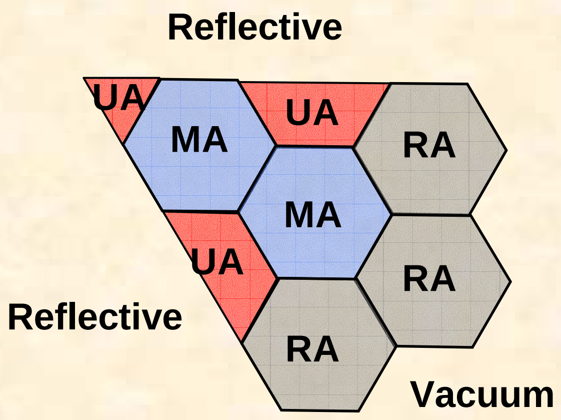
- Current Definition in the CMFD Formulation

$$J_s = -\tilde{D}_s\left(\bar{\phi}^{i+1} - \bar{\phi}^{i}\right) - \hat{D}_s\left(\bar{\phi}^{i+1} + \bar{\phi}^{i}\right)$$

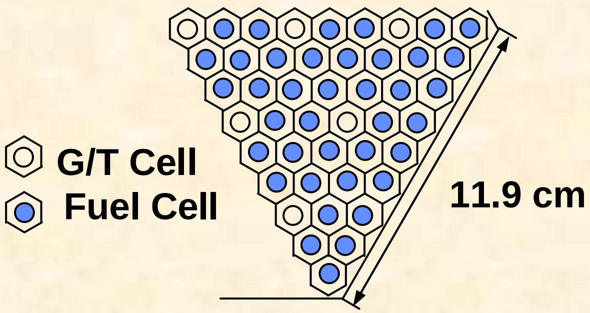
- 2-Group CMFD calculation for the acceleration of the Multi-Group CMFD calculation

C5G7 Hexagonal Variation Problems

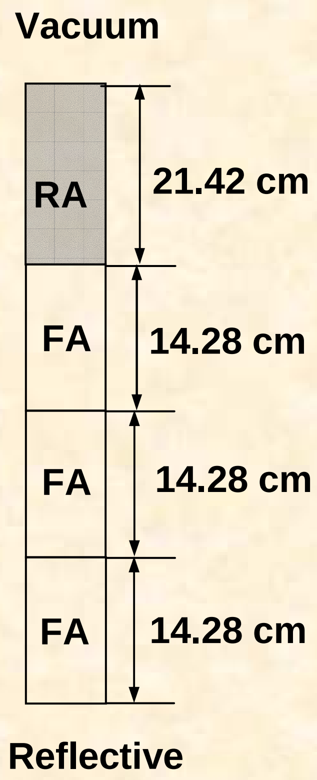
□ Core Configuration



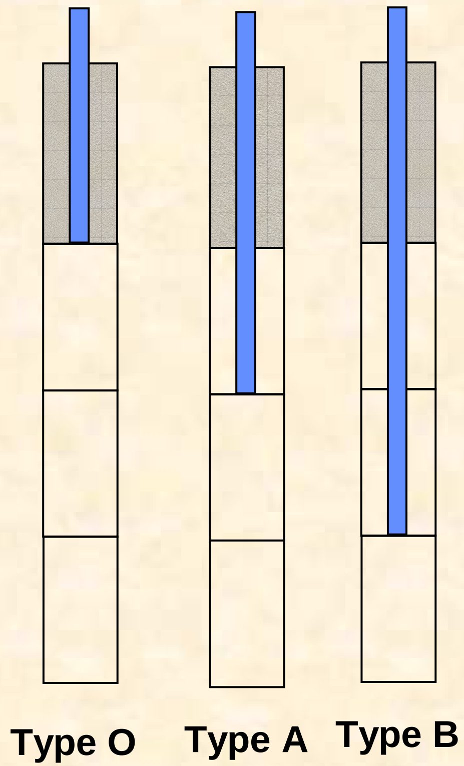
Radial Configuration



Assembly Configuration



Axial Configuration



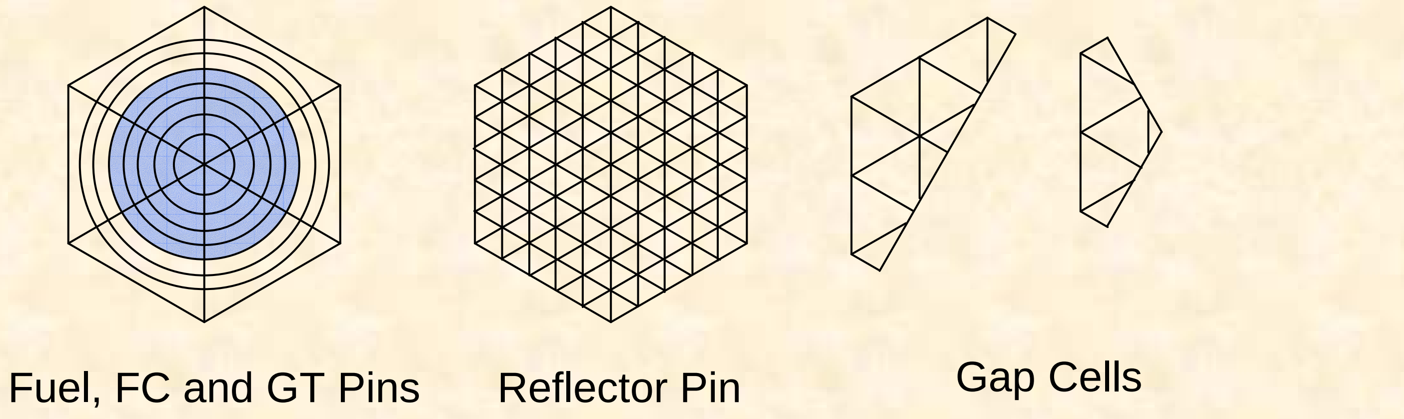
Rod Insertion Types

KAERI

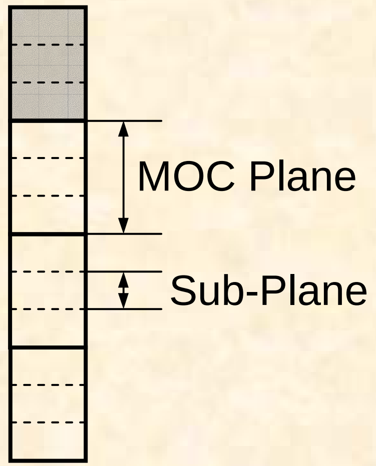
C5G7 Hexagonal Variation Problems

□ DeCART Calculation

- **Pin Model**



- **3 Sub-Planes per MOC Plane**
- **NEM-SP3 for Axial Calculation**
- **0.05/4/2 Ray Options**



C5G7 Hexagonal Variation Problems

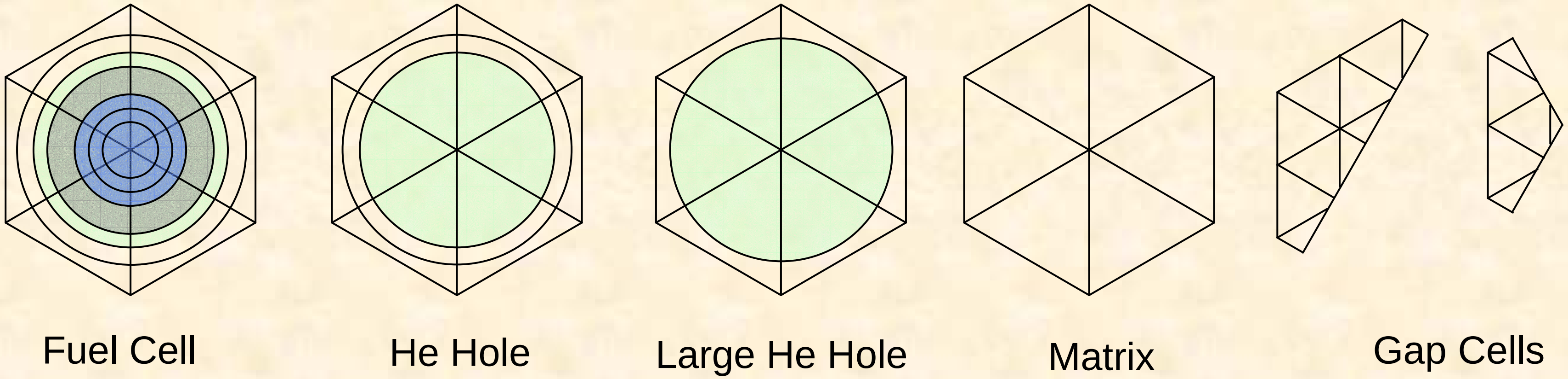
Configurations		2-D	Unrodded	Rodded A	Rodded B
Eigenvalue[1] (σ)		1.16244 (0.00009)	1.12273 (0.00001)	1.11890 (0.00001)	1.10262 (0.00001)
Eigenvalue Error, pcm		-9.8	-52.4	-52.7	-61.7
Slice 1 Pin Power[2] Error (%)	Maximum		1.87	1.84	1.92
	Mean		0.35	0.42	0.43
	RMS		0.54	0.58	0.60
Slice 2 Pin Power Error (%)	Maximum		1.77	1.88	1.92
	Mean		0.35	0.42	0.43
	RMS		0.54	0.59	0.59
Slice 3 Pin Power Error (%)	Maximum		0.90	0.78	1.17
	Mean		0.38	0.48	0.53
	RMS		0.45	0.53	0.59
Axially Integrated Pin Power Error (%)	Maximum	1.83	1.59	1.64	1.62
	Mean	0.38	0.31	0.37	0.39
	RMS	0.50	0.48	0.51	0.53

[1] Reference from McCARD (Monte Carlo Code Developed by Seoul National University)

[2] $\sigma < 0.2\%$

VHTR Problem

☐ DeCART Cell Model

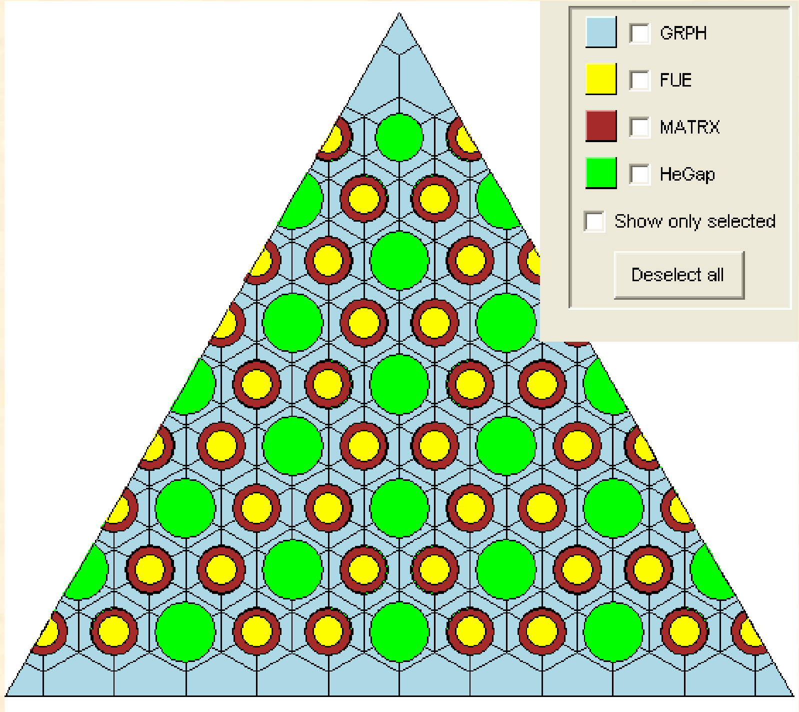


☐ DeCART Calculation

- 190g library for Block and 47g for Whole-Core Problems
- 4 Azimuthal Angles per Sextant and 2 Polar Angles
- 0.05 cm of ray spacing

VHTR Problem

☐ BLOCK-1 Assembly Problem

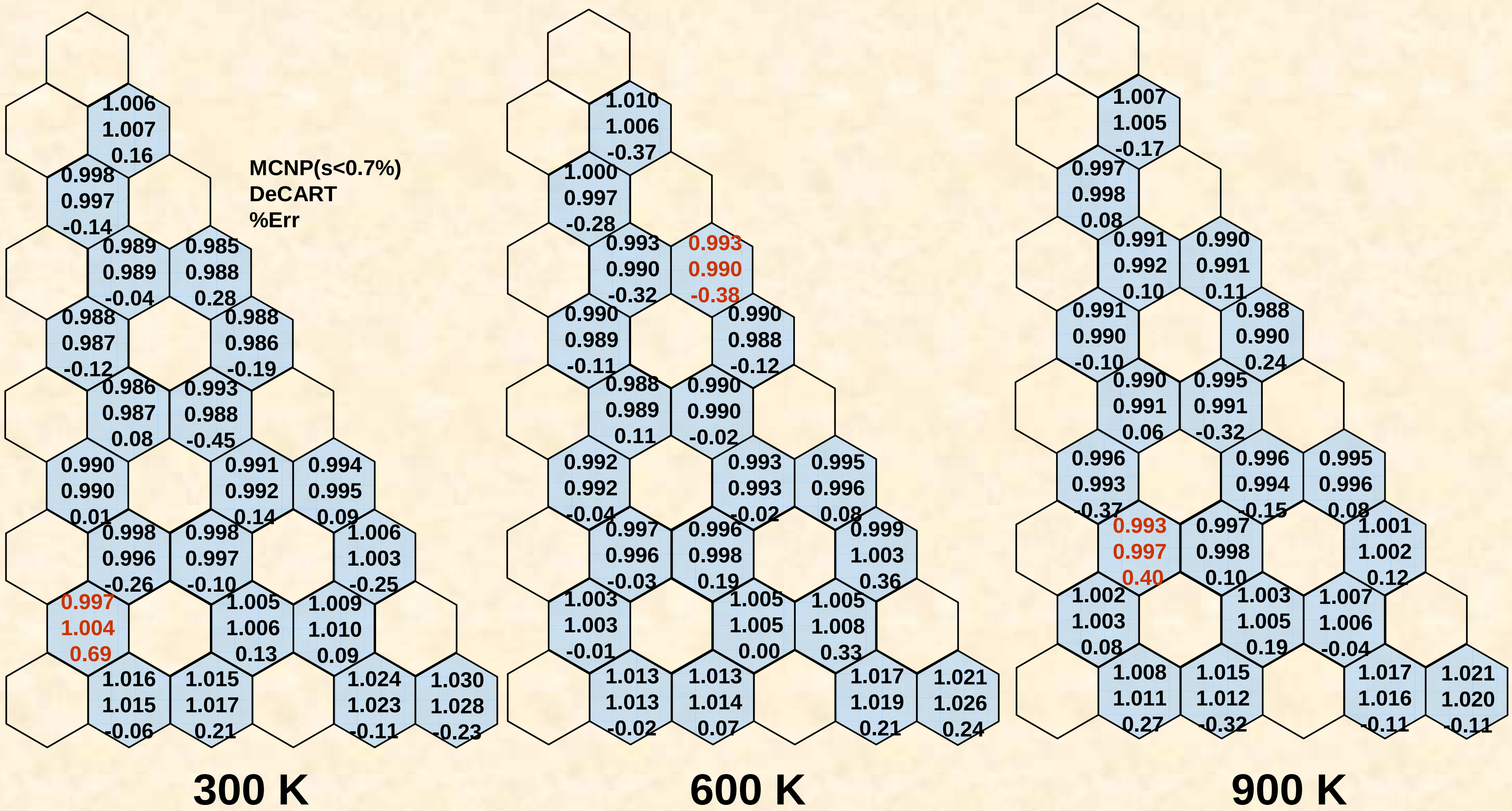


HELIOS Model

Codes	Param		300 K	600 K	900 K
MCNP	K-inf		1.53112	1.48272	1.44922
	(σ)		0.00051	0.00051	0.00048
HELIOS	K-inf		1.53113	1.48546	1.45156
	Δρ, pcm	MCNP	0	124	111
DeCART	K-inf		1.52882	1.48254	1.44833
	Δρ, pcm	MCNP	-98	-8	-42

☐ **DeCART shows Less Than 100 pcm Eigenvalue Errors**

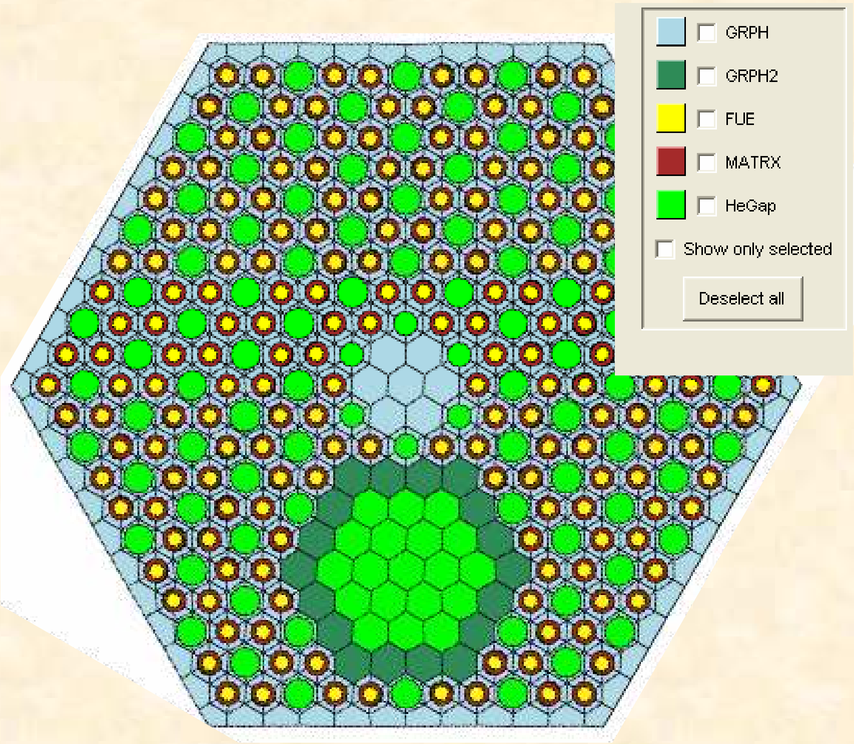
VHTR Problem



- DeCART shows Less Than 0.7 % of Pin Power Errors

VHTR Problem

☐ BLOCK-2 Assembly Problem

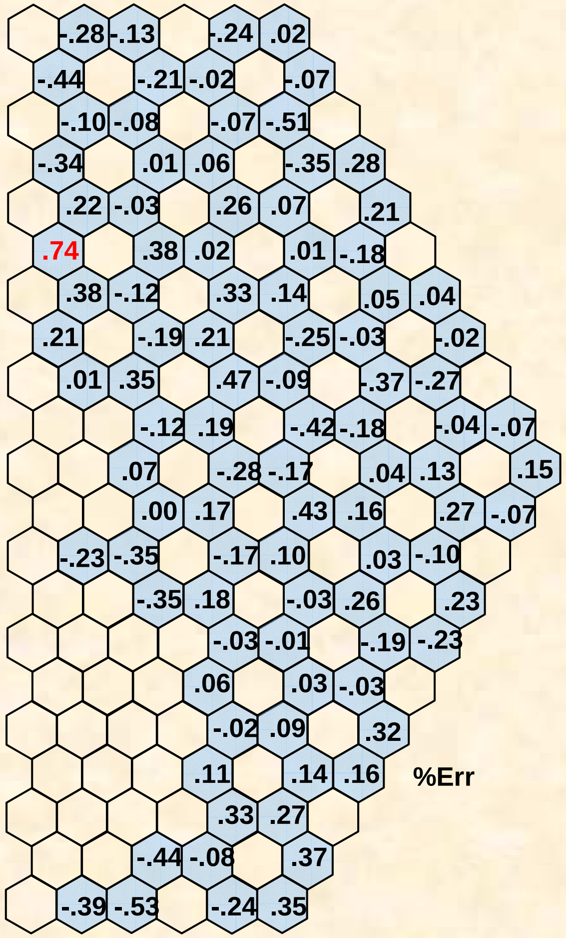


HELIOS Model

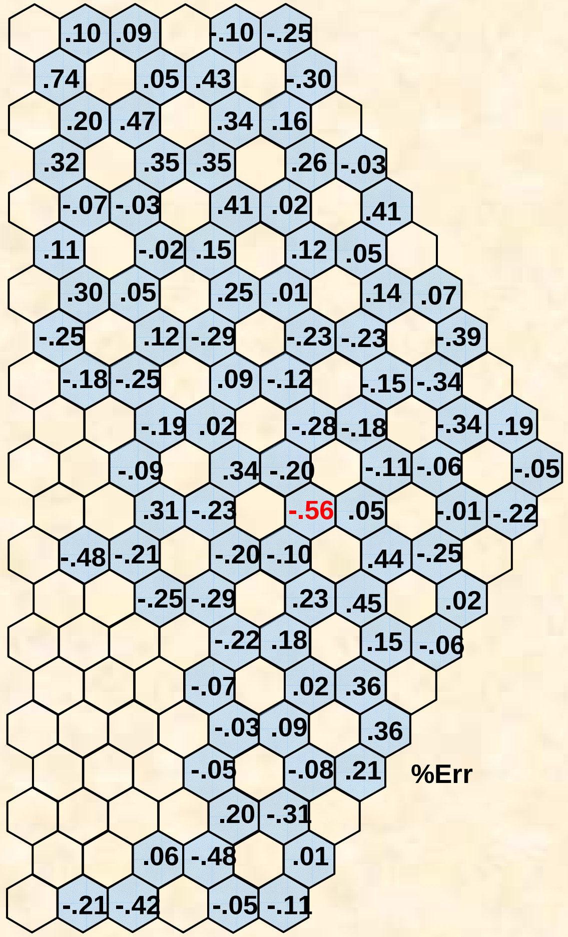
Codes	Param		300 K	600 K	900 K
MCNP	K-inf		1.54717	1.50096	1.46770
	(σ)		0.00051	0.00051	0.00045
HELIOS	K-inf		1.54806	1.50385	1.47092
	Δρ, pcm	MCNP	37	128	149
DeCART	K-inf		1.54622	1.50147	1.46826
	Δρ, pcm	MCNP	-40	22	26

☐ DeCART shows Less Than 100 pcm Eigenvalue Errors

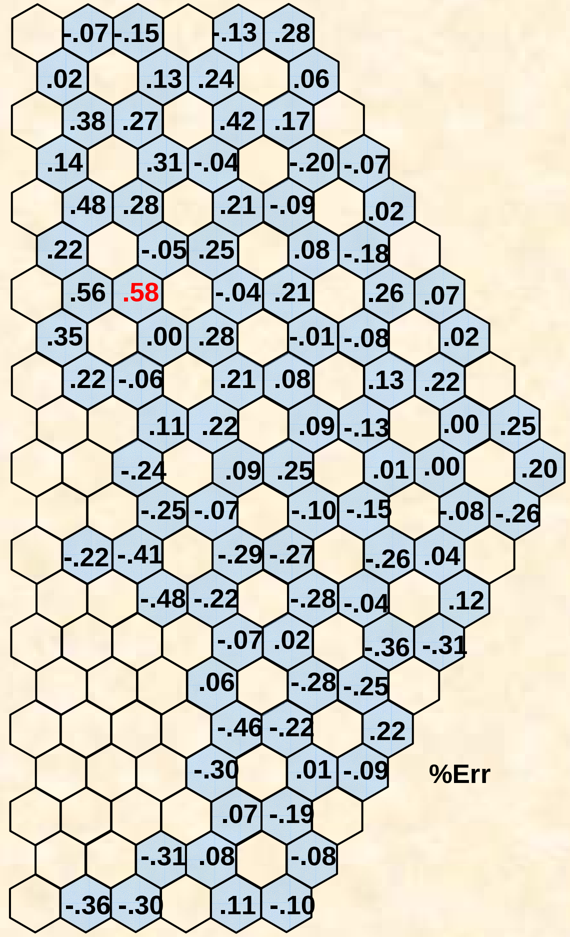
VHTR Problem



300 K



600 K

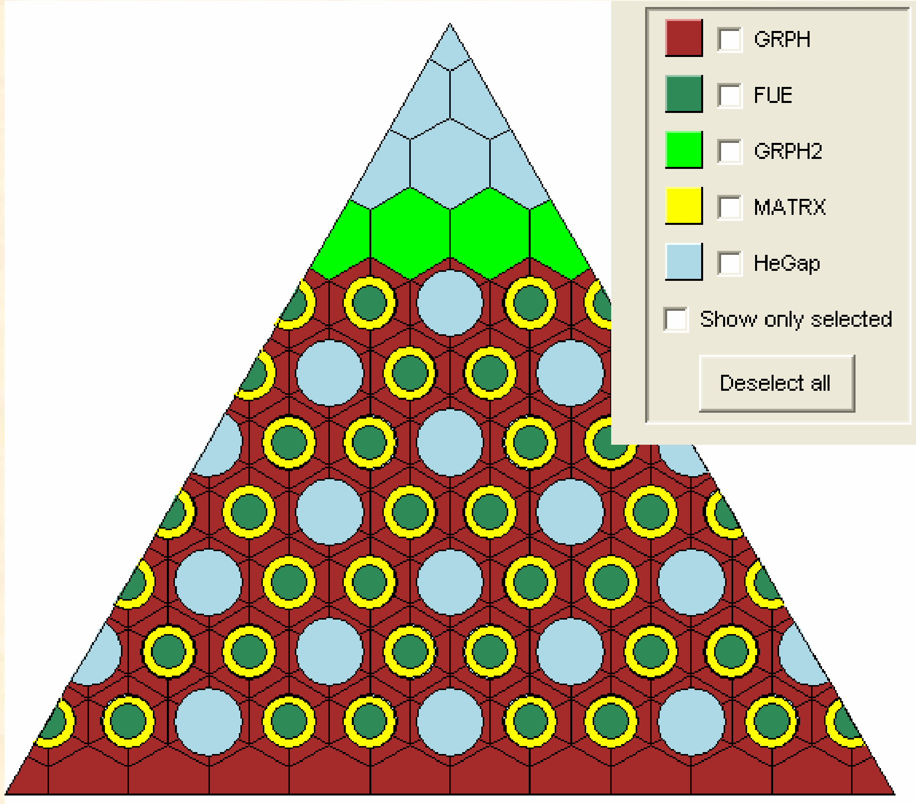


900 K

- ☐ **DeCART shows Less Than 0.7 % of Pin Power Errors**

VHTR Problem

☐ BLOCK-3 Assembly Problem

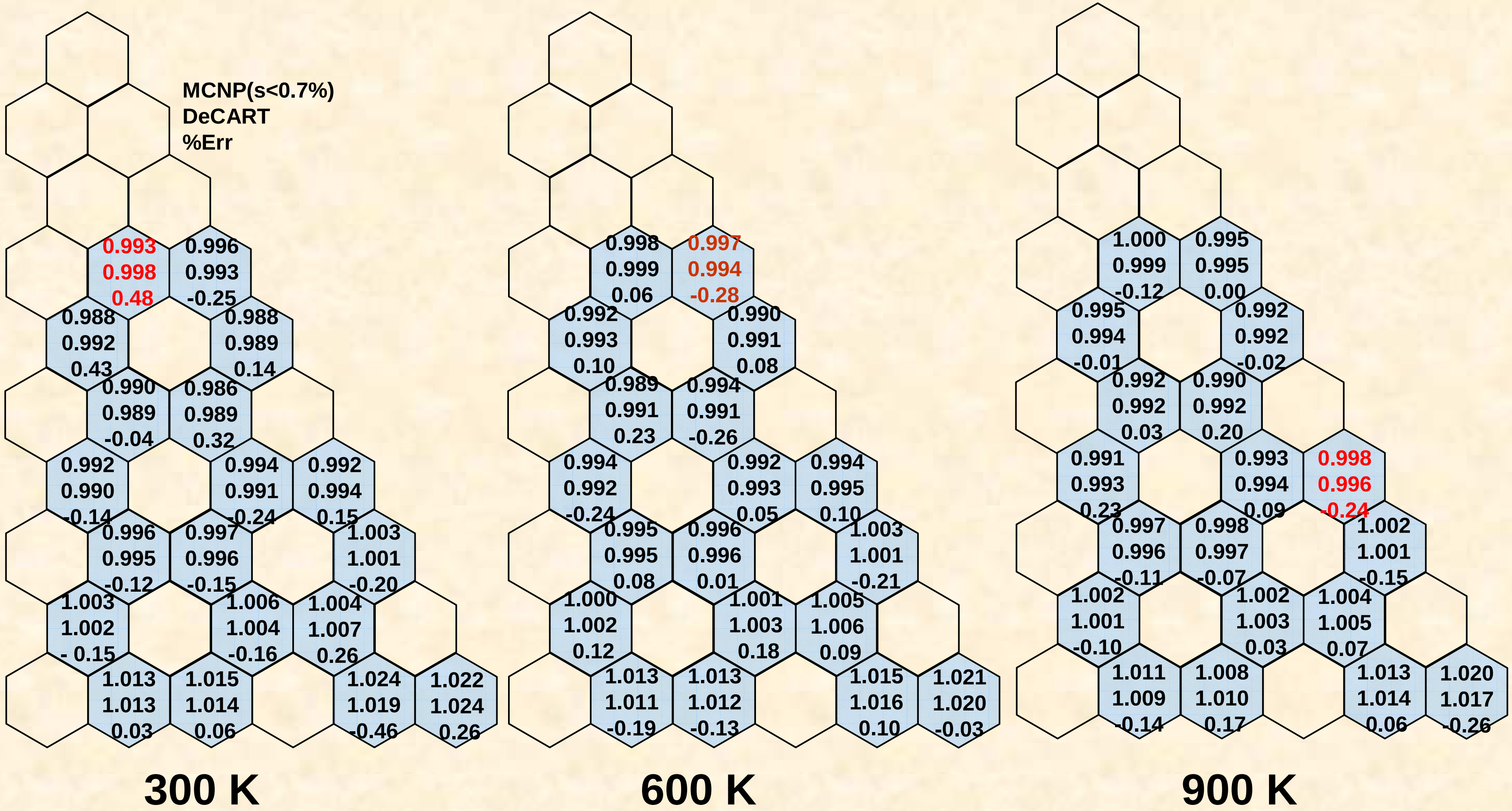


HELIOS Model

Codes	Param		300 K	600 K	900 K
MCNP	K-inf		1.53382	1.48853	1.45417
	(σ)		0.00048	0.00051	0.00057
HELIOS	K-inf		1.53586	1.49054	1.45686
	Δρ, pcm	MCNP	87	91	127
DeCART	K-inf		1.53388	1.48799	1.45405
	Δρ, pcm	MCNP	2	-24	-6

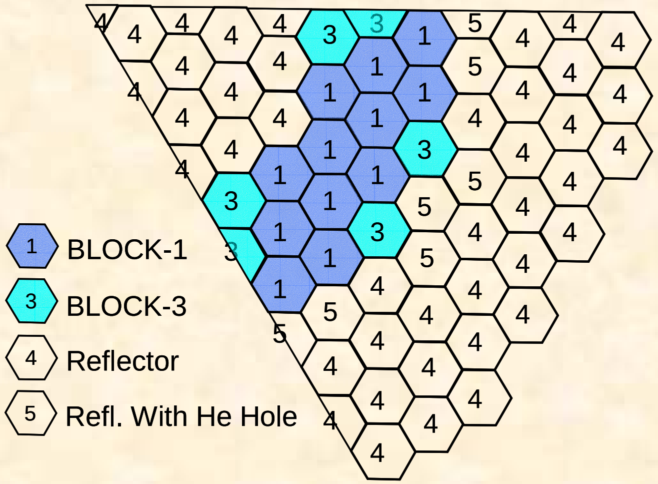
☐ **DeCART shows Less Than 100 pcm Eigenvalue Errors**

VHTR Problem

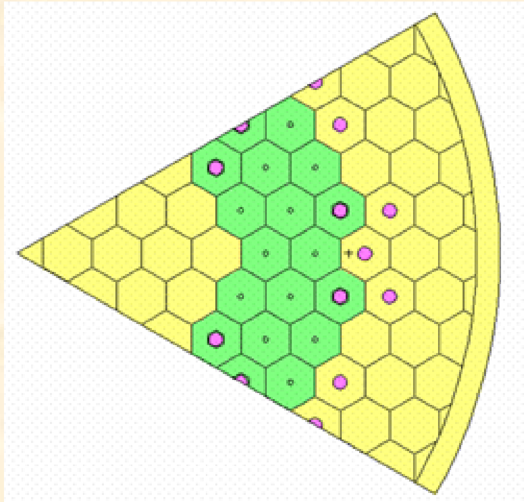


- DeCART shows Less Than 0.7 % of Pin Power Errors

VHTR 2-D Core Problem



DeCART Model



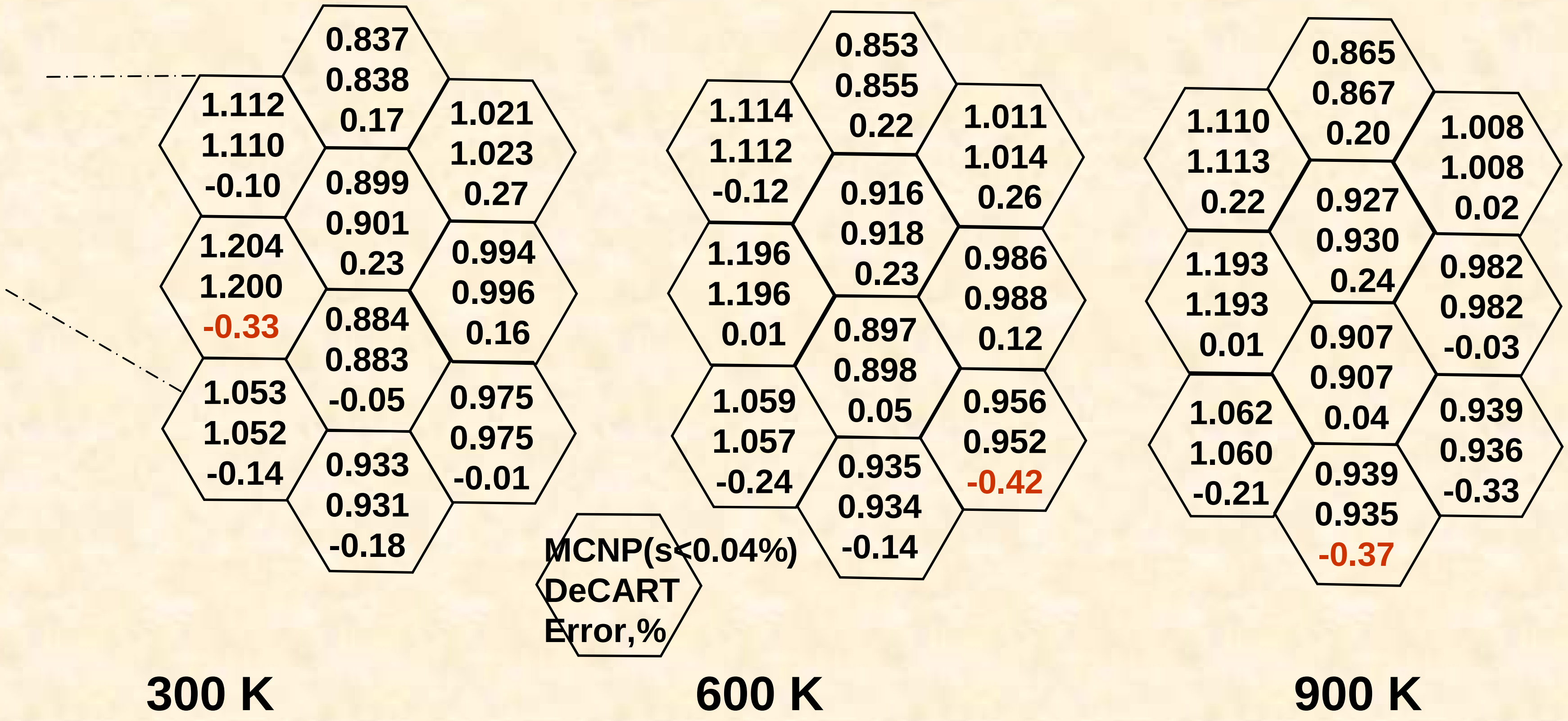
MCNP Model

Codes	Param		300 K	600 K	900 K
MCNP	K-inf		1.43657	1.41004	1.38729
	(σ)		0.00025	0.00025	0.00023
DeCART	K-inf		1.44337	1.42096	1.39902
	Δρ, pcm	MCNP	328	545	605

- ☐ DeCART shows about 300 pcm Error at 300 K and about 600 pcm at 600 K
- ☐ A Little Bit Large Error due to Different Core Boundary Models and 47-G Library Rather than 190-G Library

VHTR 2-D Core Problem

□ Block Power Comparison



□ DeCART shows Less Than 0.5 % of Block Power Errors

Conclusion

□ Implementation of Hexagonal Module to DeCART Code for Whole Core Transport Calculation

- Modular Ray Tracing Module and Multi-Group CMFD Module

□ C5G7MOX Hexagonal Variation Problem

- Shows Less Than 2 % of Local Pin Power Error, and Less Than 70 pcm of Eigenvalue Error
- Proves the Soundness of the Hexagonal Module

□ VHTR Benchmark Calculation

- < 100 pcm of Eigenvalue and 0.7 % Pin Power Errors for the Block Problems When Using 190g Library
- < 600 pcm of Eigenvalue and 0.5 % Block Power Errors for 2-D Core Problem When Using 47g Library
- Proves the Applicability of the Developed Hexagonal Module to the Realistic Problem

Conclusion

☐ Computing Time Breakup for VHTR Problems

Problems		Resonance	MOC	CMFD	Etc.	Total
Block-1	CMFD	0.89	1.36	0.78	0.10	3.13
Block-2	CMFD	4.54	7.27	2.52	0.27	14.6
Block-3	CMFD	0.87	0.99	1.11	0.08	3.05
Core-2D	CMFD	87.35	157.30	20.33	2.05	267.03

PENTIUM-IV 3.0 GHz PC, 1-CPU, Minutes

- Requires about 3 and 15 Minutes for 1/6 and Full Block Problems, and about 5 hours for 2-D Core Problem.

☐ The hexagonal module implemented on the DeCART code works very well showing good results within affordable computing time