ULSAN NATIONAL INSTITUTE OF SCIENCE AND TECHNOLOGY

Monte Carlo Code Development at UNIST

2017.03.02

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UNIST

COmputational Reactor Physics & Experiment lab

CONTENTS

OVERVIEW

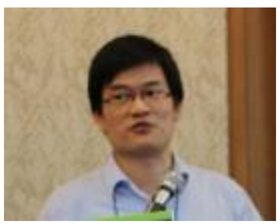
DEVELOPMENT TEAM

▪ Monte Carlo (MC) development at UNIST (Since 2013.)

- 3 Post-doc., 5 Graduate students

Deokjung Lee
- Associate Professor
- Manage the development

Jiankai Yu
- Post Doctoral Program
- On-The-Fly Xs Generation
- TH coupling



Peng Zhang
- Post Doctoral Program
- Modified Power Method
- TH coupling

Hyunsuk Lee
- Graduate Student
- Main developer

Matthieu Lemaire
- Post Doctoral Program
- MHTGR-350
- Gamma Transport

Wonkyeong Kim
- Graduate Student
- Depletion solver
- Hybrid Depletion

Jinsu Park
- Graduate Student
- Monte Carlo acceleration (CMFD)

Azamat Khassenov
- Graduate Student
- OTF-DB (multipole)

Yunki Jo
- Graduate Student
- Adjoint calculation

GENERAL OVERVIEW

- **Monte Carlo Code MCS**
  - 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
    - Gamma transport
  - Physics
    - Resonance upscattering (DBRC, FESK)
    - Probability table method
    - $S(\alpha, \beta)$
    - On the fly Doppler broadening
    - CTF coupling
  - Acceleration
    - MOC and MC Hybrid solver
    - Modified power iteration
    - Wielandt method
    - CMFD
  - Parallelism
    - Parallel fission bank
  - Depletion
    - CRAM , MEM, Krylov Subspace
    - Hybrid depletion

FUNCTIONS

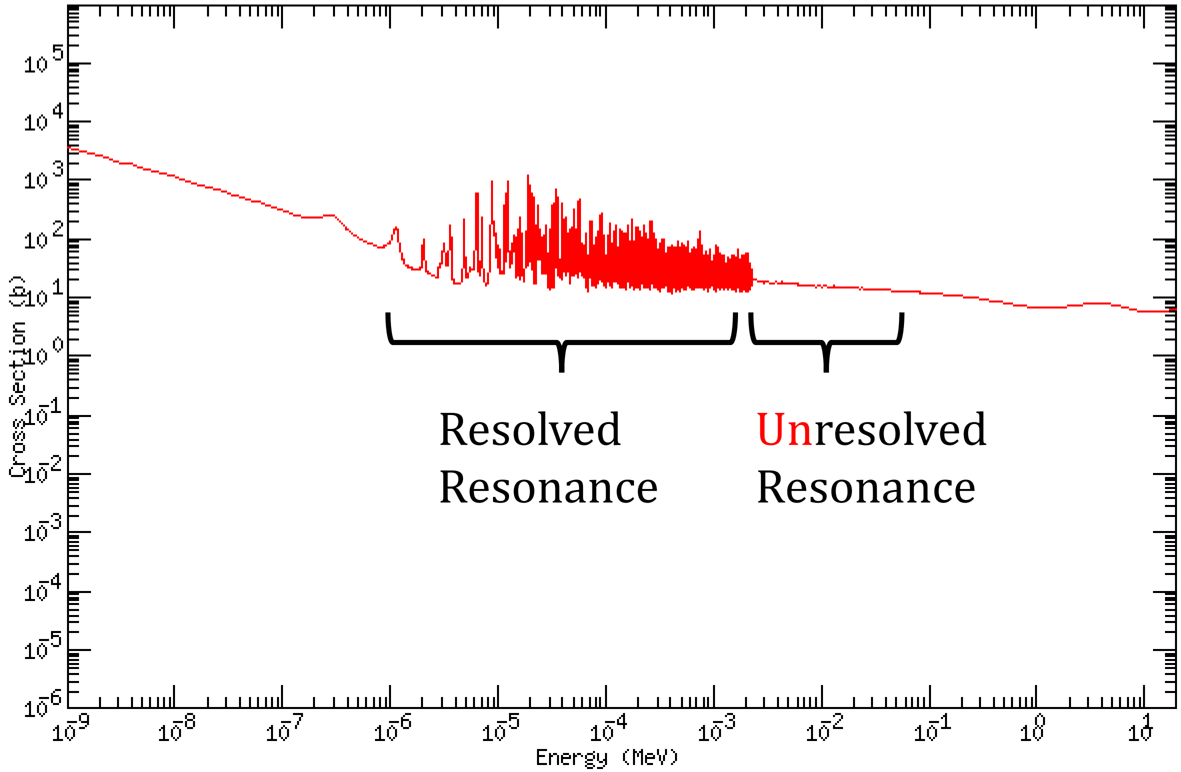
FUNCTIONS

- Collision Kernel
  - Probability-table
  - Resonance Up-scattering (DBRC)
- Acceleration Technique
  - Modified Power Method
  - Coarse Mesh Finite Difference (CMFD)
  - MC-MOC Hybrid
- Feedbacks
  - Depletion
  - Hybrid Depletion
  - Simple TH1D coupling
  - Cobra-TF (CTF) Coupling
  - Multipole (On-The-Fly Doppler broadening)
  - SIGMA1 Kernel (inline broadening)
- ETC
  - Image
  - Gamma Transport
  - Indexing
  - Triso Particle Sampling
  - Parallel Fission Bank

FUNCTIONS

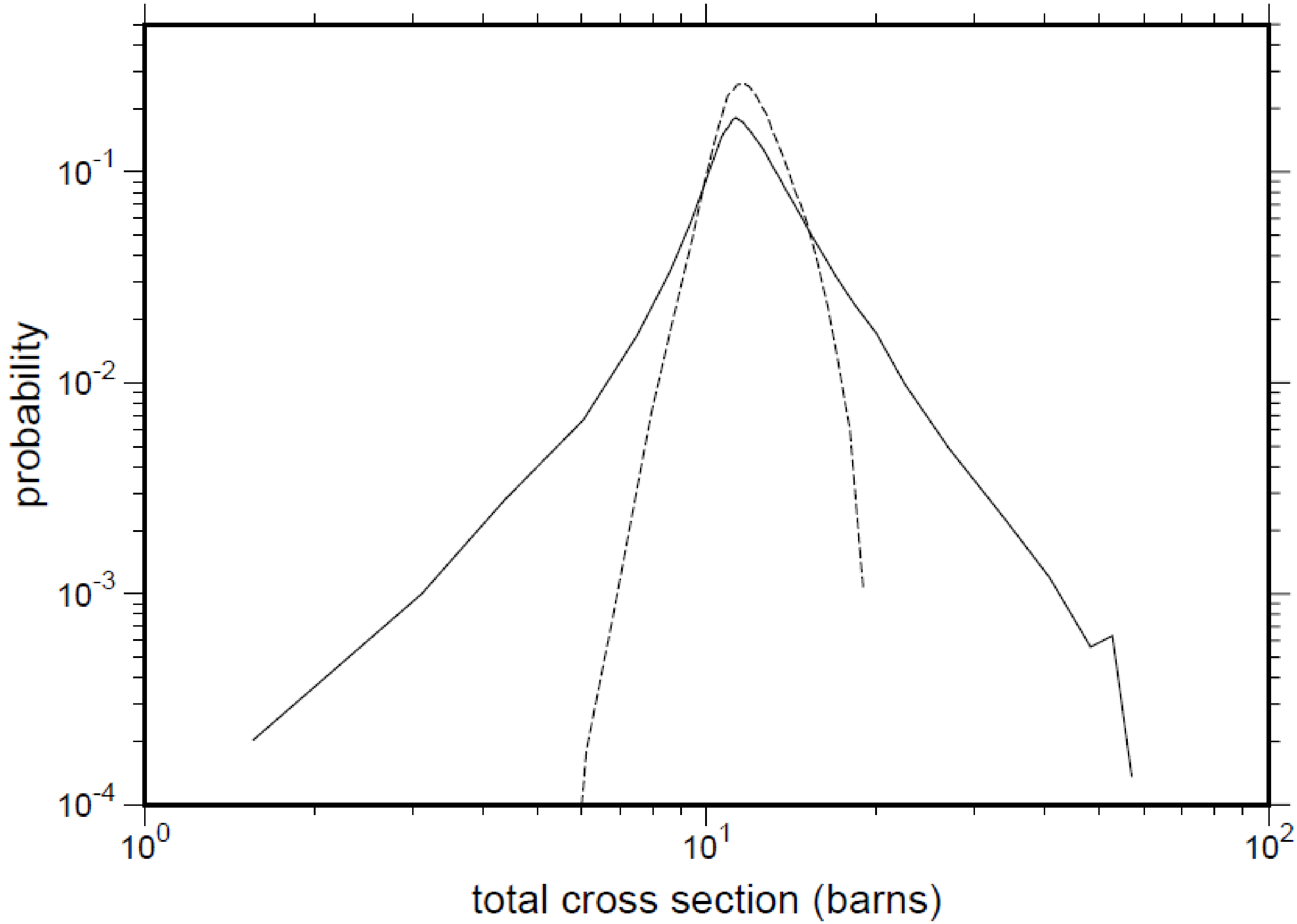
Probability-table (unresolved resonance range)

- **ENDF data provide average cross section in the unresolved resonance range**

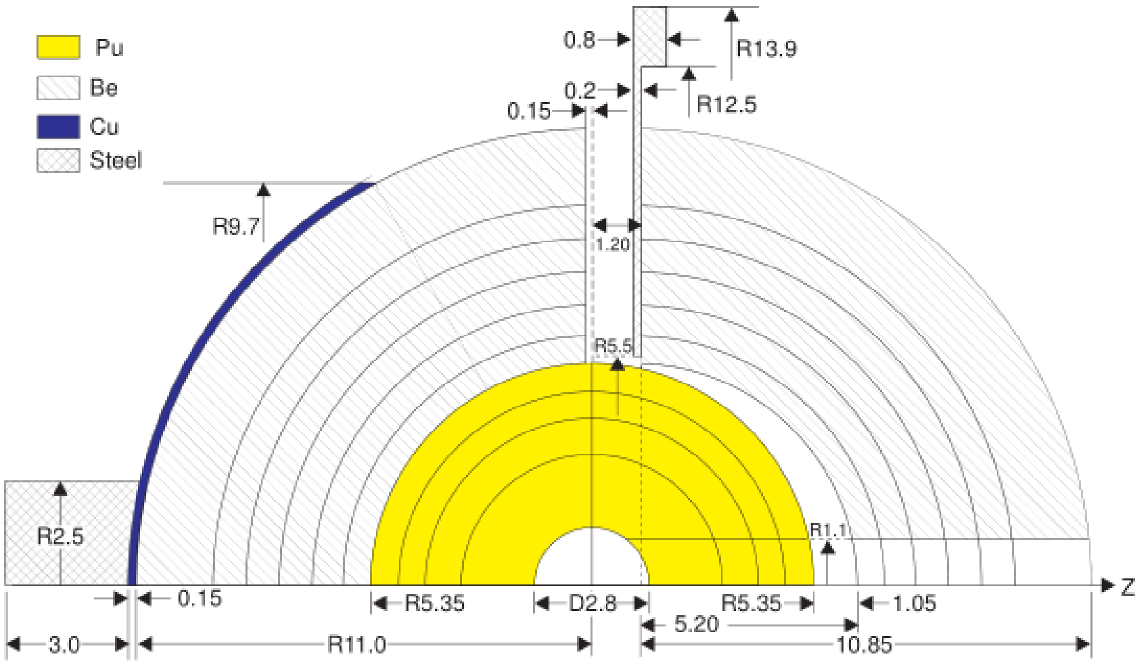


Total cross section of U-235

- **Probability distribution for the total cross section at 20 KeV (solid) and 140 Kev (dashed) of U-238**



- **The International Criticality Safety Benchmark Experimental Problem (ICSBEP)**
  - **Well-publicized neutronics benchmark problems**
  - **AEN-NEA**



PU-MET-019

International Handbook of Evaluated Criticality Safety Benchmark Experiments, NEA/NSC/DOC(95)03, OECD Nuclear Energy, 2005.

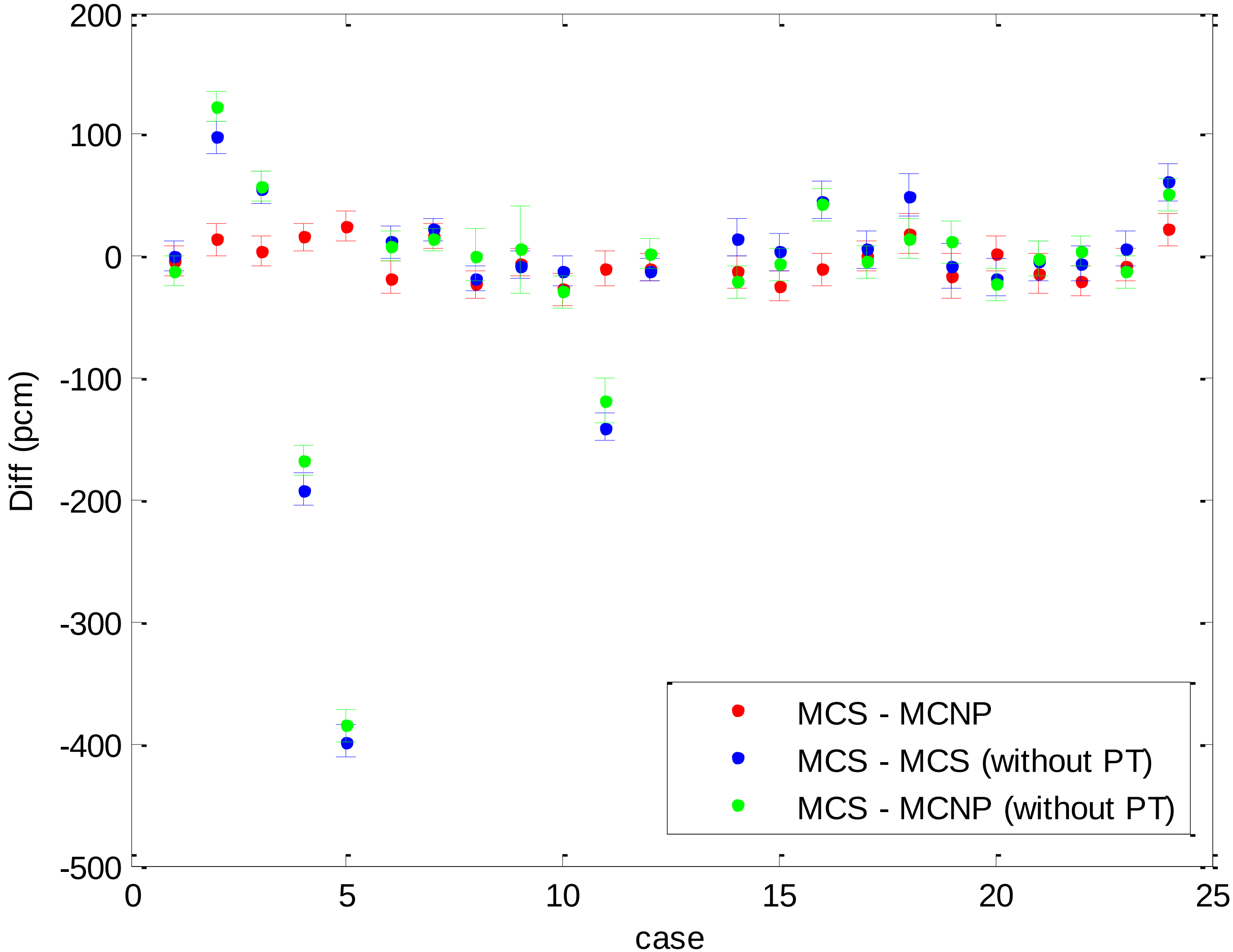
PROBABILITY TABLE METHOD

Case	Handbook ID	Experiment keff (Uncertainty)	Case	Handbook ID	Experiment keff (Uncertainty)
1	HEU-MET-FAST-001	1.00000 (0.00100)	14	PU-MET-FAST-002	1.00000 (0.00200)
2	HEU-MET-FAST-003, case2-1	1.00000 (0.00500)	15	PU-MET-FAST-019	0.99920 (0.00150)
3	HEU-MET-FAST-003, case2-2	1.00000 (0.00500)	16	PU-MET-FAST-022	1.00000 (0.00210)
4	HEU-MET-FAST-003, case2-3	1.00000 (0.00500)	17	PU-SOL-THERM-001-case16-1	1.00000 (0.00520)
5	HEU-MET-FAST-003, case2-4	1.00000 (0.00500)	18	PU-SOL-THERM-001-case16-5	1.00000 (0.00520)
6	HEU-MET-FAST-028	1.00000 (0.00300)	19	PU-SOL-THERM-011-case18-1	1.00000 (0.00520)
7	HEU-SOL-THERM-013, case 1	1.00120 (0.00260)	20	PU-SOL-THERM-011-case18-6	1.00000 (0.00520)
8	HEU-SOL-THERM-013, case 2	1.00070 (0.00360)	21	U233-MET-FAST-001	1.00000 (0.00100)
9	HEU-SOL-THERM-013, case 3	1.00090 (0.00360)	22	U233-MET-FAST-002	1.00000 (0.00100)
10	HEU-SOL-THERM-013, case 4	1.00030 (0.00360)	23	U233-MET-FAST-003	1.00000 (0.00100)
11	IEU-MET-FAST-015	1.00070 (0.00110)			
12	IEU-SOL-THERM-002	1.00010 (0.00540)			
13	PU-MET-FAST-001	1.00000 (0.00200)			

PROBABILITY TABLE METHOD

Case	with probability table				without probability table			
	MCS		MCNP		MCS		MCNP	
	keff	SD	keff	SD	keff	SD	keff	SD
1	0.99998	0.00010	0.99994	0.00008	0.99998	0.00009	0.99985	0.00007
2	1.00832	0.00010	1.00846	0.00008	1.00930	0.00009	1.00955	0.00008
3	1.00913	0.00009	1.00945	0.00008	1.00997	0.00010	1.00999	0.00008
4	1.01256	0.00009	1.01271	0.00009	1.01064	0.00010	1.01087	0.00009
5	1.01676	0.00010	1.01701	0.00008	1.01278	0.00010	1.01291	0.00007
6	1.00301	0.00009	1.00284	0.00008	1.00313	0.00009	1.00309	0.00009
7	0.99873	0.00007	0.99871	0.00007	0.99876	0.00007	0.99868	0.00007
8	0.99758	0.00007	0.99769	0.00008	0.99774	0.00008	0.99793	0.00024
9	0.99426	0.00008	0.99421	0.00008	0.99419	0.00008	0.99432	0.00042
10	0.99597	0.00009	0.99570	0.00009	0.99585	0.00008	0.99568	0.00009
11	0.99938	0.00008	0.99928	0.00012	0.99798	0.00008	0.99820	0.00019
12	1.00849	0.00006	1.00852	0.00011	1.00850	0.00006	1.00864	0.00011
13	1.00017	0.00011	0.99986	0.00007	1.00013	0.00011	0.99977	0.00008
14	1.00028	0.00011	0.99990	0.00008	1.00033	0.00010	1.00008	0.00008
15	0.99770	0.00011	0.99782	0.00008	0.99838	0.00011	0.99835	0.00008
16	0.99861	0.00011	0.99857	0.00007	0.99862	0.00012	0.99852	0.00008
17	1.00992	0.00012	1.01009	0.00011	1.01013	0.00013	1.00990	0.00010
18	1.00618	0.00013	1.00614	0.00012	1.00622	0.00013	1.00642	0.00011
19	0.99424	0.00011	0.99448	0.00009	0.99429	0.00010	0.99423	0.00009
20	1.00028	0.00011	0.99999	0.00012	1.00009	0.00011	1.00010	0.00010
21	0.99967	0.00010	0.99959	0.00007	0.99973	0.00010	0.99983	0.00007
22	0.99922	0.00011	0.99912	0.00007	0.99926	0.00010	0.99907	0.00008
23	0.99838	0.00011	0.99860	0.00008	0.99899	0.00011	0.99889	0.00008

PROBABILITY TABLE METHOD



FUNCTIONS

Resonance Up-scattering (DBRC)

RESONANCE UPSCATTERING

ref: Dr. Becker's presentation at 2010 May 17-21 ORNL Meeting

- **The sampling of the target velocity method is based on the probability function:**

$$P\left(V,\mu_t\right)=\frac{\sigma_s\left(v_r,0\right)v_r p\left(V\right)}{2\sigma_s(E,T)v}$$

which is directly obtained from the Doppler broadening equation.

- Commonly Monte Carlo codes assume:

$$\mathrm{P}\left(\mathrm{V},\mu_{\mathrm{t}}\right)\approx\frac{\mathrm{v_r}\cdot\mathrm{p(V)}}{2\mathrm{v}}\cdot\cancel{\frac{\sigma_{\mathrm{s}}(\mathrm{v_r},0)}{\sigma_{\mathrm{s}}(\mathrm{E},\mathrm{T})}}$$

- The temperature effect is kept but the XS dependence is neglected: Wigner-Wilkins scattering kernel

RESONANCE UPSCATTERING

ref: Dr. Becker's presentation at 2010 May 17-21 ORNL Meeting

- **Direct implementation of the resonant scattering kernel: *Doppler Broadening Rejection Correction (DBRC)***
  - **Idea: Modification of the approximated MCNP SVT probability function; removal of the constant XS assumption**
- **The basic PDF can be rewritten as:**

$$
\begin{aligned}
P(V,\mu_t) &= C\left\{\frac{\sigma_s(v_r,0)}{\sigma_s^{max}(v_\xi,0)}\right\}\left\{\frac{v_r}{v+V}\right\}\{(v'+V)p(V)\} \\
&= C\left\{\frac{\sigma_s(E_r,0)}{\sigma_s^{max}(E_\xi,0)}\right\}\left\{\frac{v_r}{v+V}\right\}\{(v'+V)p(V)\}
\end{aligned}
$$

with the normalization constant C: $C = \dfrac{\sigma_s^{max}(E_\xi,0)}{2v\sigma_s(E,T)}$

$\sigma^{max}(E_\xi,0)$ is the maximal cross section in an specific dimensionless speed interval ξ (like in NJOY):

$$\sqrt{\frac{AE}{k_BT}}-4 \le \sqrt{\frac{AE_\xi}{k_BT}} \le \sqrt{\frac{AE}{k_BT}}+4$$

RESONANCE UPSCATTERING

ref: Dr. Becker's presentation at 2010 May 17-21 ORNL Meeting

- **This leads to:**

$$P\left(V,\mu_t\right)=C'\left\{\frac{\sigma_s\left(E_r,0\right)}{\sigma_s^{max}\left(E_\xi,0\right)}\right\} \quad (1)$$

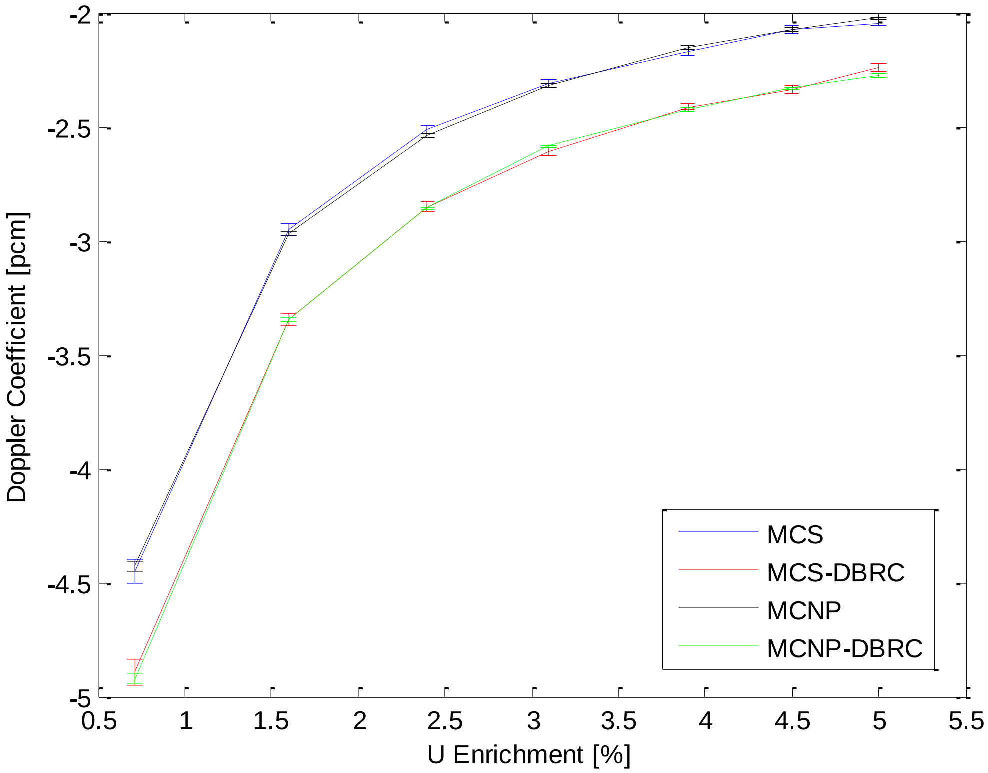
$$\left\{\frac{v_r}{v+V}\right\} \quad (2)$$

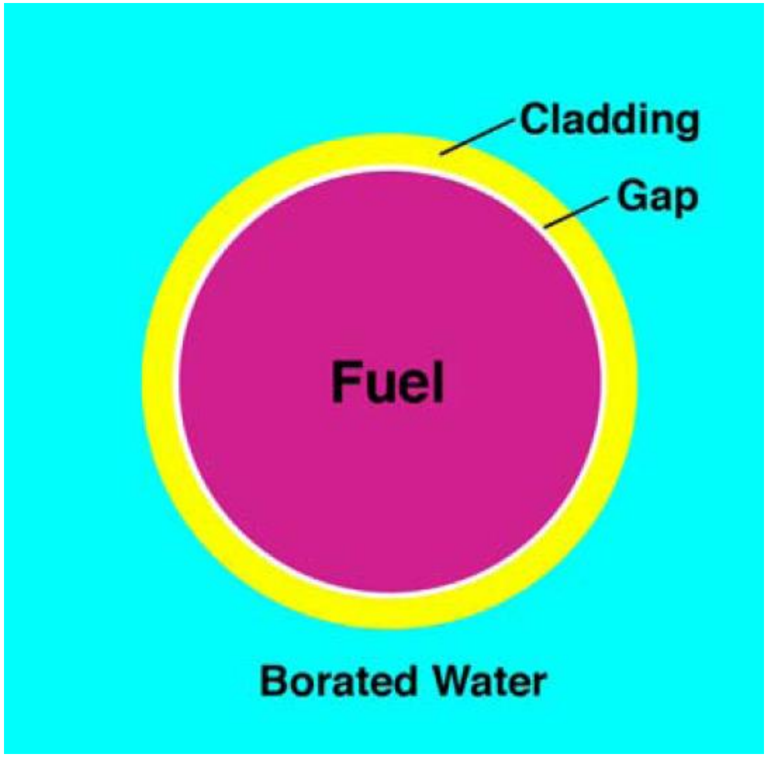
$$\left\{\frac{2\beta^4V^3e^{-\beta^2V^2}+(\beta v\sqrt{\pi}/2)(4\beta^3/\sqrt{\pi})V^2e^{-\beta^2V^2}}{1+\beta v\sqrt{\pi}/2}\right\} \quad (3)$$

$$C'=\frac{\sigma_s^{max}\left(E_\xi,0\right)\left(1+\beta v\sqrt{\pi}/2\right)}{2v\sigma_s\left(E,T\right)\beta\sqrt{\pi}/2}$$

- (2) + (3): standard MCNP rejection and sampling
- (1): an additional rejection in terms of cross sections is added to the code. This term completes the full Doppler broadening of the kernel

- **Mosteller UO2 benchmark problem**





FUNCTIONS

Modified Power Method

Power Method (PM)

Operator Form:

$$M\phi = \frac{1}{k} F\phi$$

$$A\psi = k\psi$$

$$A = FM^{-1}, \psi = F\phi$$

$$\psi^{(l)} = A^l \psi^{(0)} = A^l \left(c_1 u_1 + c_2 u_2 + \cdots\cdots + c_N u_N \right)$$

$$= k_1^l \left(c_1 u_1 + \sum_{i=2}^{N} \left[\left(\frac{k_i}{k_1} \right)^l c_i u_i \right] \right)$$

$$\approx k_1^l c_1 u_1 \qquad (\text{as } l \to \infty)$$

Eigenvalues: $k_0 > k_1 \geq k_2 \geq \ldots$

Eigenfunctions: $u_0, \; u_1, \; u_2$

Only fundamental mode is not enough.

Decay ratio of n-th mode: k_n / k_0

Dominance Ratio (DR): k_1 / k_0

Converge slow if DR≈1.

Modified Power Method (MPM)

Start with two arbitrary functions: $\phi_1^{init} = \sum_{i=0}^{\infty} a_i u_i, \quad \phi_2^{init} = \sum_{i=0}^{\infty} b_i u_i.$

Power Iteration: $A^n \phi_1^{init} = \sum_{i=0}^{\infty} k_i^n a_i u_i, \; A^n \phi_2^{init} = \sum_{i=0}^{\infty} k_i^n b_i u_i.$

The linear combination:

$$A^n \phi(x) = A^n \phi_1^{init} + x A^n \phi_2^{init}$$

$$= \sum_{i=0}^{\infty} k_i^n \left(a_i + x b_i \right) u_i$$

$A^n \phi(x)$ Do not have 1st mode if $x = -a_1 / b_1$

$$A^n \phi(x) \approx k_0^n (a_0 + (-a_1 / b_1) b_0) u_0 \qquad CR \sim \frac{k_2}{k_0}$$

$A^n \phi(x)$ Do not have fundamental mode if $x = -a_0 / b_0$

$$A^n \phi(x) \approx k_1^n (a_1 + (-a_0 / b_0) b_1) u_1 \qquad CR \sim \frac{k_2}{k_1}$$

1st mode solution.

The general solution strategy

- **Algorithm:**
  - **1. Apply power iteration to** $\psi_0, \psi_1, \ldots \psi_{n-1}$.
  - **2. Obtain the integrations over every subregions:**

$$\mathbf{V} = \begin{pmatrix} V_{0,1} & \cdots & V_{n-1,1} \\ \vdots & \ddots & \vdots \\ V_{0,n} & \cdots & V_{n-1,n} \end{pmatrix}, \mathbf{W} = \begin{pmatrix} W_{0,1} & \cdots & W_{n-1,1} \\ \vdots & \ddots & \vdots \\ W_{0,n} & \cdots & W_{n-1,n} \end{pmatrix}.$$

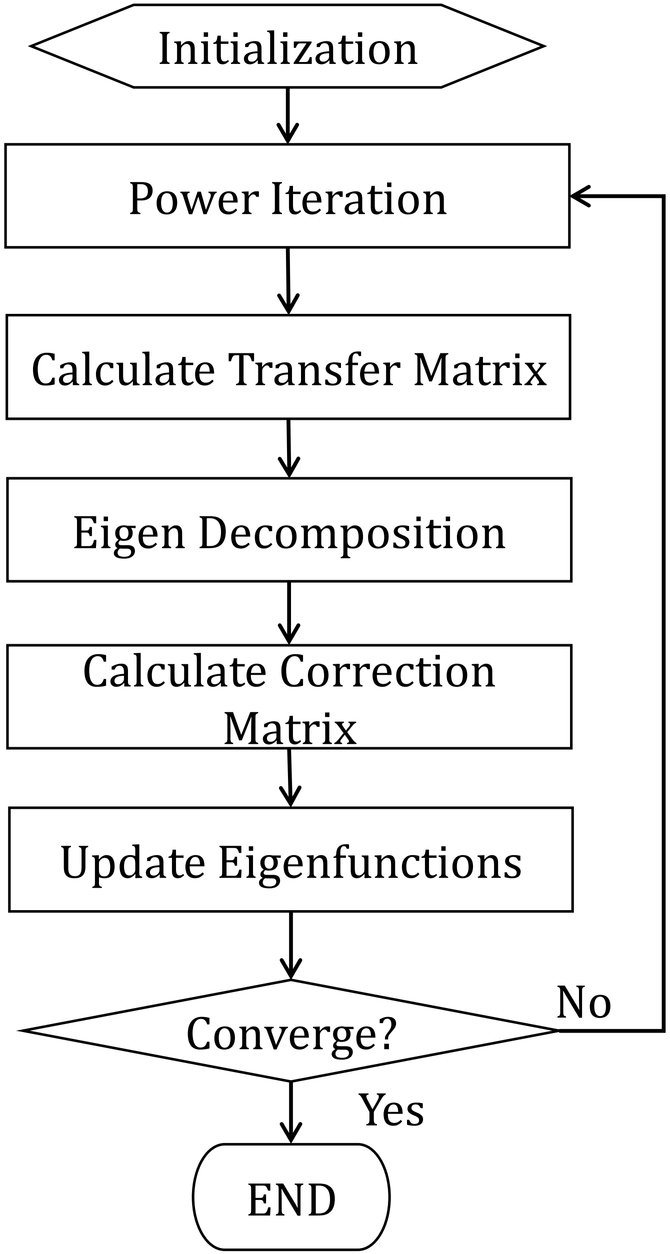
  - **3. Calculate the transfer matrix:** $\mathbf{P} = \mathbf{W}\mathbf{V}^{-1}$.
  - **4. Apply eigen decomposition to transfer matrix:**

$$\mathbf{PQ} = \mathbf{Q\Lambda}, \ \mathbf{P} = \mathbf{Q\Lambda Q}^{-1}.$$

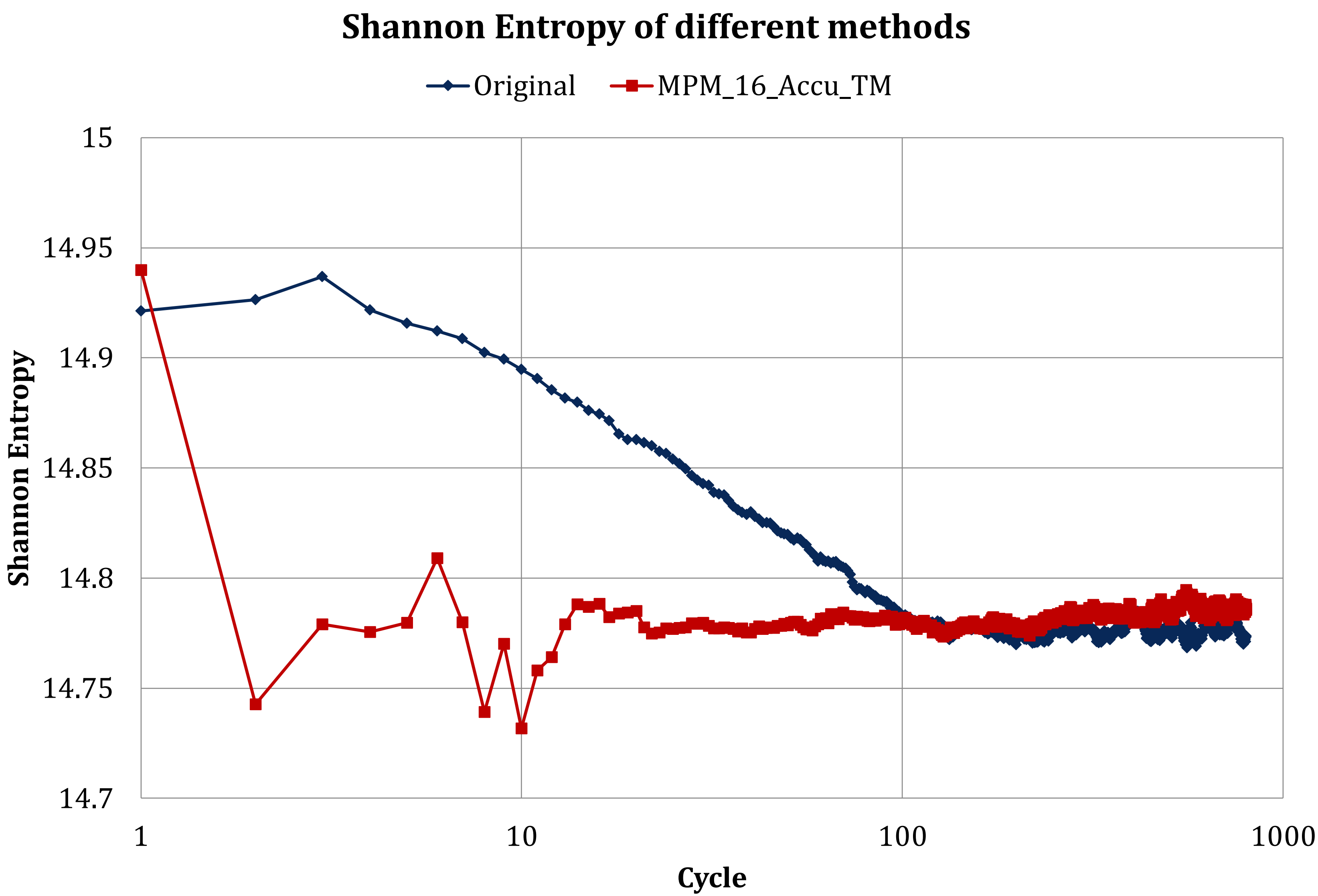
  - **5. Get the correction matrix:** $\mathbf{X} = \mathbf{W}^{-1}\mathbf{Q}$.
  - **6. Update the eigenfunctions:**

$$\begin{pmatrix} \psi_0 & \cdots & \psi_{n-1} \end{pmatrix} = \begin{pmatrix} \psi_0 & \cdots & \psi_{n-1} \end{pmatrix} \mathbf{X}.$$

  - **7. Determine the convergence.**
    If not, goto 1.



3D PWR core problem

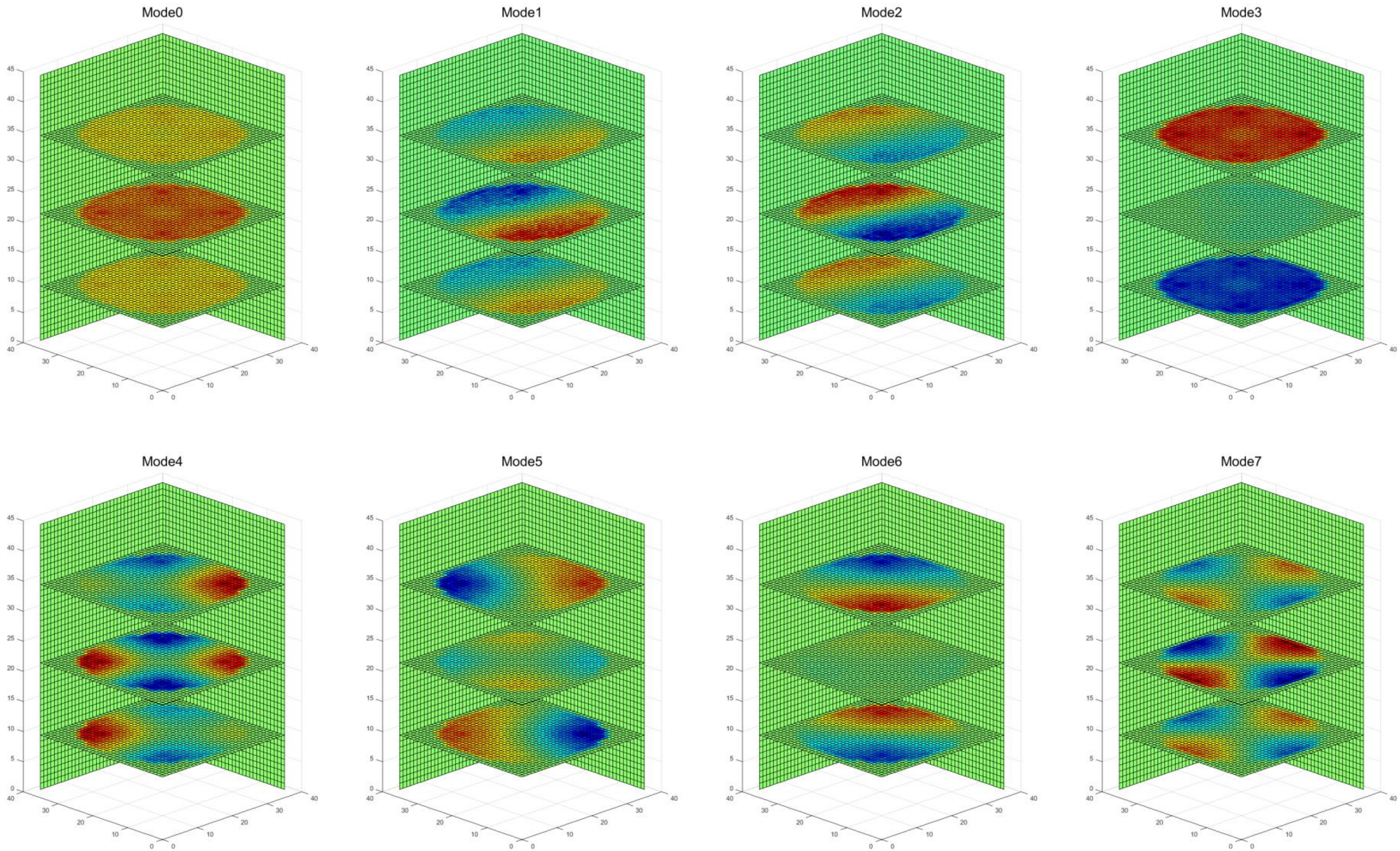


Simulation parameters: 200 inactive cycles / 600 active cycles / 500000 histories per cycle.

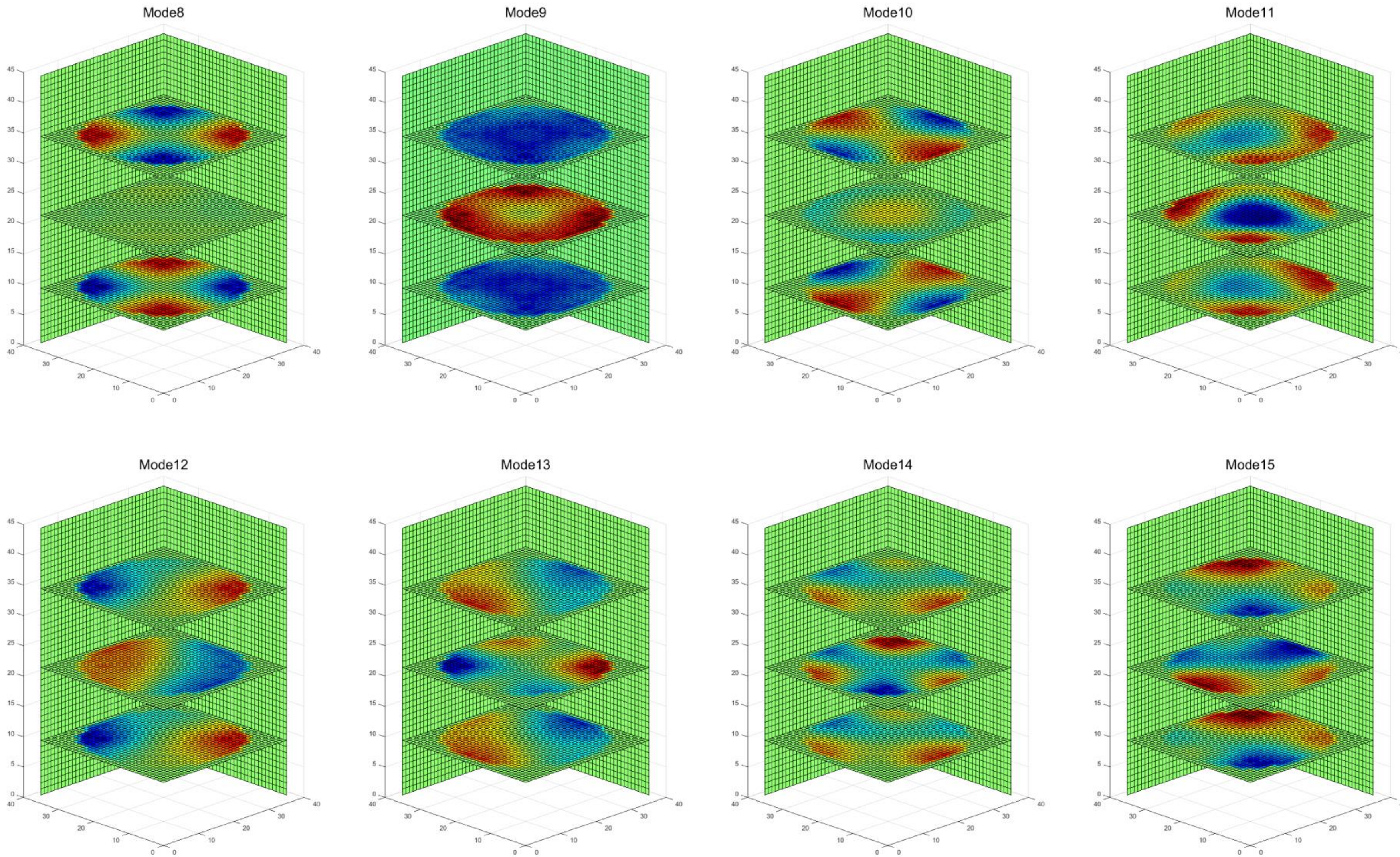
3D PWR core problem

Method	Eigenvalue	Results	ki/k0
Original power method	k0	1.01936 (4)	--
MPM_6_6_6_16modes	k0	1.01945 (4)	--
	k1	1.01084 (8)	0.9916
	k2	1.01078 (7)	0.9915
	k3	1.00635 (7)	0.9872
	k4	0.99907 (8)	0.9800
	k5	0.99827 (8)	0.9792
	k6	0.99816 (7)	0.9791
	k7	0.99138 (8)	0.9725
	k8	0.98691 (7)	0.9681
	k9	0.98498 (7)	0.9662
	k10	0.97937 (8)	0.9607
	k11	0.97999 (9)	0.9613
	k12	0.97695 (8)	0.9583
	k13	0.97672 (7)	0.9581
	k14	0.97523 (8)	0.9566
	k15	0.97603 (8)	0.9574

3D PWR core problem



3D PWR core problem



FUNCTIONS

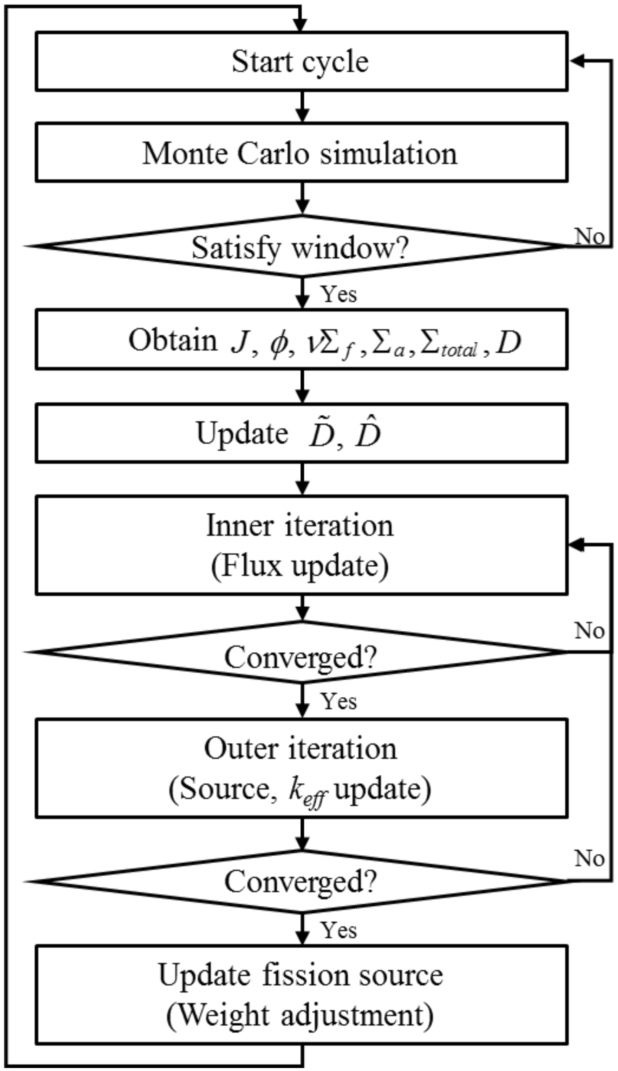
Coarse Mesh Finite Difference Method (CMFD)

Effect of MC-CMFD on active cycle

▪ CMFD Method

- Coarse Mesh Finite Difference Method.
- Originally developed for storage reduction.
- Fast convergence of nodal solutions.
- Very effective in accelerating source convergence in direct whole core transport calculation.
- Significant reducing in the number inactive cycles in MC eigenvalue calculation.

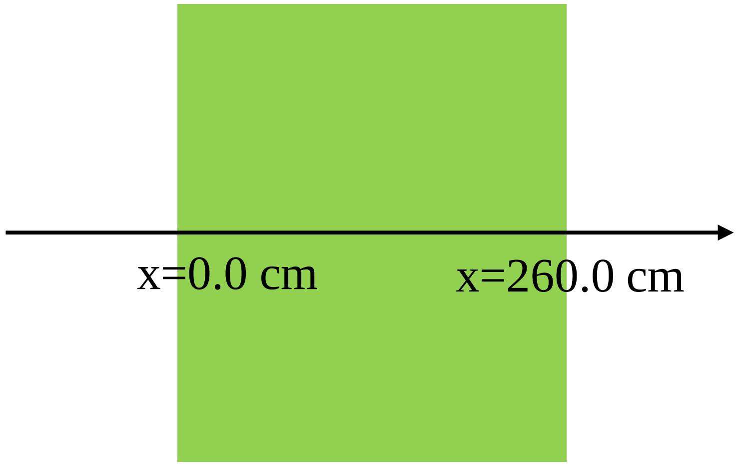
▪ Algorithm



Monte Carlo - CMFD

▪ 1-Dimensional CE Problem

- Problem specification
  - 1D slab problem
  - 2.1wt% enriched UO_2 fuel, zirconium cladding, and water were mixed.
  - 1,000,000 histories per cycle/ 1,000 inactive cycles / 1,000 active cycles
  - Black boundary condition
  - CMFD start from 1,000 inactive cycle
  - CMFD mesh = 260
  - Window size = 10

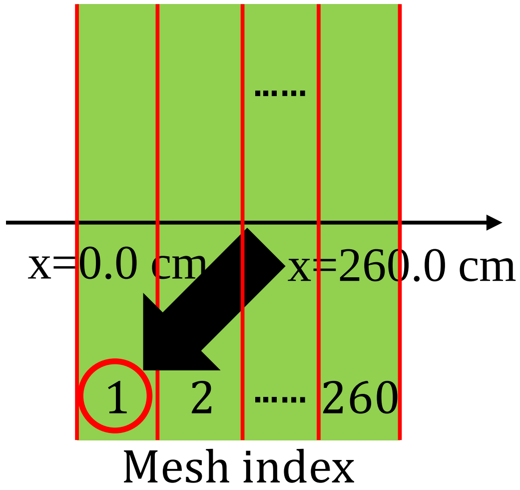


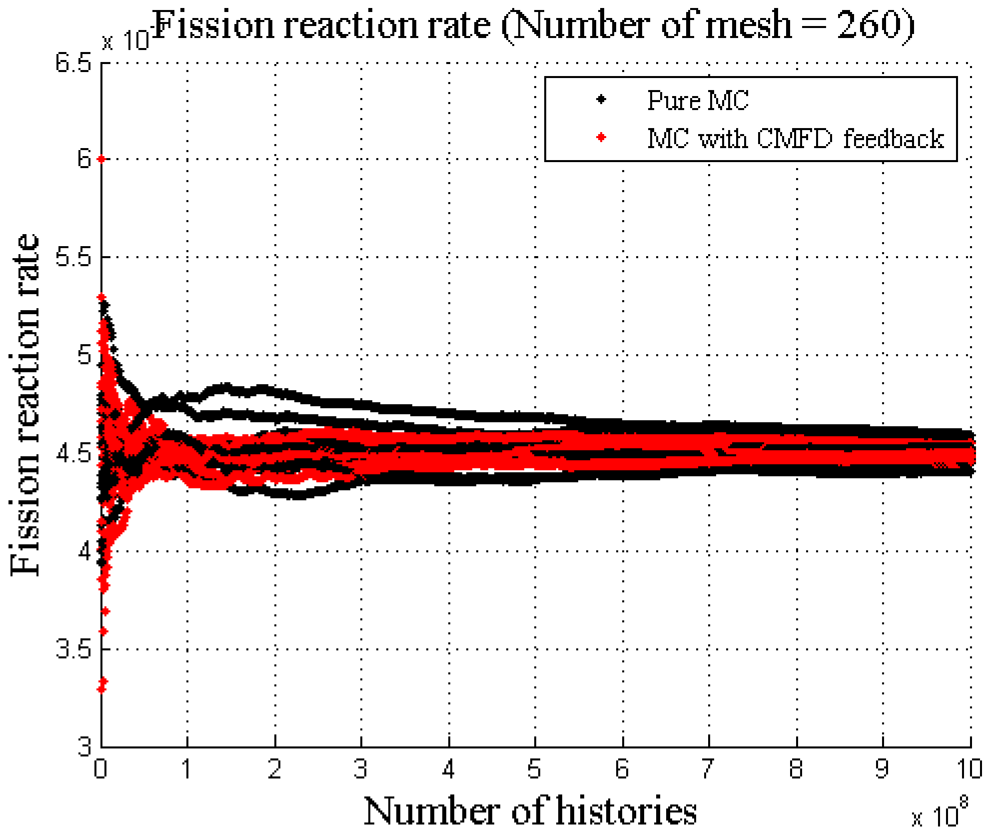
Isotope	Density (g/cm^3)
^{235}U	1.88E-01
^{238}U	8.50E+00
^{237}Np	2.90E-03
^{238}Pu	5.99E-04
^{16}O	1.21E+00
^{91}Zr	6.45E-01
^{92}Zr	9.97E-01
^{94}Zr	1.03E+00
^{96}Zr	1.70E-01
^{1}H	8.27E-02

Effect of MC-CMFD on active cycle

▪ 1D CE Problem

- Plot the fission reaction rate for each cycle and simulation
- To check the CMFD gave the correct solution or not
- Fission reaction rate at most left mesh for 260 mesh tally

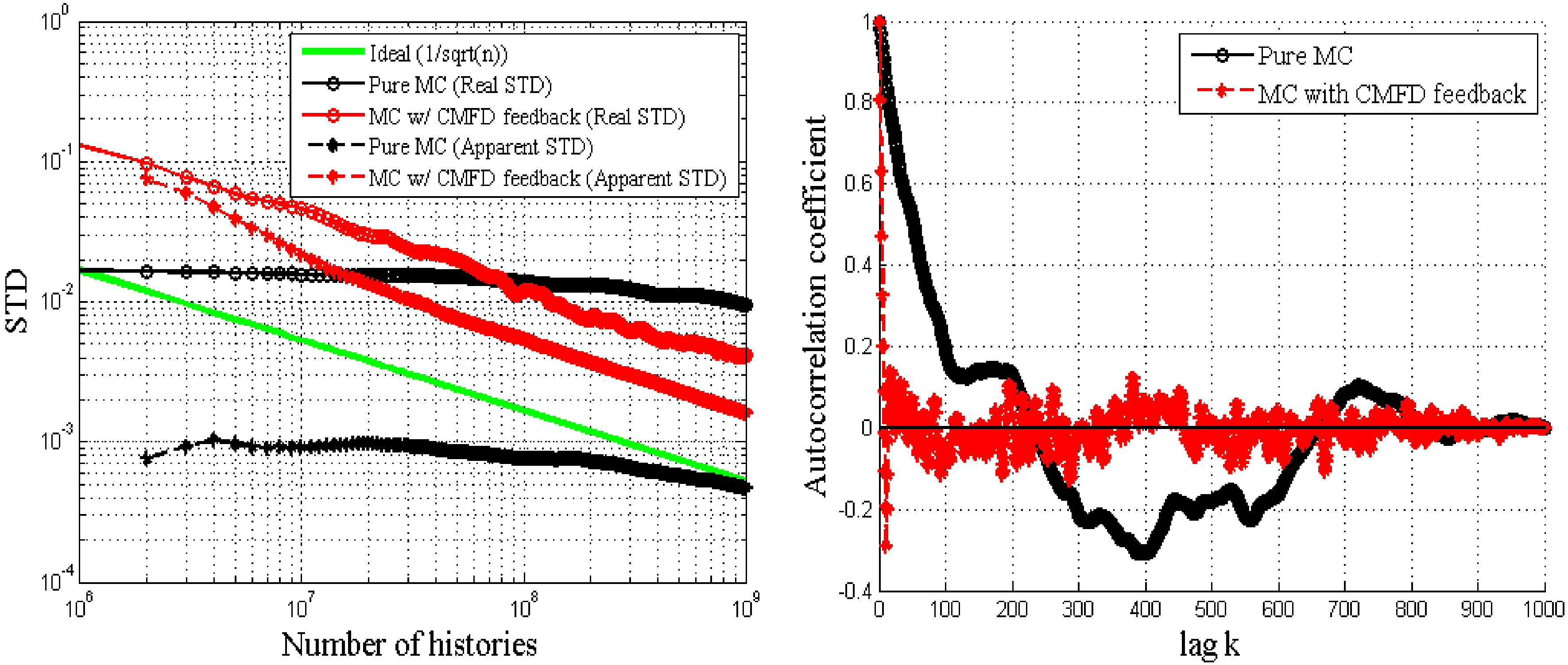




Effect of MC-CMFD on active cycle

▪ 1D CE Problem

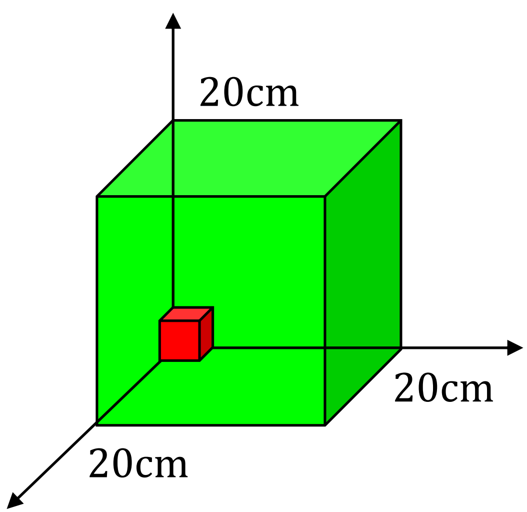
- **Dominance ratio = 0.9956**

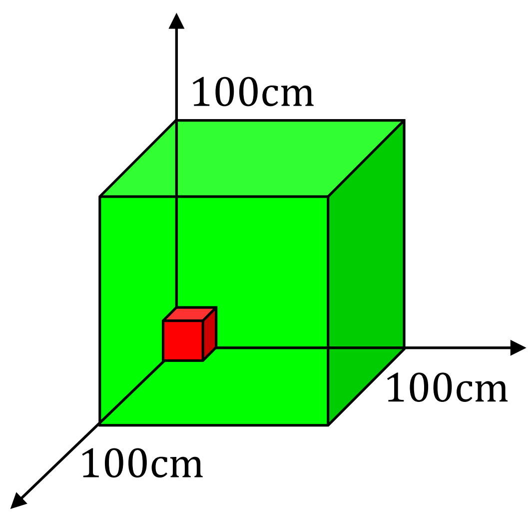


Numerical test results

- **3D 1G Problem (20.00cm)**
  - 3-Dimensional 1-Group
  - Black boundary condition
  - Active cycle: 1,000
  - Inactive cycle: 100
  - Histories/cycle: 1,000,000
  - Number of simulation : 10

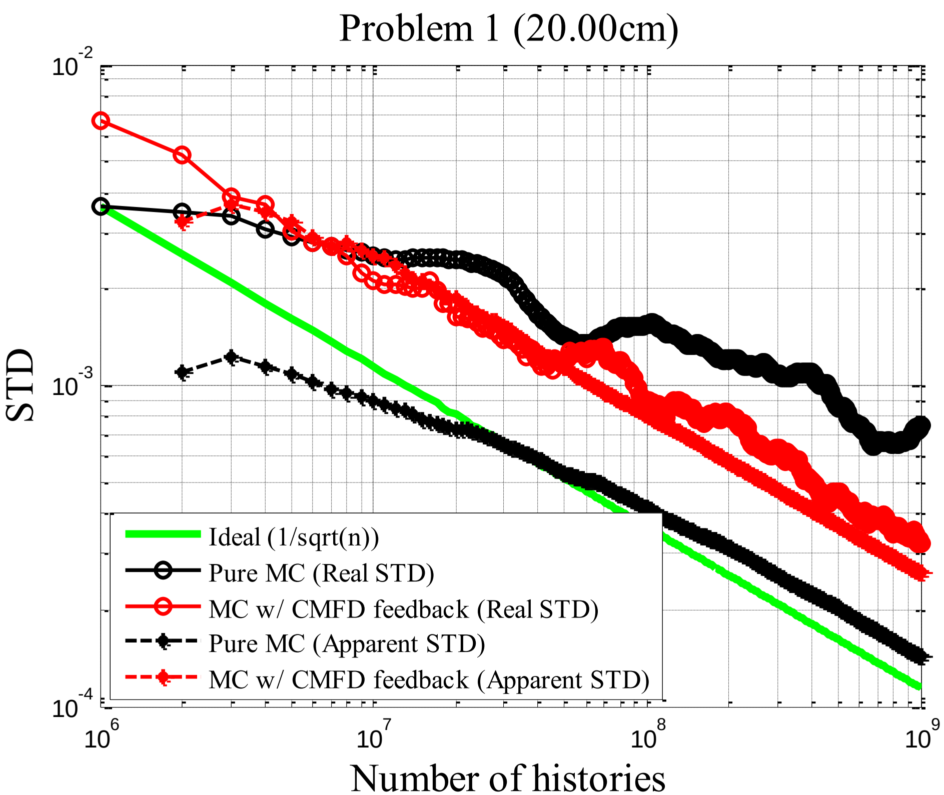
- **3D 1G Problem (100.00cm)**
  - 3-Dimensional 1-Group
  - Black boundary condition
  - Active cycle: 1,000
  - Inactive cycle: 100
  - Histories/cycle: 1,000,000
  - Number of simulation : 10
  - Window size: 10

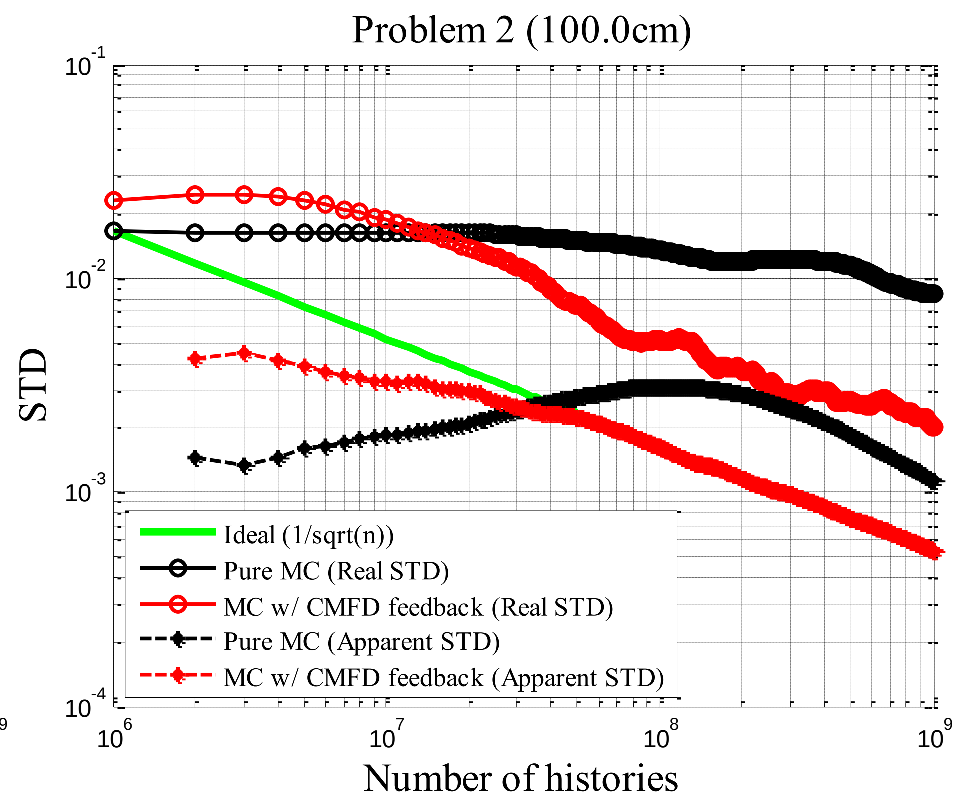




Numerical test results

- **3D 1G Problem**
  - **Real & Apparent RMS STD**

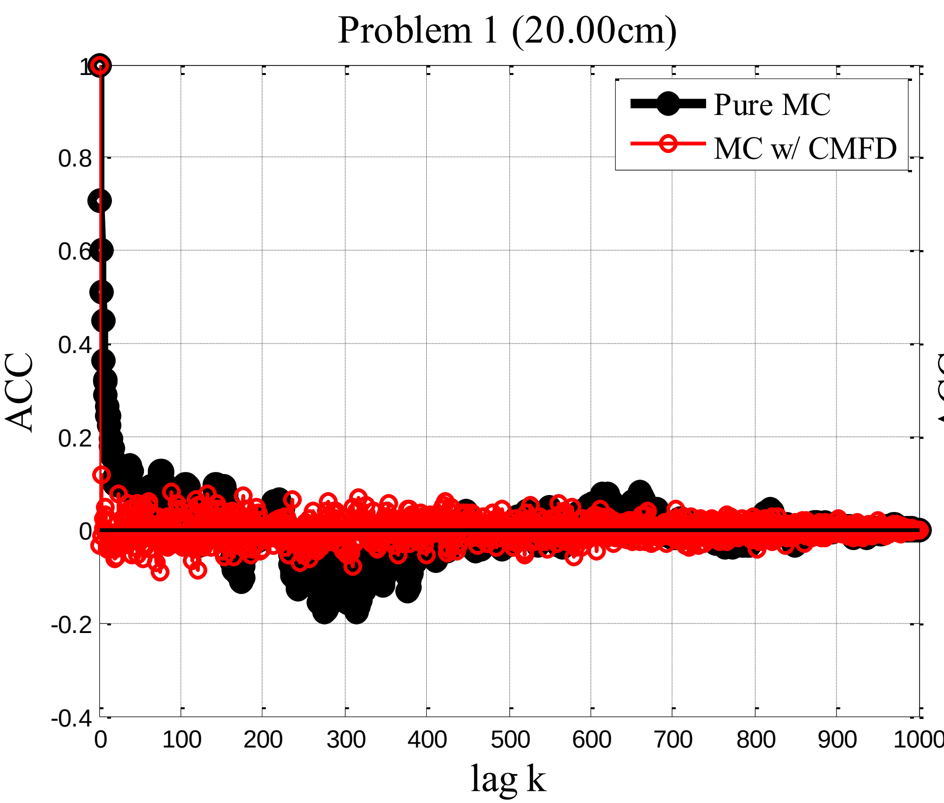


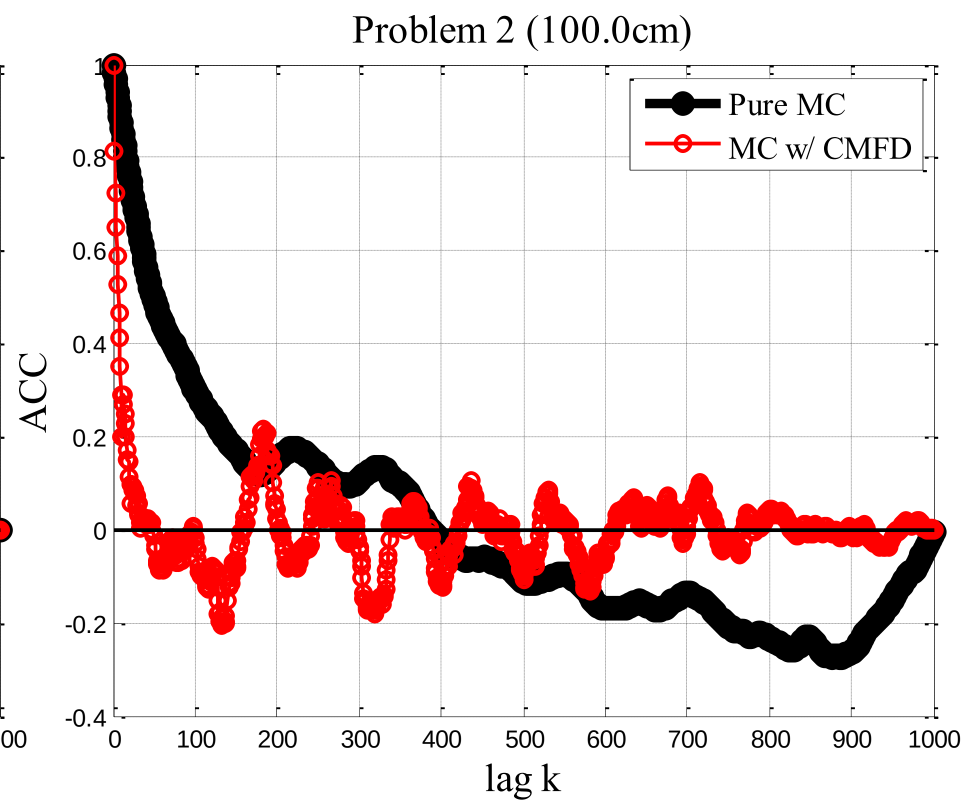


Numerical test results

▪ 3D 1G Problem

• Autocorrelation Coefficient



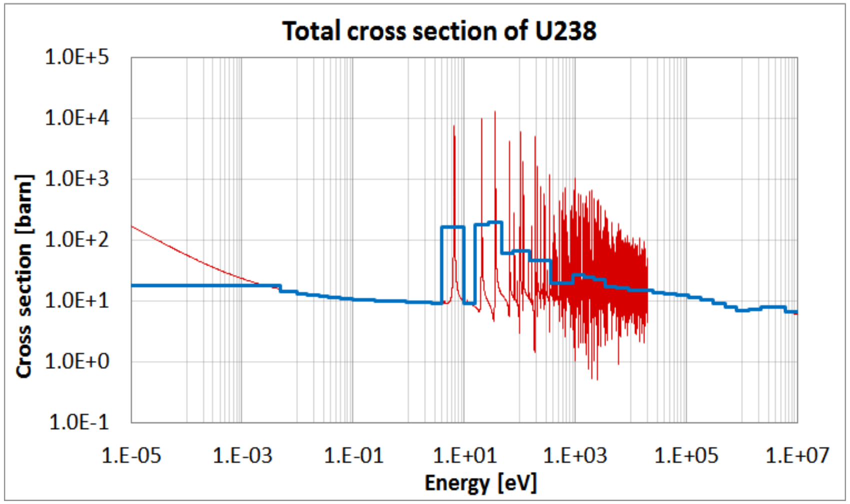


FUNCTIONS

MC-MOC Hybrid Method

MC-MOC HYBRID

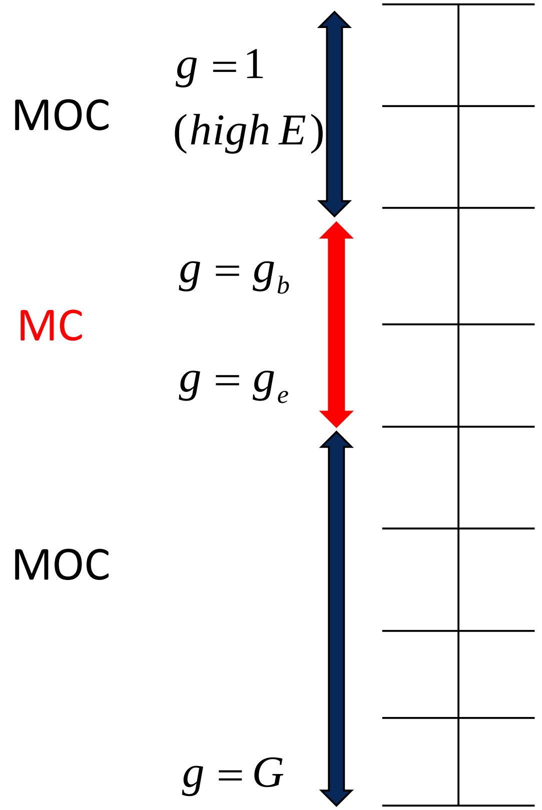
- **Hybrid of MC & MOC**
  - **MC for resonance energy**
  - **MOC for thermal and fast energy**

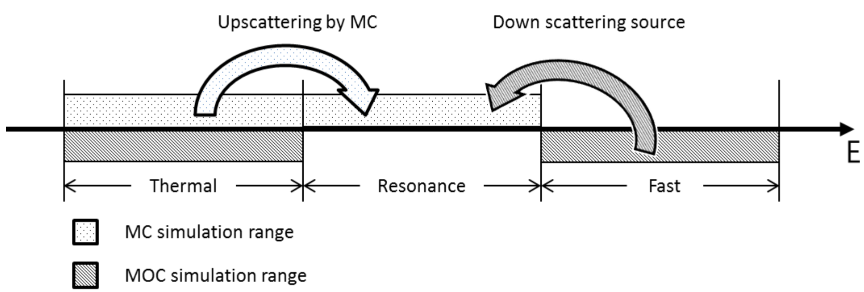


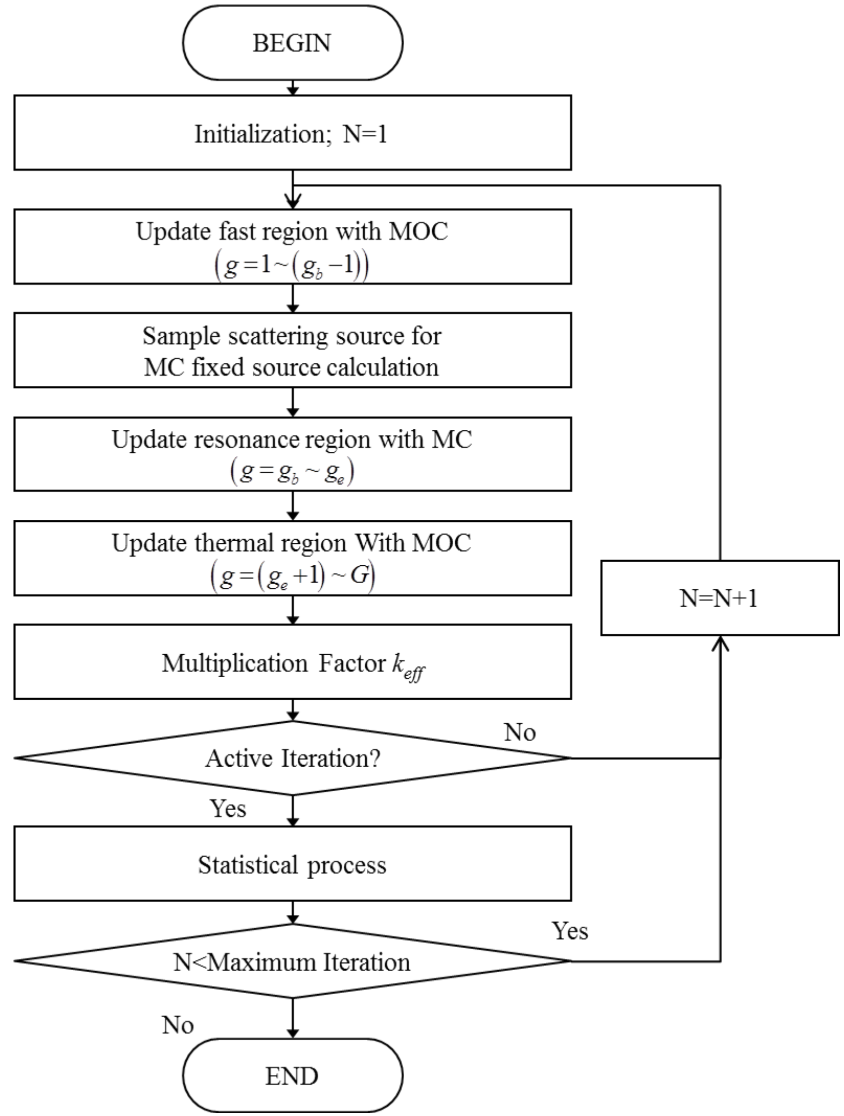
	MC	MOC
Method	Probabilistic	Deterministic
Data	Continuous energy	Multi-group
Accuracy	High	Low

H. Lee, S. Choi, D. Lee, “A Hybrid Monte Carlo/Method-of-Characteristics Method for Efficient Neutron Transport Analysis, “ Nucl. Sci. Eng., 180 (1) pp.30-40 (2015)

Hybrid form of neutron transport equation

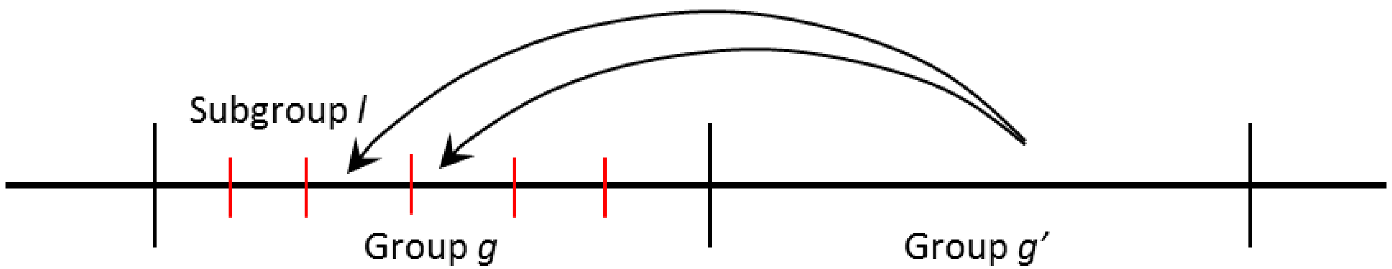






▪ Scattering source from MOC to MC

- **Multi-group -> continuous energy**



▪ Slowing-down source neutron energy distribution

- **Analytic form of slowing down equation is derived**

$$P(E)^{g'\to g} = \begin{cases} \dfrac{C}{Q(1-\alpha)}\left(\dfrac{1}{E_b^g} - \dfrac{1}{E_e^g}\right) & \left(E \ge \alpha E_e^g\right) \\ \dfrac{C}{Q(1-\alpha)}\left(\dfrac{1}{E_b^g} - \dfrac{\alpha}{E}\right) & \left(E < \alpha E_e^g\right) \end{cases}$$

$E_{g_b}^g$ is the upper boundary energy of group
$E_{g_e}^g$ is the lower boundary energy of group

$$\alpha = \left(\frac{A-1}{A+1}\right)^2$$

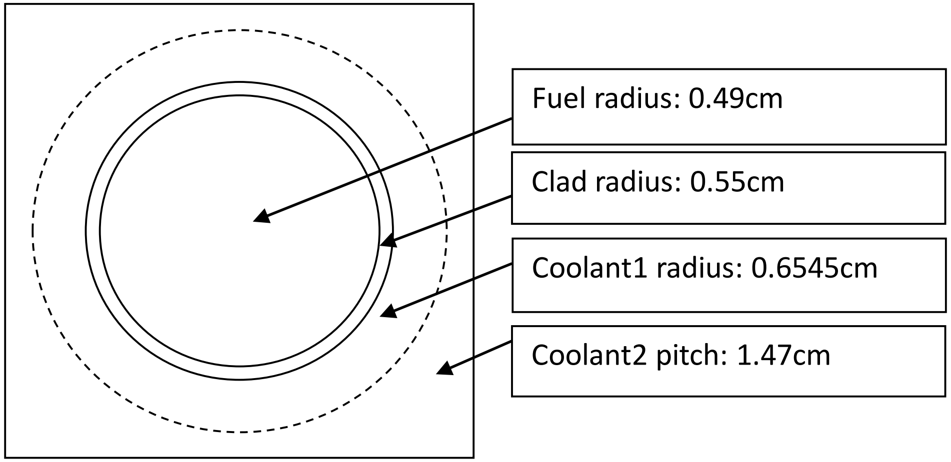
$$Q = \int_{E_e^g}^{E_b^g}\int_{E_e^{g'}}^{E_b^{g'}} \frac{\Sigma_s(E')\varphi(E')}{(1-\alpha)E'}\,dE'dE$$

$C = \Sigma_s(E')\varphi(E')E' = \Sigma_s(E_e^{g'})\varphi(E')E'$ is constant

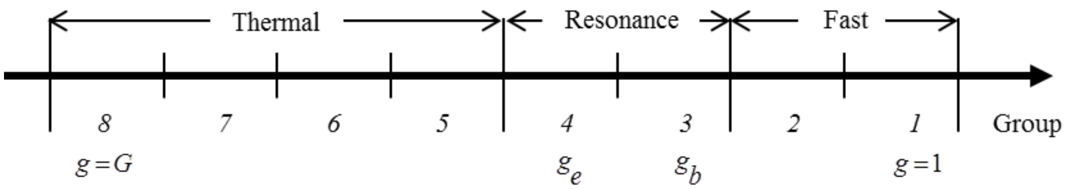
A is atomic weight

MODEL PROBLEM

A single pin cell with 8 group macroscopic cross section



- **Monte Carlo**
  - Multi-group
  - Continuous energy
- **MOC**
  - Azimuthal/polar/ray space = 128/10/0.01
- **Hybrid**
  - 1 – 2 groups: MOC
  - 3 – 4 groups: MC
  - 5 – 8 groups: MOC



MODEL PROBLEM

- **Material composition**

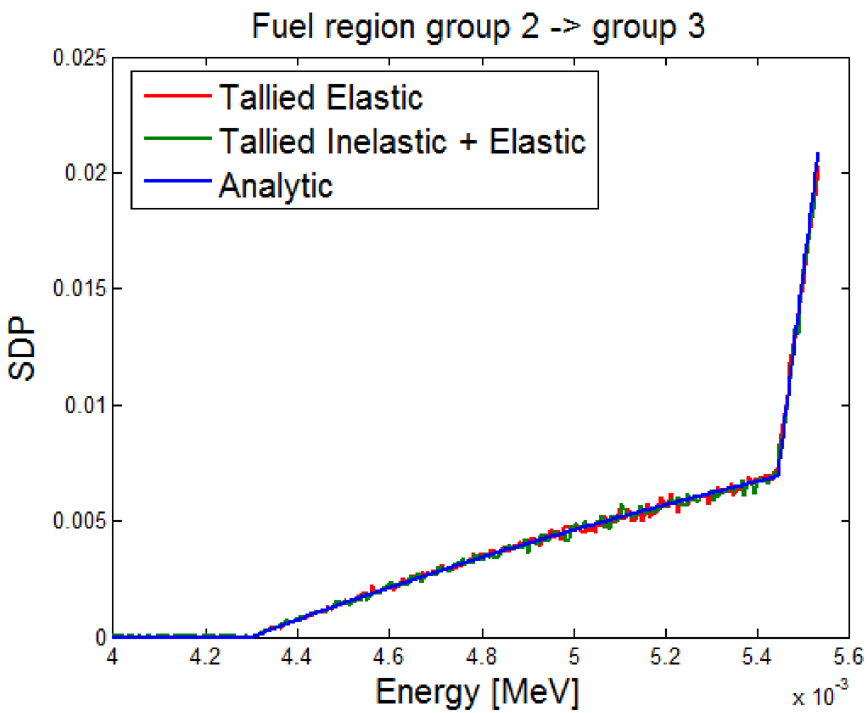
Region	T(K)	Nuclide	Number Density (#/barn-cm)
Fuel	300	U-235	7.30E-04
		U-238	2.18E-02
		O-16	4.51E-02
Clad	300	Zr-90	2.23E-02
Coolant 1&2	300	H-1	4.86E-02
		O-16	2.43E-02

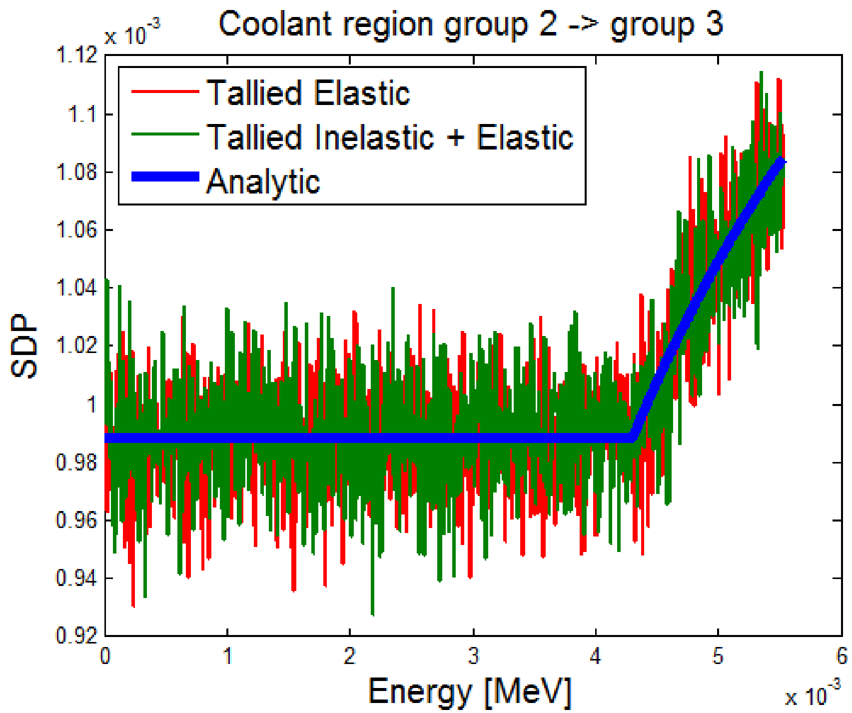
- **Energy boundary**

Group	Upper boundary	Lower boundary
1	1.00E+07	8.21E+05
2	8.21E+05	5.53E+03
3	5.53E+03	4.00E+00
4	4.00E+00	6.25E-01
5	6.25E-01	2.80E-01
6	2.80E-01	1.40E-01
7	1.40E-01	5.80E-02
8	5.80E-02	1.00E-05

VERIFICATION

- **Tallied Elastic: tallied during elastic Monte Carlo**
- **Tallied Inelastic + Elastic: tallied during Monte Carlo**
- **Inelastic SDP is small relative to elastic SDP**





VERIFICATION

MC: 50/1000/100000 (active/inactive/history)
HYBRID: 10/100/100000 (active/inactive/history)

Method	Keff	Stdev[3)]	Error (pcm)	FOM
MC	1.38339	0.00010	-	9,531
MOC	1.38011	-	328	-
HYBRID_A[1)]	1.38303	0.00004	36	612,130
HYBRID_T[2)]	1.38311	0.00004	28	54,796

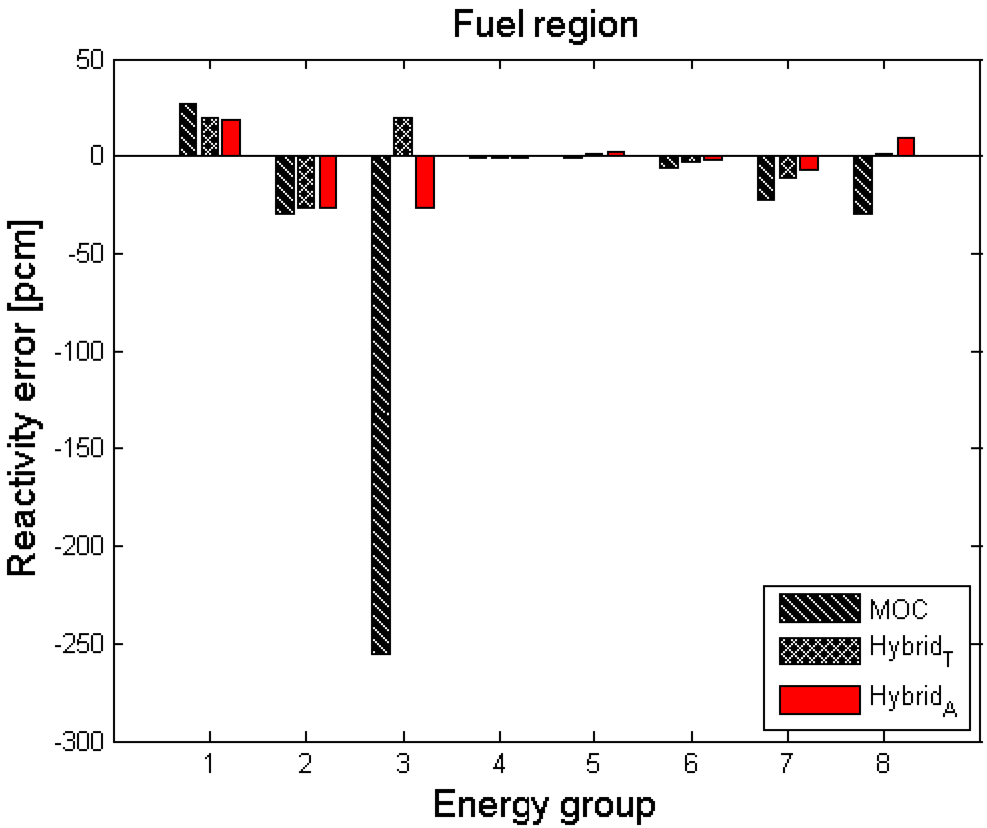
1) HYBRID_A = hybrid method with analytic SDP
2) HYBRID_T = hybrid method with tallied SDP
3) Stdev = standard deviation

▪ Reactivity error

$$\Delta\rho^{g,i} = \left(\frac{1}{k_{eff}^{MC}} - \frac{1}{k_{eff}^{g,i}}\right)\times 10^5$$

$$k_{eff}^{g,i} = \frac{\sum_{i'}\left[\left(\sum_{g'=1}^{G} \nu R_{f,i'}^{MC,g'}\right)V_{i'}\right]}{\sum_{i'}\left[\left(\sum_{g'=1}^{G} R_{a,i'}^{MC,g'}\right)V_{i'}\right] + \Delta R_{a,i}^{g} V_i}$$

$$\Delta R_{a,i}^{g} = R_{a,i}^{M,g} - R_{a,i}^{MC,g}$$



FUNCTIONS

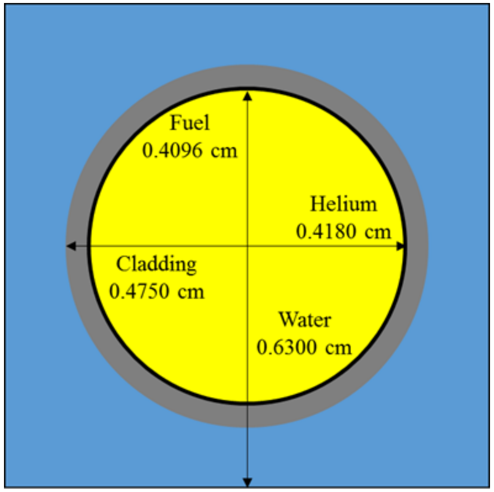
Depletion

Implementation of depletion module

- **Data library**
  - ENDF/B-VII.0 for transport calculation
  - Same decay and fission yield data with McCARD
  - 1,374 isotopes is considered in burnup calculation
- **Depletion solver**
  - Chebyshev Rational Approximation Method(CRAM) with 16 order
  - Acceleration of the matrix solver with sparse Gauss Seidel
  - Parallel depletion
- **Burnup interval treatment**
  - Semi/full predictor-corrector method
- **Hybrid depletion**
  - 72-group XSs from STREAM(in-house lattice code)
  - 1-group condensation with 1-group flux solution of MCS
  - Memory reduction in reaction rates tally

Verification(Model description : 1/3)

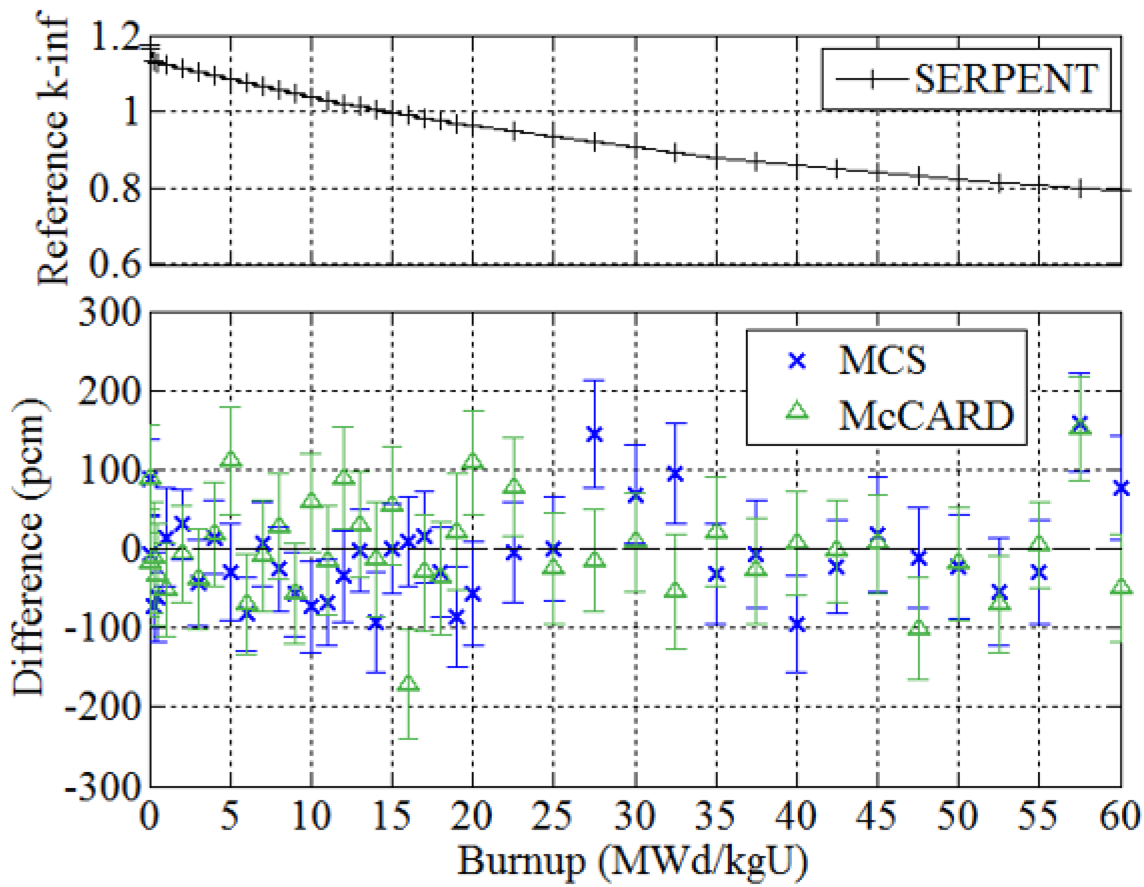
- **3.1% enriched UO_2 fuel pin from VERA Benchmark**
  - **Geometry**



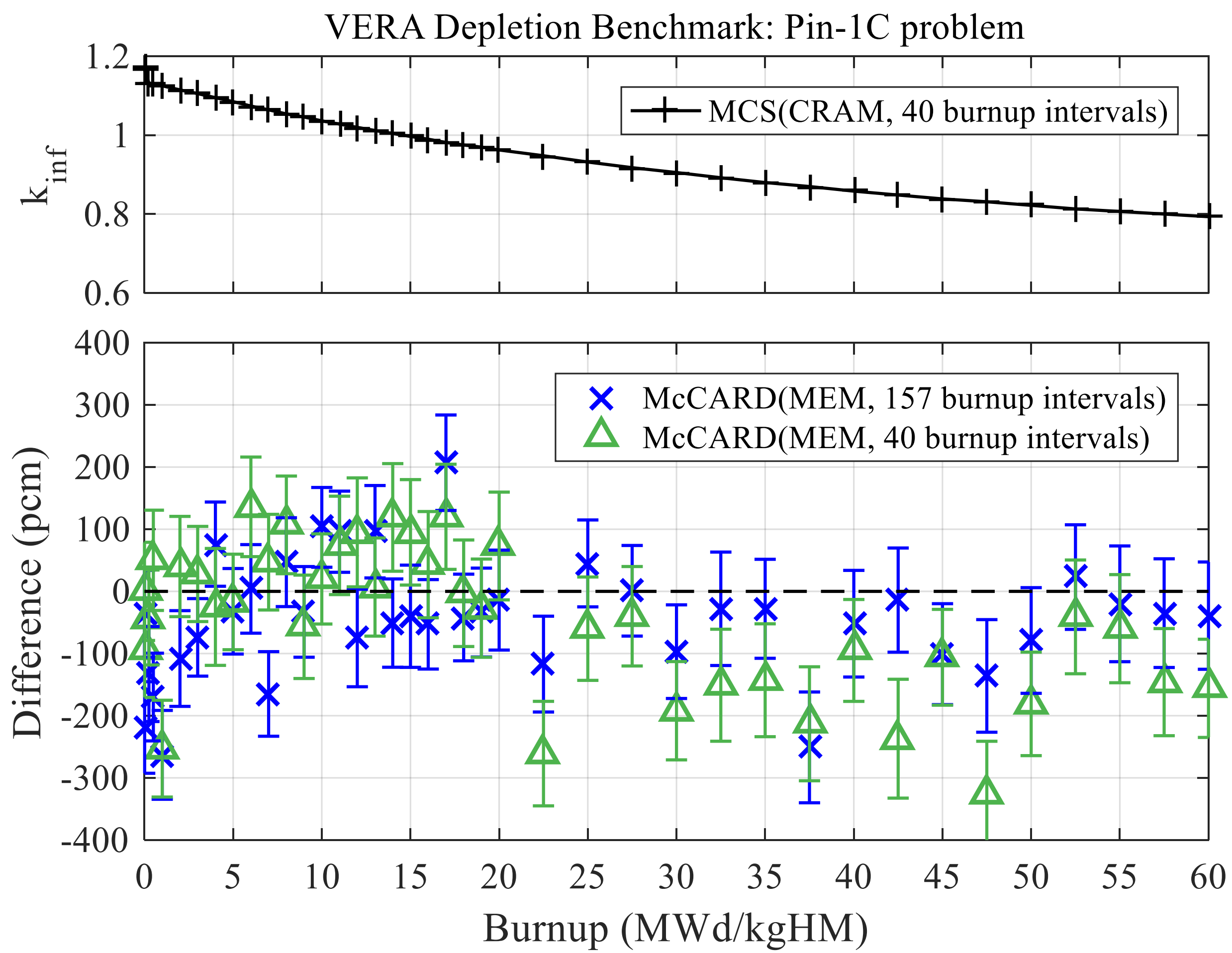
  - **Temperature: Fuel – 900K / Clad and Moderator – 600K**
  - **Power density: 40W/gU**
  - **3 equi-volumetric burnup regions**
  - **20000(Histories per cycle)/80(Active)/20(Inactive)**
  - **Full predictor-corrector**
  - **HELIOS kappa(McCARD default)**

▪ VERA Benchmark

- **3.1% Enrichment, No BP**



MEM vs CRAM



VERA Depletion Benchmark: Pin-1C problem
k_inf
1.2
1
0.8
0.6
MCS(CRAM, 40 burnup intervals)
Difference (pcm)
400
300
200
100
0
-100
-200
-300
-400
McCARD(MEM, 157 burnup intervals)
McCARD(MEM, 40 burnup intervals)
0
5
10
15
20
25
30
35
40
45
50
55
60
Burnup (MWd/kgHM)

FUNCTIONS

Hybrid Depletion

Introduction

- **High-fidelity full-core modelling capabilities for LWRs**
  - **Kord Smith Challenge**
    - Depletion sub-regions(100 axial and 10 radial zones in a fuel pin)
      - 50~60 million burnup regions(200~300 fuel pins for 200 fuel assemblies in a core)
    - 1% pin-power accuracy
    - Within one hour on a desktop computer
    - Estimated that it will be 2030 before

- **MCS**
  - **The current MCS functions for the whole core depletion**
    - Acceleration of depletion solver
    - Parallelization of depletion module
    - Indexing technique for high performance tally
    - Hybrid depletion method for the reduction of computational requirements

Introduction

- **The main drawback of depletion calculation in Monte-Carlo method**
  - **9 reaction types are considered during the depletion calculation**
    - **(n, a), (n, γ), (n, α), (n, 2n), (n, 3n), (n, p) and 3 * (n, f)**
      - **3-group fission reaction rates are required by employing 3-group fission yields**
  - **400 axial burnable regions and 10 radial zones for one fuel rod**
  - **~250 isotopes in a burnup region (EOC for VERA pin depletion)**
  - **50,952 burnable regions (BEAVRS whole core)**
  - **8 byte for double precision data type**

  - **Variables for the statistical process**
    - $x, \sum x, \sum x^2$
    - **In the MCS, "$\sum x, \sum x^2$" are allocated in only one process for parallel depletion**

  - $9 \times 250 \times 50,952 \times 400 \times 10 \times 8byte =$ **3.7 Tb**

Introduction

▪ Hybrid depletion method

- No reaction rate tallies since STREAM resonance treated XSs
- 72-group structures

	MC	Hybrid
Reaction type1)	9	-
Flux2)	1	72
Fuel pin cell	50,000	50,000
Axial domain	400	400
Radial ring	10	10
Nuclides	300	-
Data type	8 byte	8 byte
Total3)	4,322 Gb	115 Gb

Reduced factor
: **~40 times**

- 1) reaction rates are calculated for every nuclides in every burnable regions
- 2) Flux is calculated in every burnup region
- 3) (# of reaction type * # of nuclides + # of flux groups) * # of burnable regions

Implementation(1/2)

- **Hybrid depletion method**
  - **72-group flux(MCS) + 72-group XSs(STREAM) → 1-group effective XSs**
  - **Parallel algorithm**

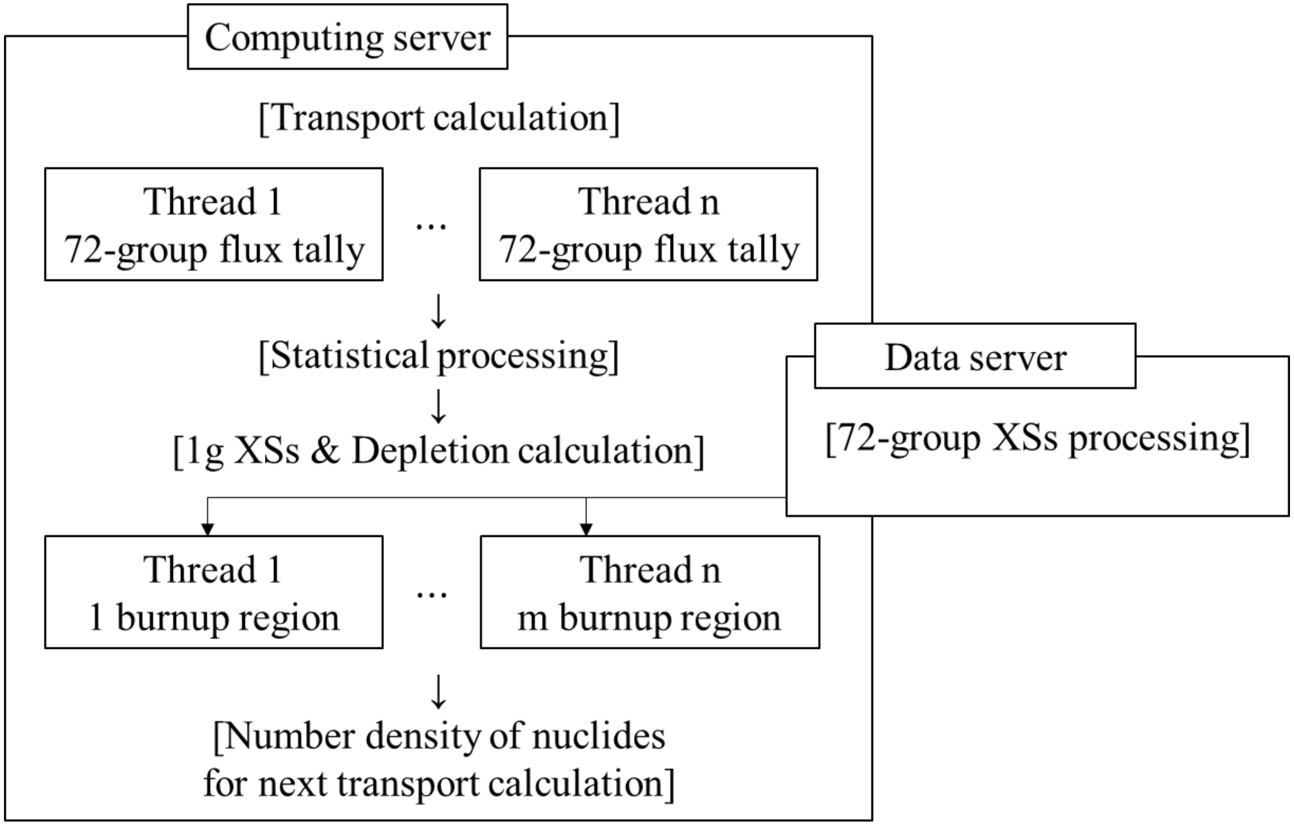
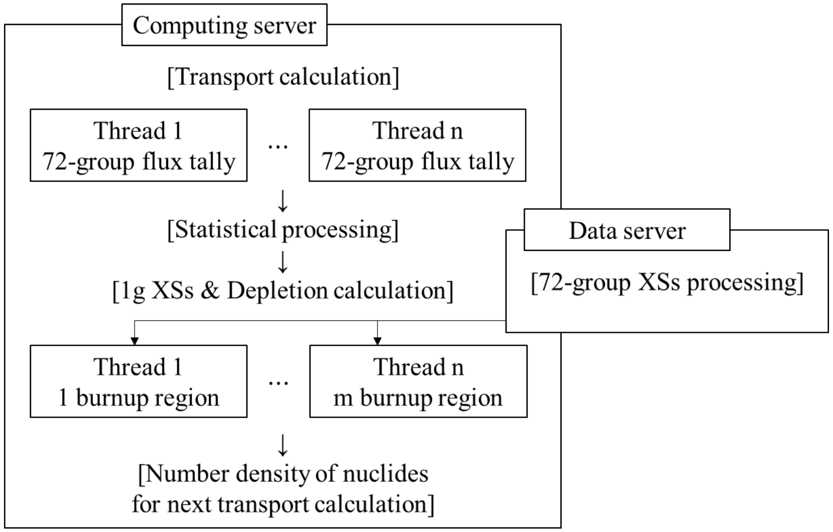


Fig. Flow scheme for parallel hybrid depletion

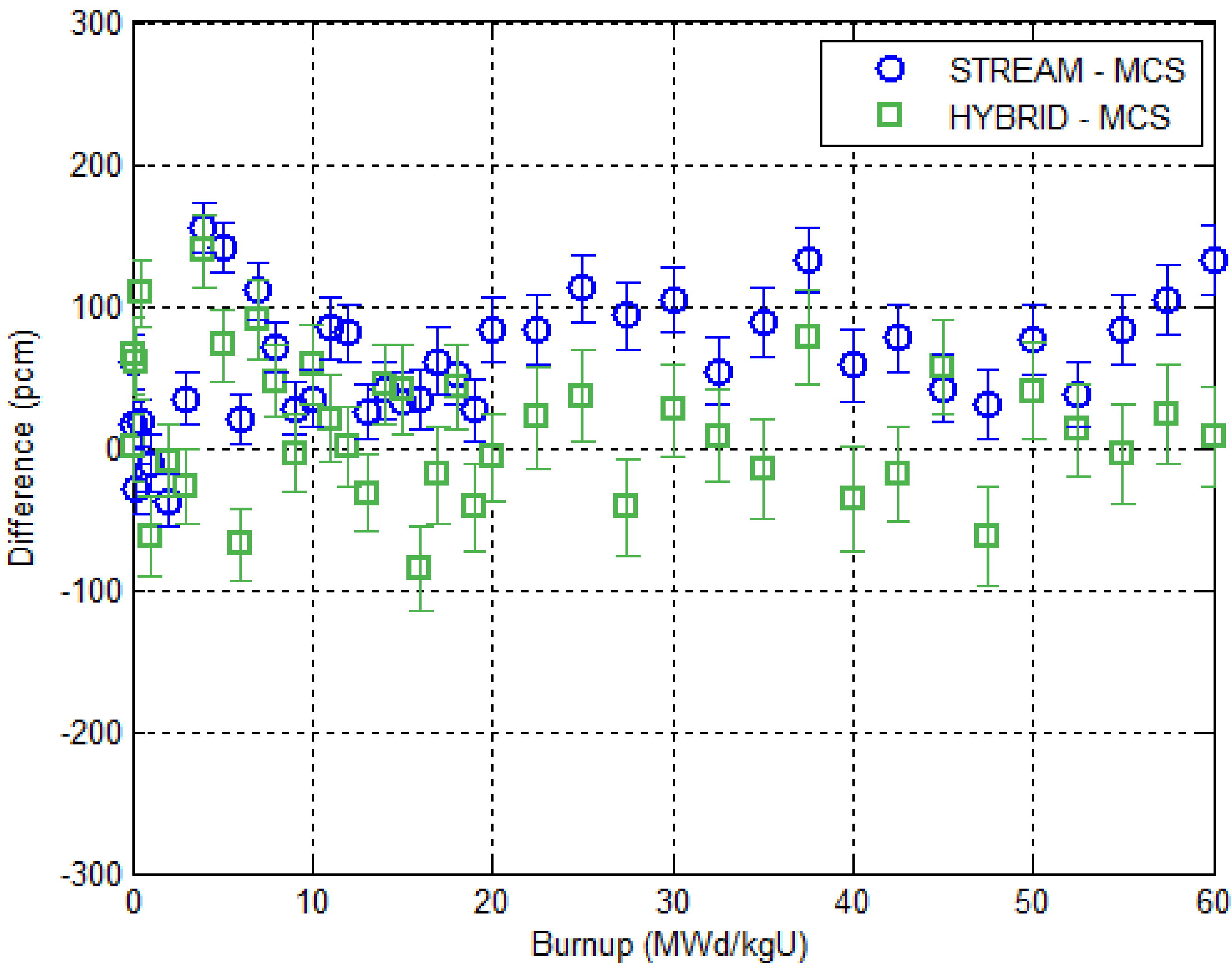
▪ Hybrid depletion method

- Data server
  - Management of the memory usage for generating MG
  - Independently managed in other computational node
    - MG XSs can be generated during the transport simulation
    - No time requirement for reaction rates tally
- Parallel depletion
  - Burnable regions are allocated as tasks in each thread
  - MG XSs from STREAM are provided when they proceed the burnup
    - Data communication



Verification

- **3.1% enriched UO_2 fuel assembly from VERA Benchmark**



Preliminary results (1/2) – Time requirement

- **3.1% enriched UO_2 fuel assembly from VERA Benchmark**
  - **Single core calculation**

		Unit. Second
	MCS	Hybrid
Transport	163,886	147,640
Read ACE XSs	252	258
Read Input	0.1	0.6
Depletion	771	678
Execution time	164,909	148,577

  - **Hybrid method takes 10% less time than original MC depletion**

The specification of calculation cluster :
Intel Xeon CPU E5-2690 v2 3.00GHz, 250Gb memory

Preliminary results (2/2) – Memory requirement

- **3.1% enriched UO_2 fuel assembly from VERA Benchmark**
  - **Parallel calculation(40 thread)**

		Unit. Kb
	MCS	Hybrid
Geometry	6.6	6.6
Tracking	193.4	193.4
Indexing	6.6	6.6
Read ACS XSs	5.1Gb	5.1Gb
Material	4,734.9	4,738.3
Depletion	24,887	1,013

  - **The reduction factor is around 24.5 times**

The specification of calculation cluster :
Intel Xeon CPU E5-2690 v2 3.00GHz, 250Gb memory

FUNCTIONS

TH1D

▪ Radial heat conduction

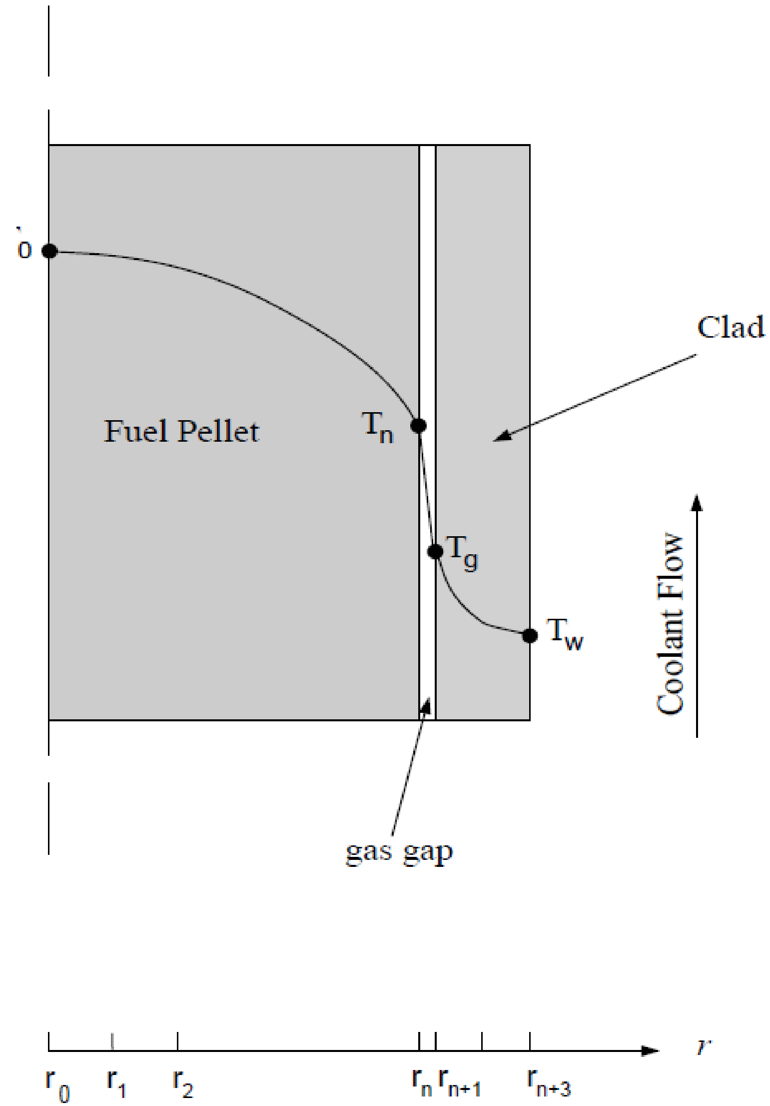
- axial heat conduction is neglected
- fuel rod is divided into multiple rings to get the radial temperature distribution

$$C_p \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(k(T)\, r \frac{\partial T}{\partial r}\right) + q$$

Cp: the production of the heat capacity and the material density, $c_p\rho,\ J/cm^3 \cdot °C$;

$k(T)$: the heat conductivity, $w/cm \cdot °C$;

q: the volumetric heat source, w/cm^3.

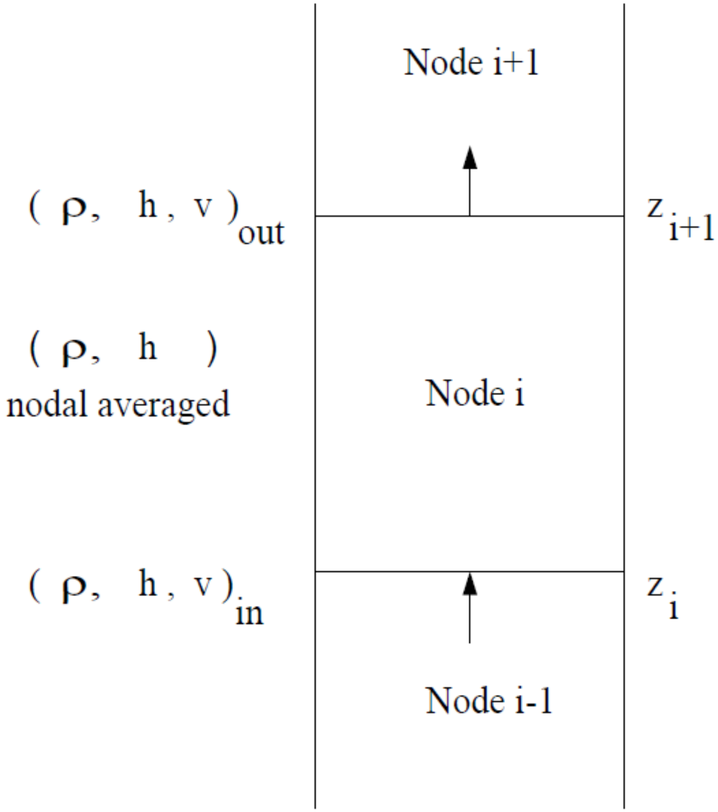


Mesh structure fir heat conduction calculation

TH1D Solution Method

▪ Axial heat convection in Coolant

- **1D, single-phase model**
  - no boiling is considered
- **constant pressure**
  - only mass continuity and energy conversation equations are solved



Node structure and variables

$$\boxed{\begin{aligned} &\frac{\partial \rho}{\partial t} + \frac{\partial \rho v}{\partial z} = 0 \\ &\frac{\partial \rho h}{\partial t} + \frac{\partial \rho h v}{\partial z} = q_c + \frac{\zeta}{A_c} q_w \equiv q \end{aligned}}$$

ρ: the coolant density, kg/m^3; h: the coolant enthalpy, J/kg;

v: the coolant velocity, m/s; ζ: the heated perimeter, m;

A_c: the cross section of the channel, m^2;

q_c: the heat source generated inside the coolant, w/m^3;

q_w: the heat flux of the fuel, w/m^2.

Coupled Problem Formulation

- **Notation:**
  - **nuclide field** $N(r)$
  - **temperature distribution** $T(r)$
  - **neutron flux** $\phi(r,\Omega,\mathrm{E})$
- **MCS find ϕ and k by solving *k*-eigenvalue form of neutron transport equation:**

$$B(N,T)\begin{bmatrix}\phi \\ k\end{bmatrix} = \left[L(N,T) - \frac{1}{k}F(N,T)\right]\phi = 0$$

- **TH1D solves $T(r)$ and $N(r)$:**

$$M(\phi)\begin{bmatrix}T(r) \\ N(r)\end{bmatrix} = 0$$

Iteration Methods

- **Gradient-based methods (Newton's method)**
  - **Jacobian**
  - **JFNK**

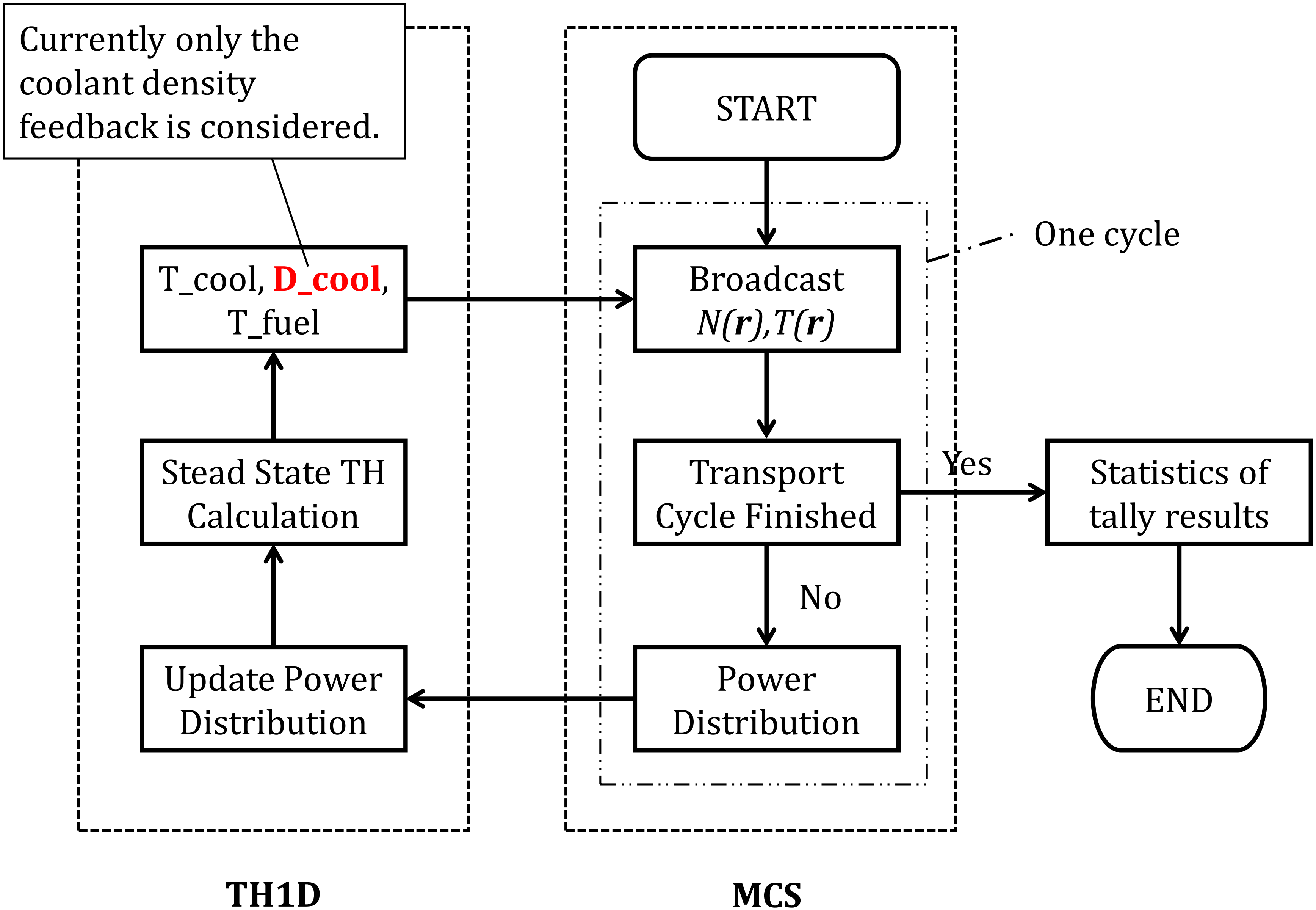
- **Fixed-point (Picard) iteration**
  - **The most common iterative approach**
  - **Allows for independent MC and TH solvers which exchange flux, temperatures and desities.**
    - **MCS starts with nuclide composition and temperature of last iteration:**

$$B\left(N^n, T^n\right)\begin{bmatrix}\phi^{n+1} \\ k^{n+1}\end{bmatrix} = 0$$

    - **TH1D is called with updated flux distribution:**

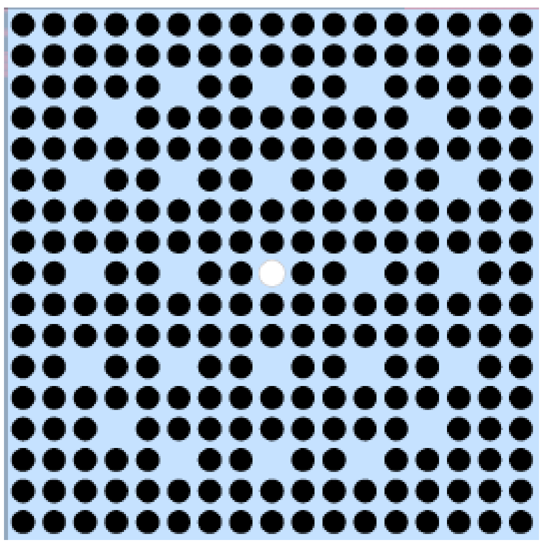
$$M\left(\phi^{n+1}\right)\begin{bmatrix}T^{n+1} \\ N^{n+1}\end{bmatrix} = 0$$

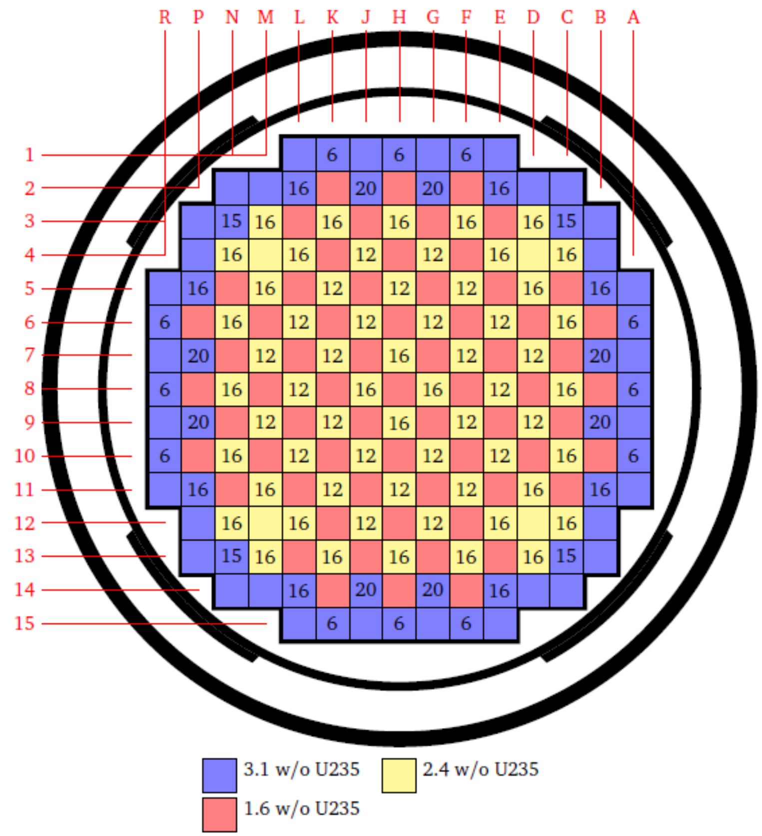
Iteration Methods



▪ BEAVRS benchmark (2013)

- Published by MIT reactor physics group
- Updated reactor challenge problem to replace the H-M benchmark
- 4 Contains detailed description of most reactor core components
- loop Westinghouse PWR





BEAVRS TH CALCULATION

BEAVRS CORE

- # of fuel cells : 50952
- # of axial meshes : 20
- # of radial meshes : 3

- Cell tallies : Fission (collision and track-length), absorption, flux

- Library : ENDF-B/VII.1
- OpenW : On
- Equilibrium Xenon : On
- TH feedback : On
- Critical Boron Search : On
- Tempdiff : 30 K

- Active : 40
- Inactive : 4
- Multicycle : 300
- Histories : 100,000

BEAVRS TH CALCULATION

Core Power	3,411 MW
Inlet Coolant Temperature	560 °F
Pressure	2,250 psia
Core Flow Rate	61.5×10^6 kg/hr
Control Rod Position	ARO

k_{eff}	1.00001 ± 0.00004
CBC	660 ± 0.281 ppm
Memory per Process	$\sim$ 17 GB
Simulation Time	29.8 hours
# of processes	48

CONVERGENCE CHECK

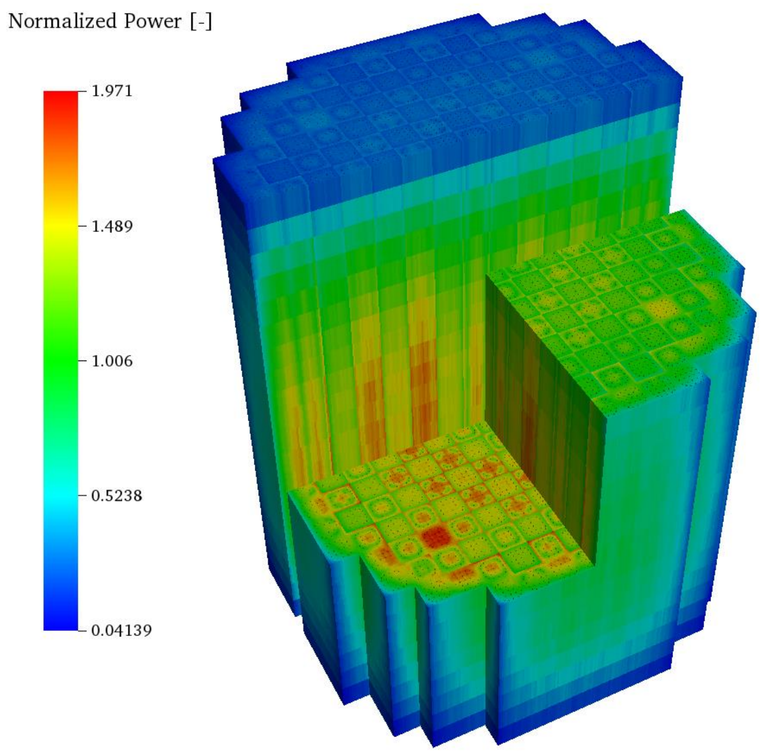
- **Simulation time for TH1D solver is about 20 seconds**

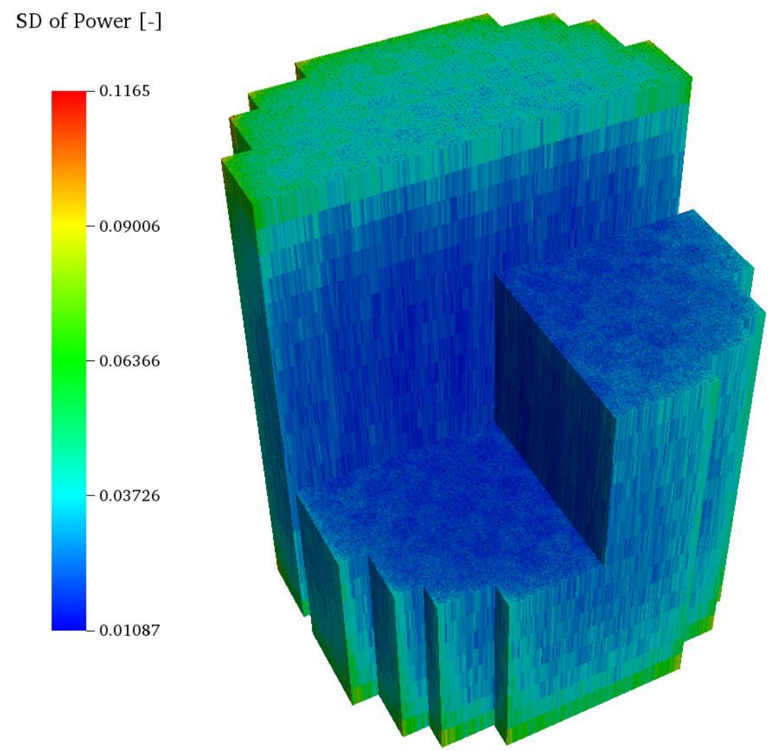
```
Solving TH1D solver...

          TH1D summary:
              # of pins: 50952
    # of pins converged: 50952
     # of pinx diverged: 0
   # of zero power pins: 0

...done // it took 20.28 sec
```

- **Diverged pin**
  - **If TH1D solver diverges**
  - **If The solution is wrong**
    - **Fuel temperature is too high (> 3,000 K)**
    - **Water density is negative**

3D FIGURES

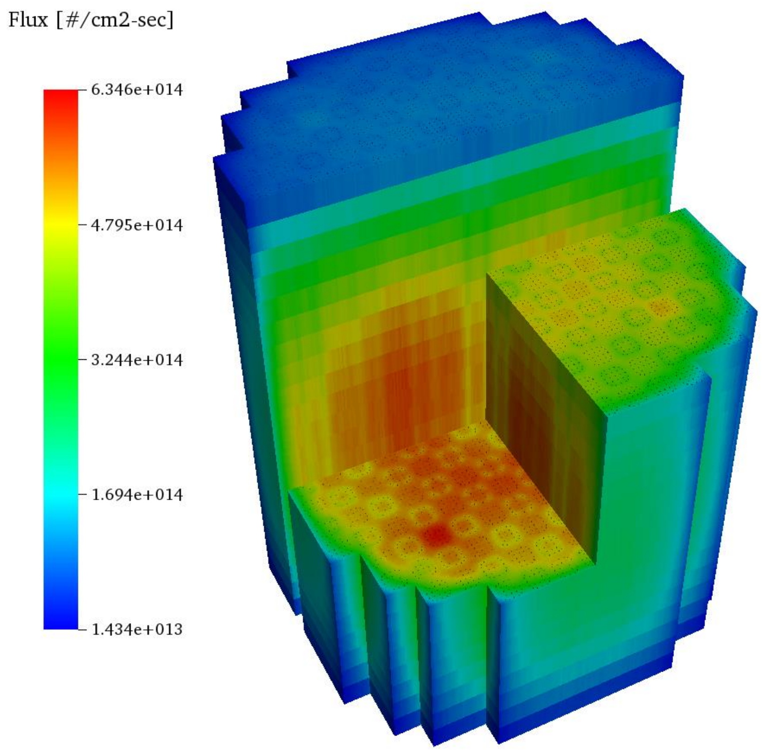
- **Normalized power and Relative Standard Deviation**

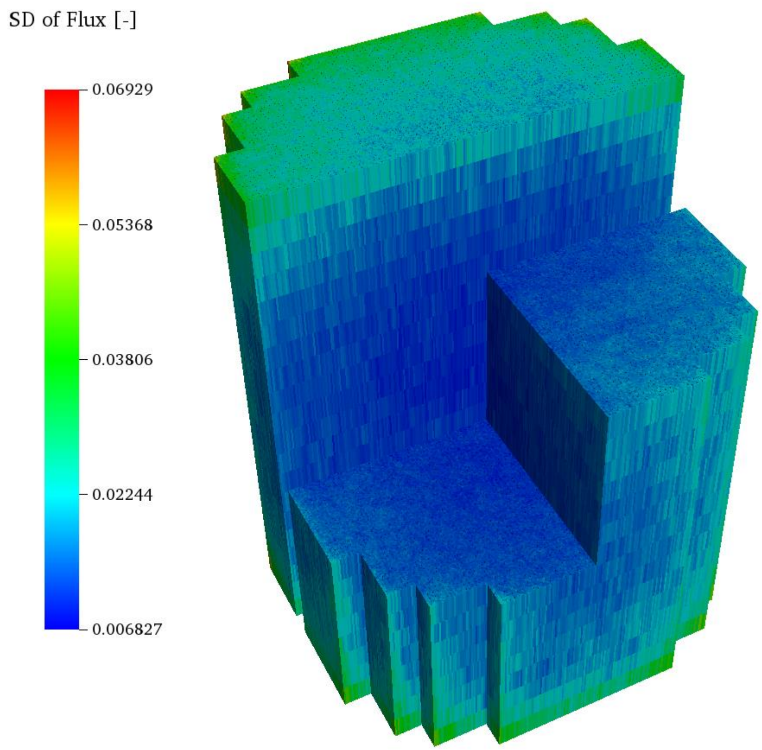




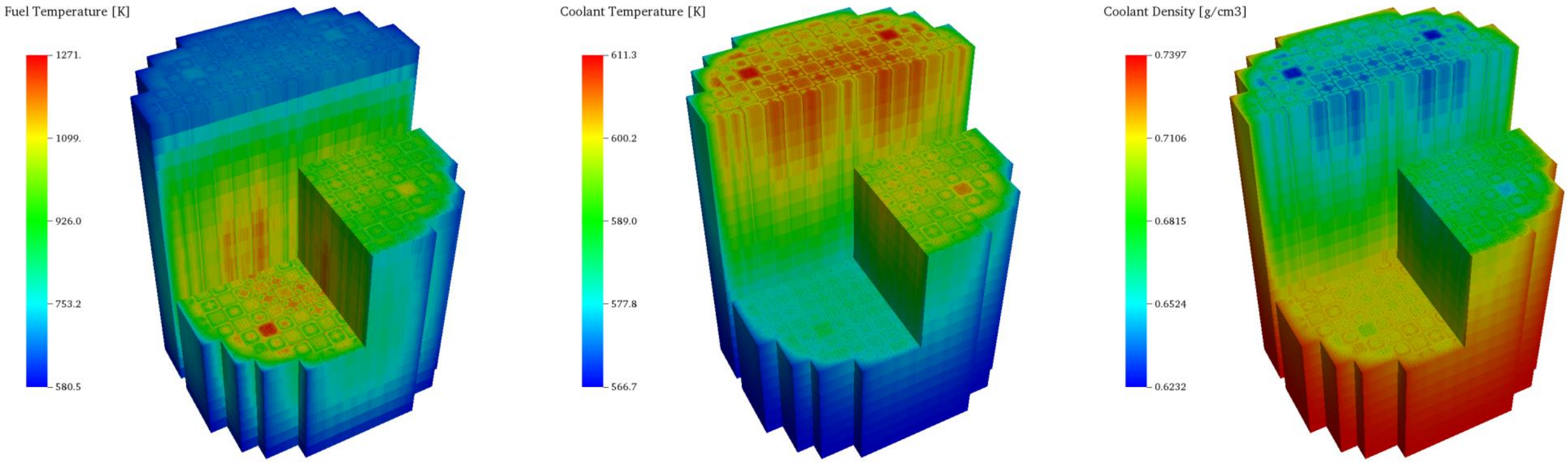
3D FIGURES

▪ Flux and Relative Standard Deviation



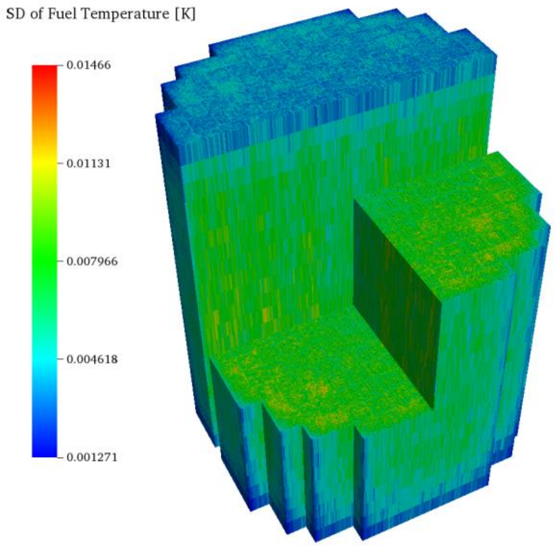


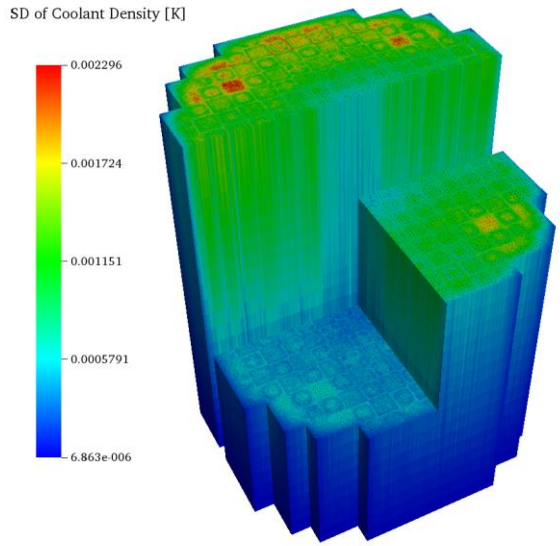
- **Fuel temperature, coolant temperature, and coolant density**

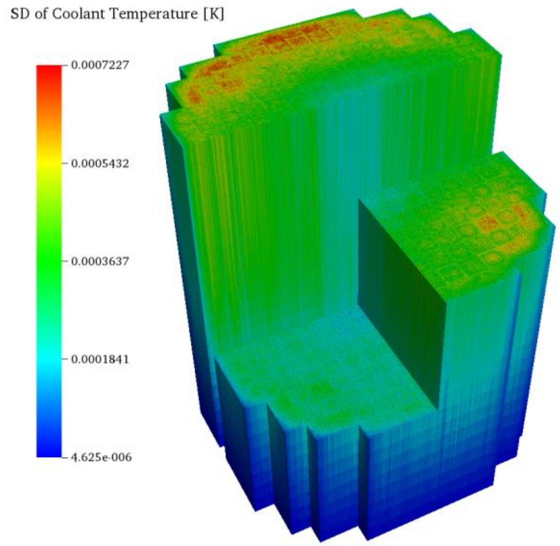


▪ Relative Statistical Error

- Fuel temperature : ~ 1.4 %
- Coolant temperature : ~ 0.07 %
- Coolant density : ~ 0.2 %







FUNCTIONS

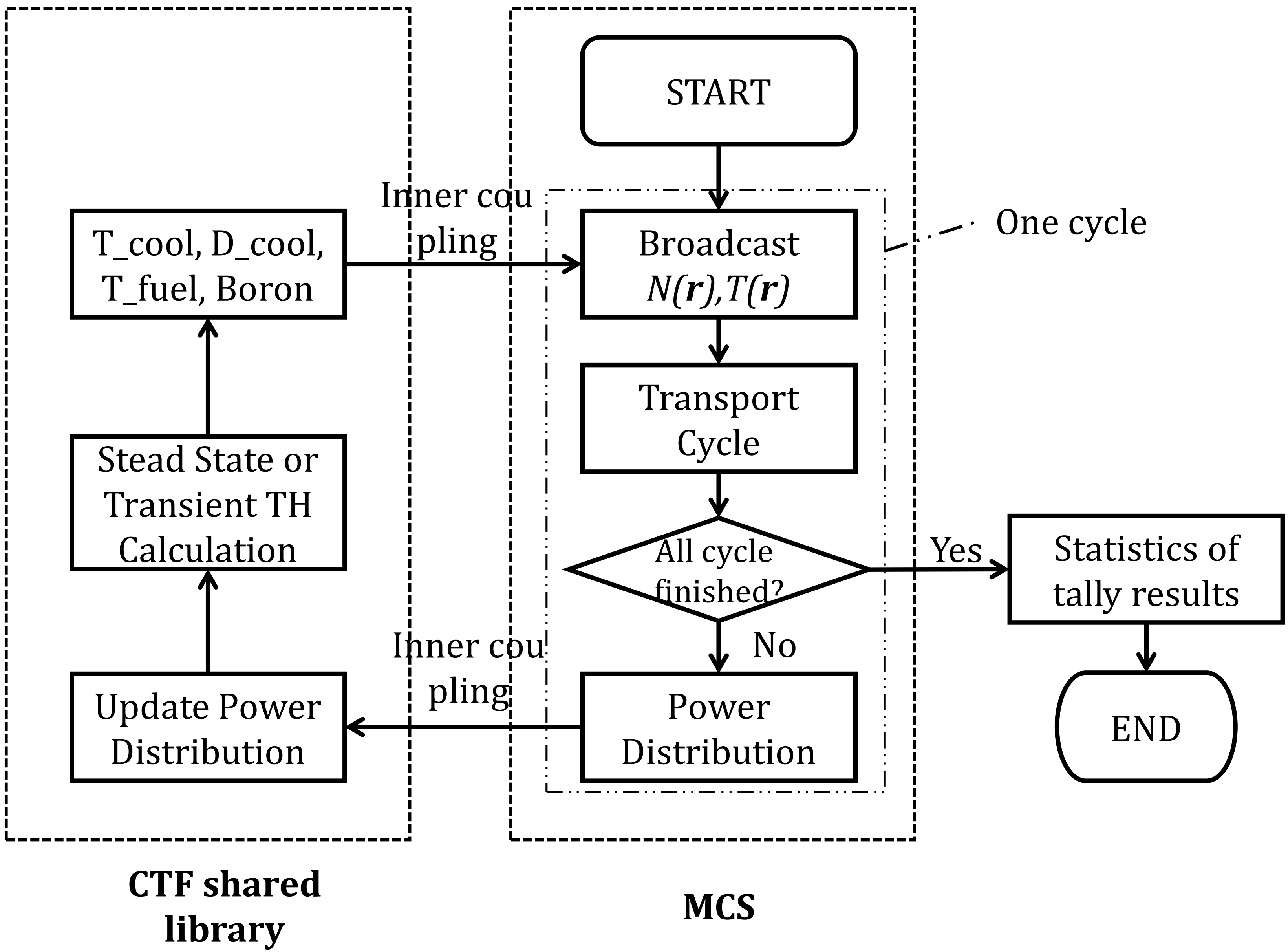
CTF Coupling

Introduction to CTF coupling

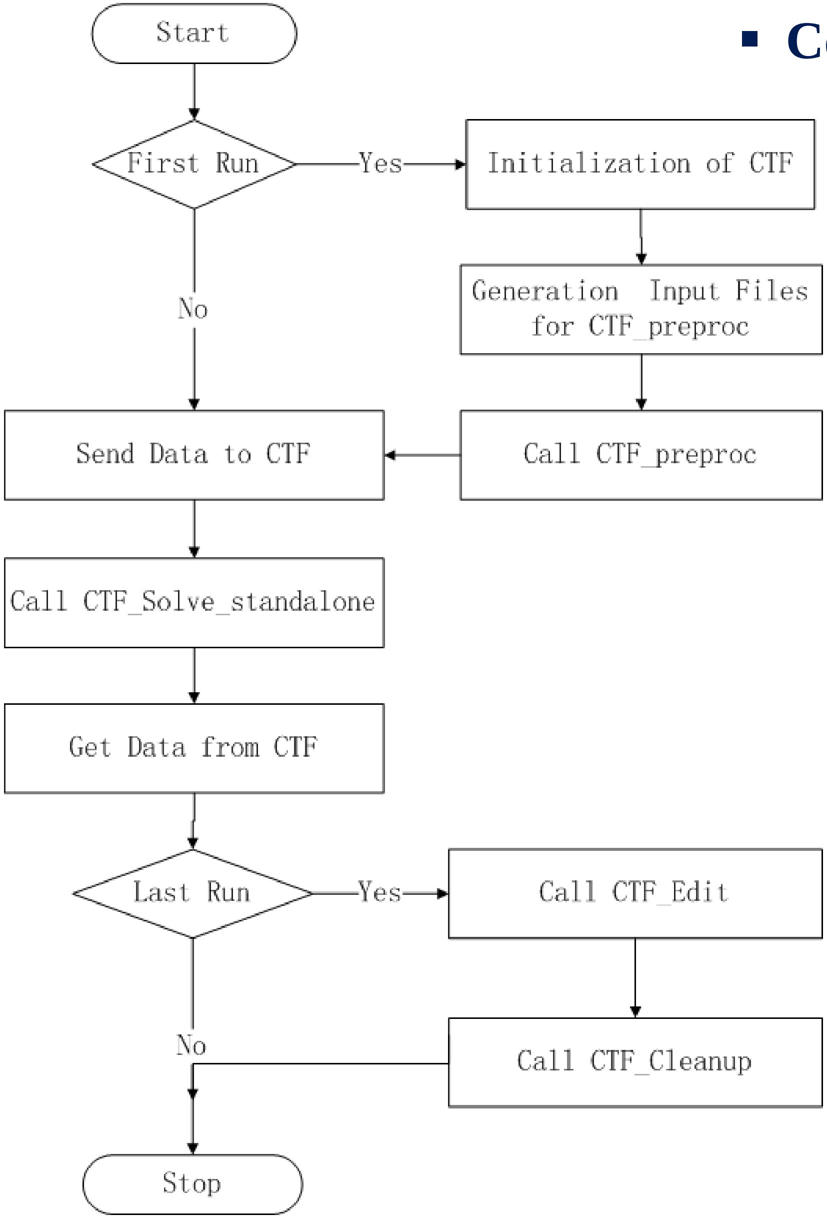
- **T/H Feedbacks**
  - **TH1D**
    - **Very simplified model**
  - **CTF**
    - **Sub-channel TH solver**

	TH1D	CTF
Conserved Eqas	Mass+Energy	Mass+Energy+Momentum
Two-phase Model	No	Yes(Liquid+Vapor+Droplet)
Cross-Flow Model	No	Yes
Boron Tracking	No	Yes
DNBR Analysis	No	Yes
Calculation Efficiency	High	Low
Parallelism	No	Yes(Assembly-based)

Iteration Methods – On the fly feedback



Coupling Interface

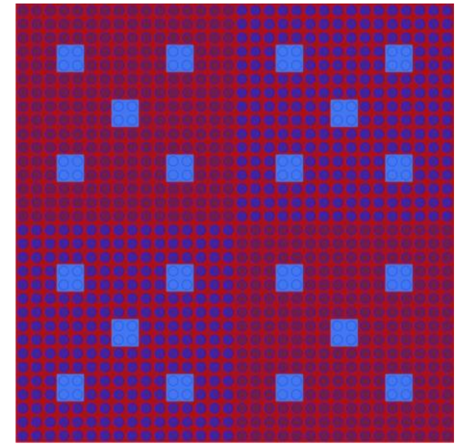


- **Coupling Procedure**
  - **Read MCS input file and generate input files for CTF_Preprocessor**
  - **Initialize CTF and allocate memory**
  - **Call CTF_Preprocessor to generate input file for CTF**
  - **Transfer pin-by-pin power distribution to CTF variables**
  - **Execute CTF_Solver_Standalone to solve T/H models**
  - **Transfer temp. and density distribution from CTF to MCS**
  - **Print visualized result and release memory**

```
use ctf_prepro,      only: preprocessor
use CTF_Coupling_Interface, only : CTF_Initialize
use CTF_Coupling_Interface, only : CTF_Solve_Standalone
use CTF_Coupling_Interface, only : CTF_Cleanup
use CTF_Coupling_Interface, only : CTF_Edits
use CTF_Coupling_Interface, only : CTF_set_rodpowers_W_cm3
use CTF_Coupling_Interface, only : CTF_set_rodpowers_W_cm
use CTF_Coupling_Interface, only : CTF_set_inlet_temp
use CTF_Coupling_Interface, only : CTF_get_coolant_temp
use CTF_Coupling_Interface, only : CTF_get_coolant_dens
use CTF_Coupling_Interface, only : CTF_get_clad_temp
use CTF_Coupling_Interface, only : CTF_get_fuel_temp
use CTF_Coupling_Interface, only : CTF_print_coupling_data
use transfer_io, only: basefn, filename_set_in_CTF_Coupling_Interface
```

Index Mapping

- **Index numbering**
  - **CTF**
    - Global core-wise index
    - Homogenized gap b/w assemblies
  - **MCS**
    - Assembly-wise index
    - Detailed gap b/w assemblies



Index Mapping

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CTF

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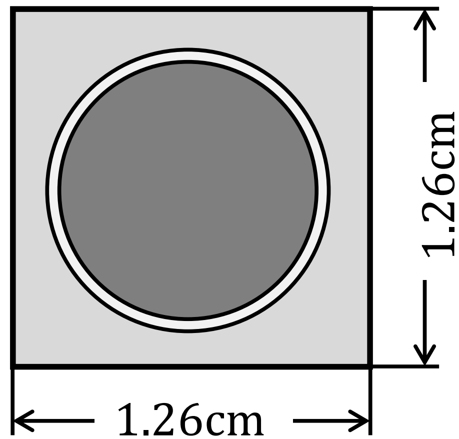
MCS

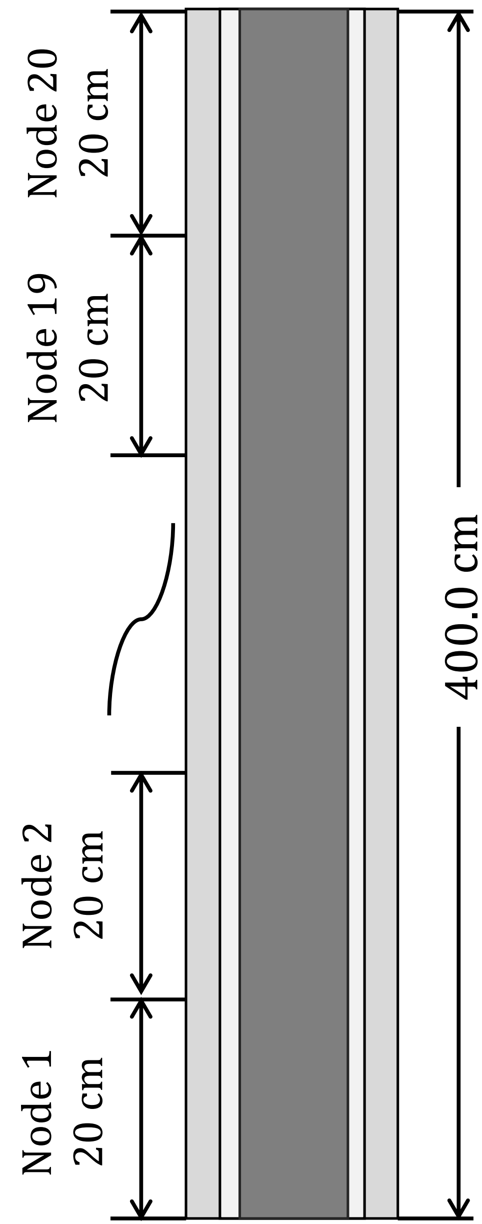
Numerical test

- **4m pin-cell problem**

Material	Composition (#/barn-cm)
Fuel	U-235 7.0473E-4 U-238 2.2499E-2 O-16 4.6407E-2
Clad	Zr-90 2.2158E-2 Zr-91 4.8322E-3 Zr-92 7.3862E-3 Zr-94 7.4852E-3 Zr-96 1.2059E-3
Coolant	H-1 4.6838E-2 O-16 2.3419E-2 B-10 1.5613E-5 B-11 6.2450E-5



Initial Temperature:
293.6K (all)
Initial Coolant Density:
0.7 g/cc



Numerical test

▪ Results

• Eigen-values

<criticality active="200" inactive="200" history="500000" k-initial="1.0" />

Pin power: 0.0834684 MW
Flow rate: 0.335276 kg/sec
Inlet Temperature: 566.6 K (293.45 ℃)
Gap conductance: 5678.3 W/m-K

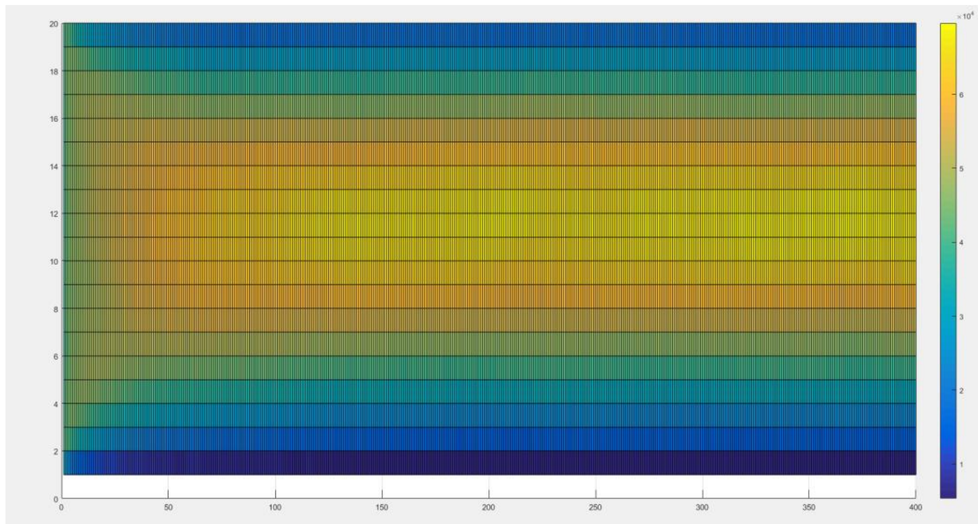
Table 1. Result of difference TH feedback

Case #	TH_mode	keff	Time/sec	Ratio
Pin	w/o	1.12999±0.00005	61664.2	--
Pin	TH1D	1.12747±0.00006	75257.8	1.22
Pin	CTF	1.12761±0.00007	72853.3	1.18

Numerical test

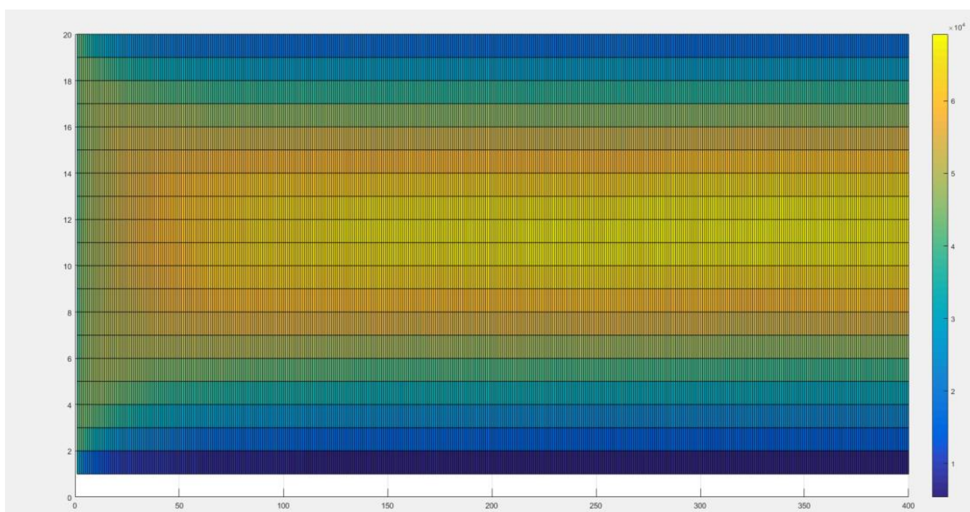
- **Results**
  - **Power distributions**

Axis node



TH1D

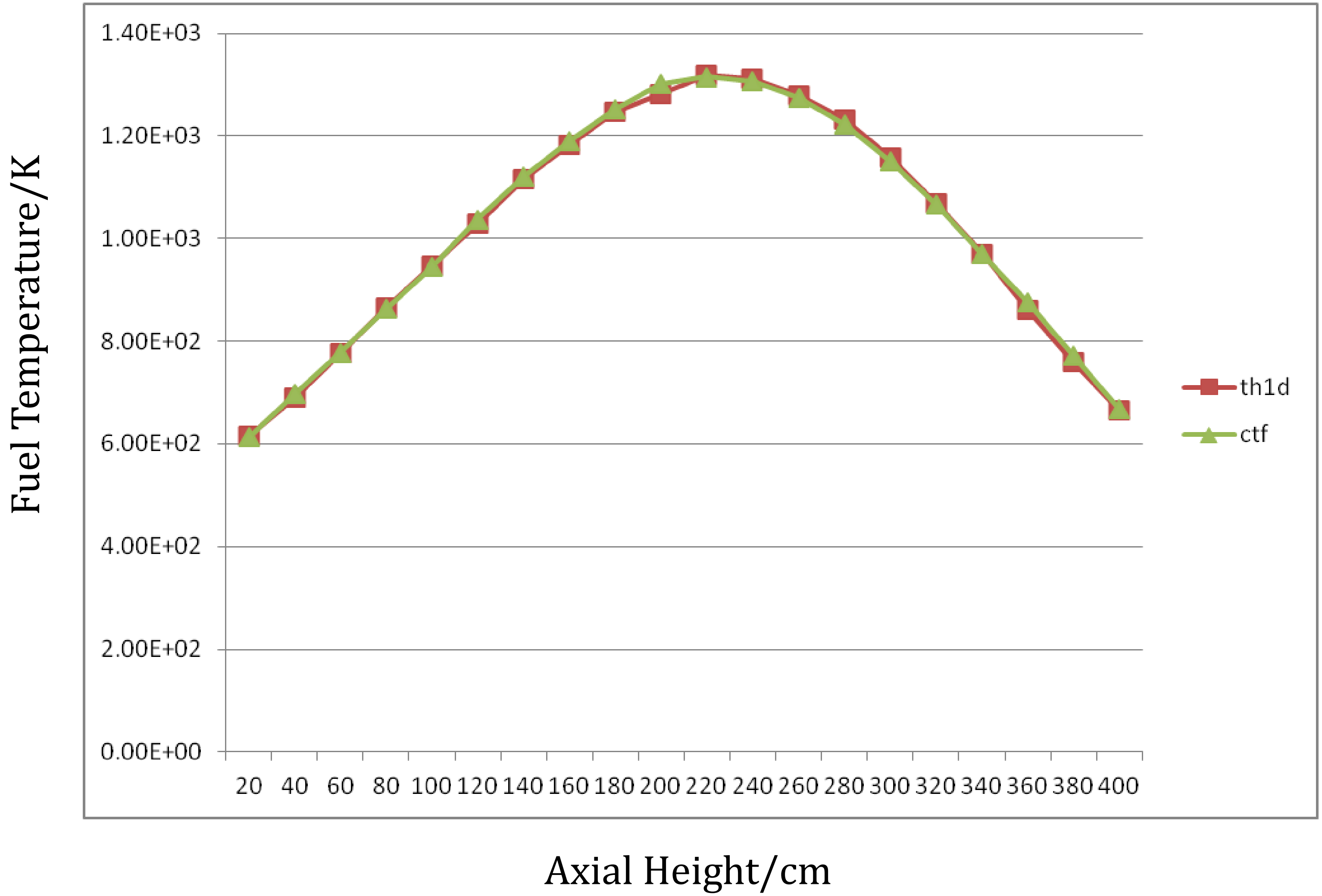
Axis node



CTF

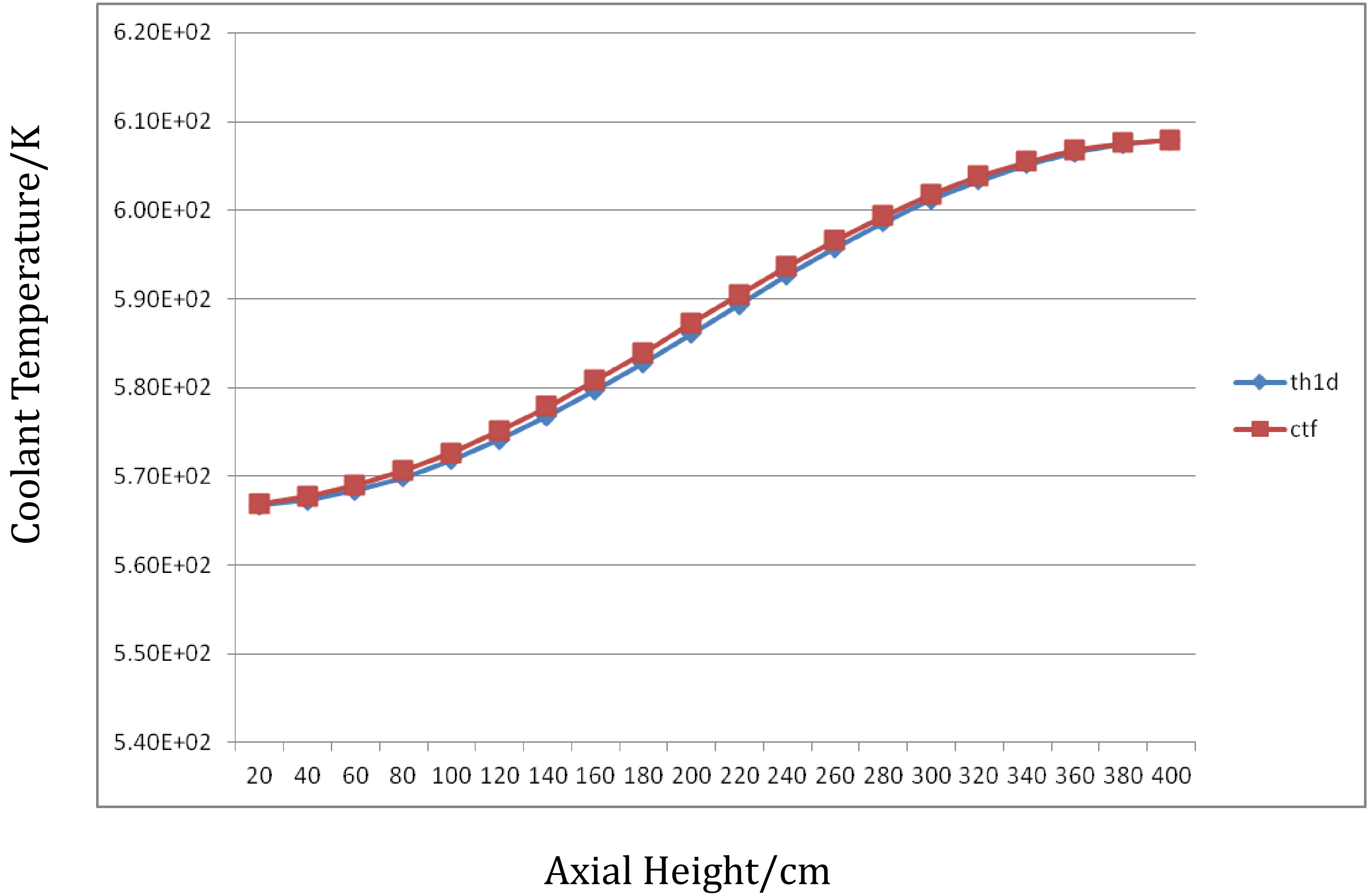
# of Iterations

- **Results**
  - **Fuel Temperatures**



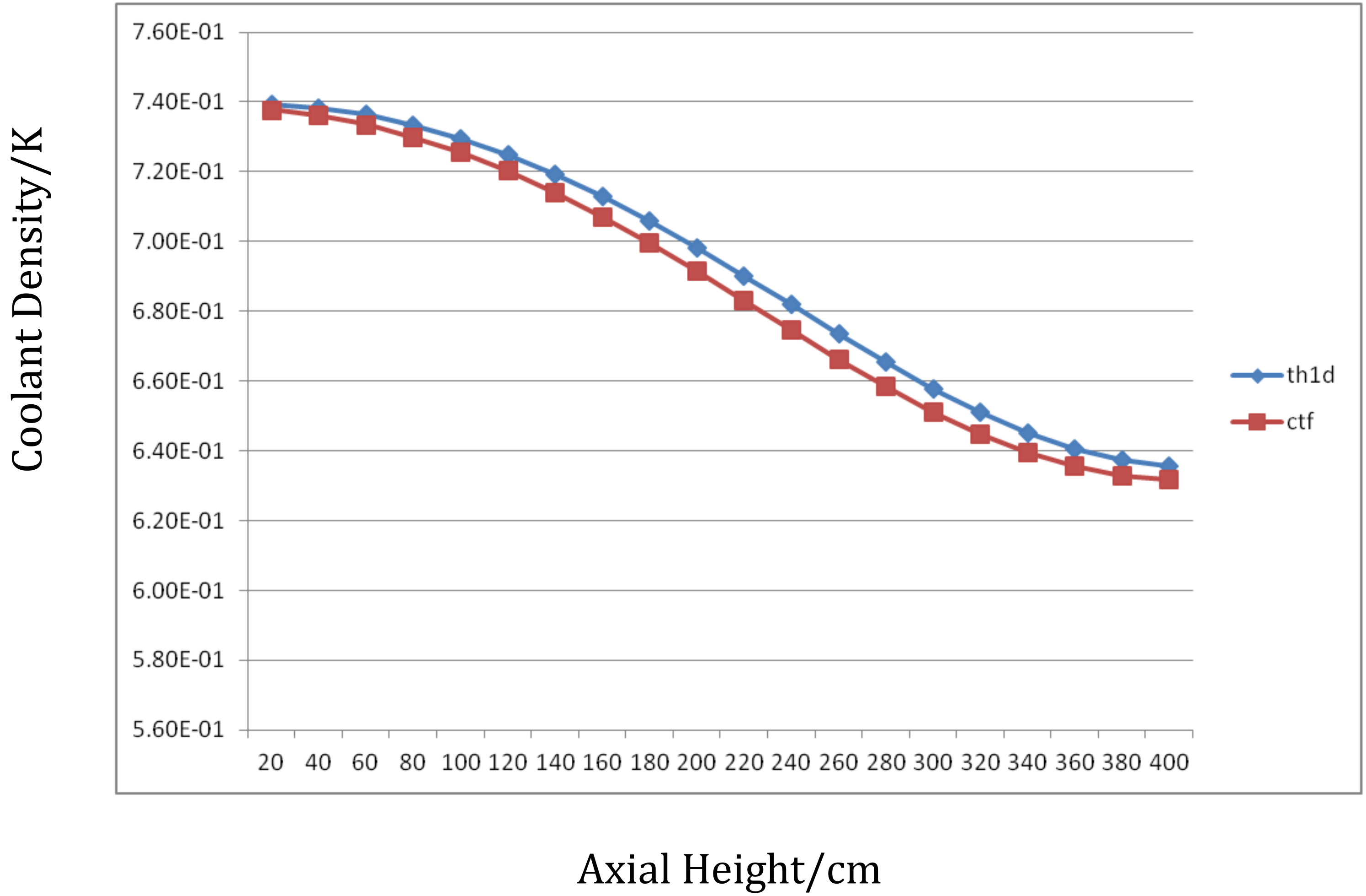
Numerical test

- **Results**
  - **Coolant Temperatures**



Numerical test

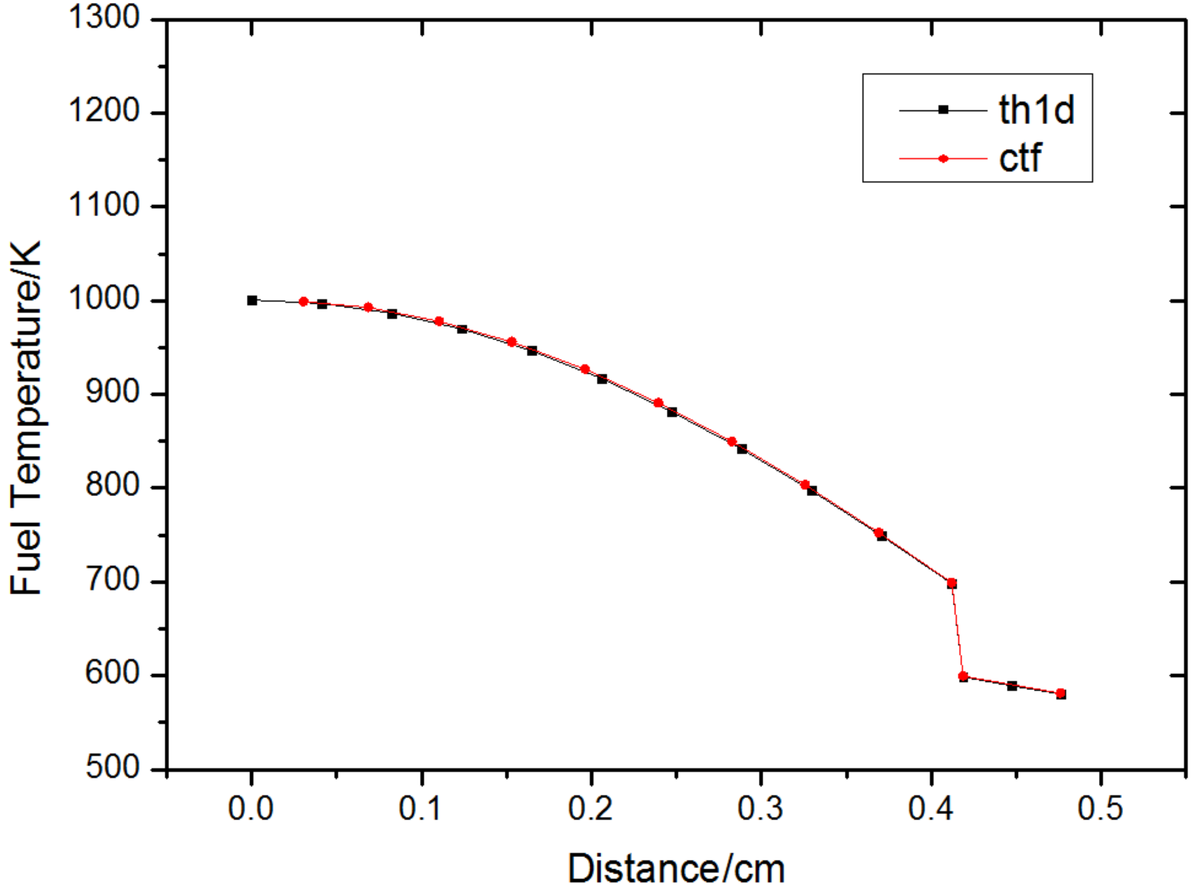
- **Results**
  - **Coolant Density**



Numerical test

▪ Results

- **Radial Fuel Temperature**



FUNCTIONS

Multipole
(On-The-Fly Doppler Broadening)

Multi-pole Representation

- **Alternative to the conventional R-Matrix theory**
- **Hwang converted resonance parameters given in nuclear data files into multipoles.**

$u = \sqrt{E}$

Energy Space, Resonance Half-Widths	Momentum Space, Poles and Residues
Energy-dependent	Energy-independent
Less parameters	More parameters: $2(l+1)$
Real parameters	Complex parameters

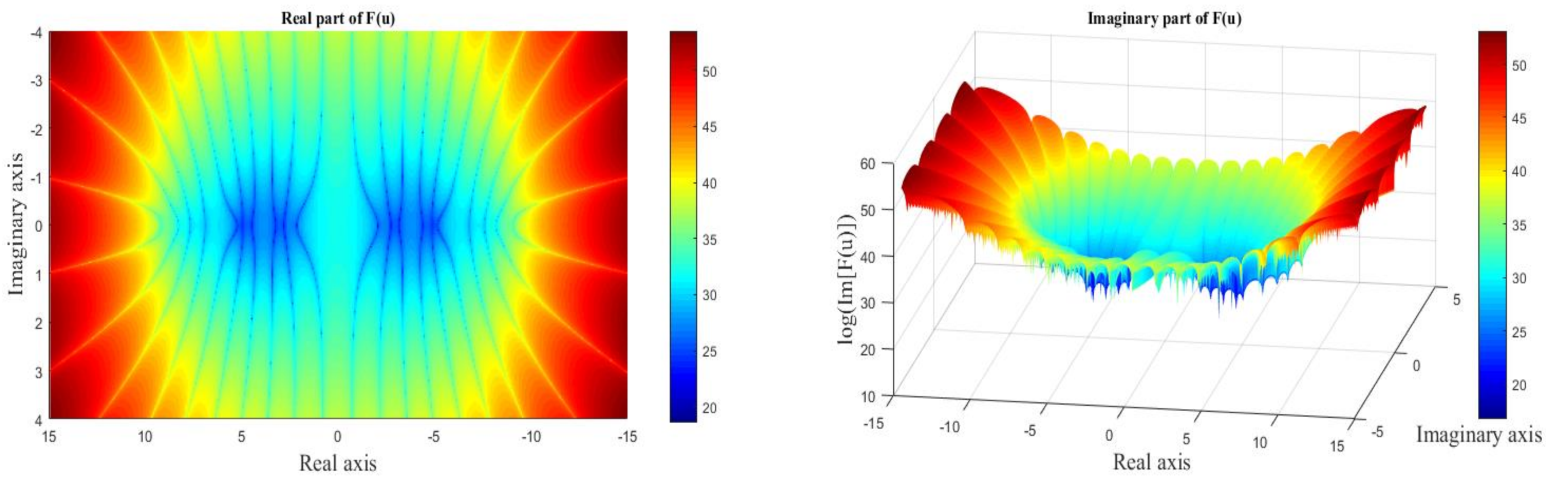
- **Hwang proposed using pseudo-poles to decrease number of parameters**

In order to obtain poles, following polynomial equation should be solved:

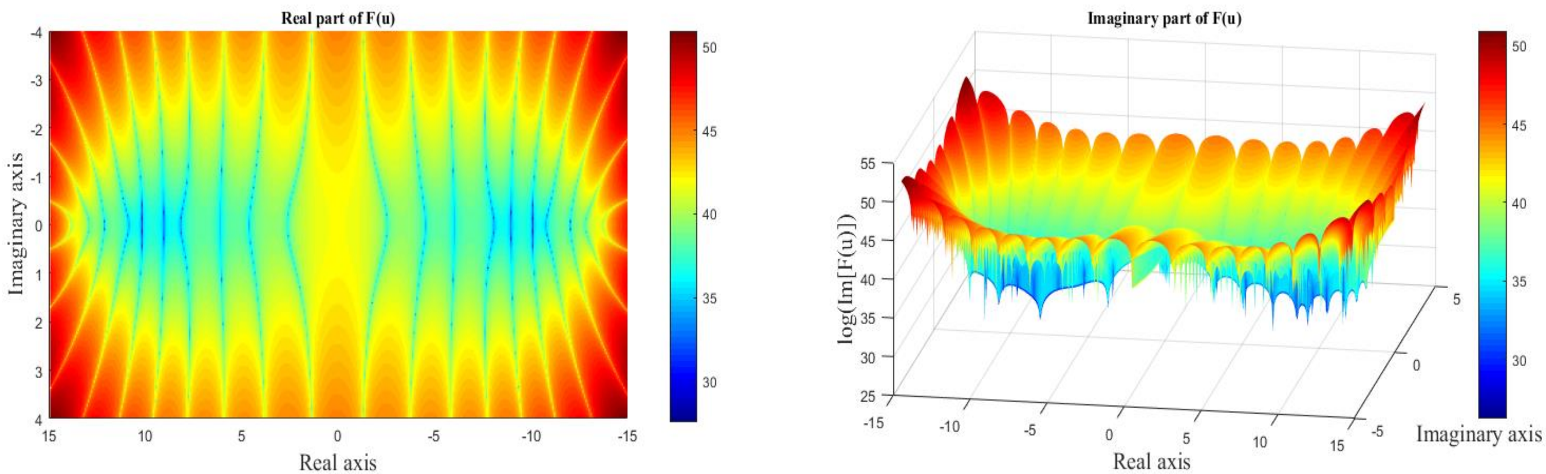
$$F(u) = \det(I-K) \times q_l(u) \times \prod_{\lambda}^{N} \left(E_\lambda - u^2 - i\frac{\Gamma_{\gamma\lambda}}{2} \right) = 0$$

Multi-pole representation

Real and Imaginary parts of $F(u)$ for the first 10 p-wave resonances of U^{238} (s-wave like poles)



Real and Imaginary parts of F(u) for the first 10 s-wave resonances of U^{238}



Multi-pole representation

Isotope: Am^{241} (SLBW)
Temperature: 0K
Energy range: 10^{-5}eV ~ 150eV

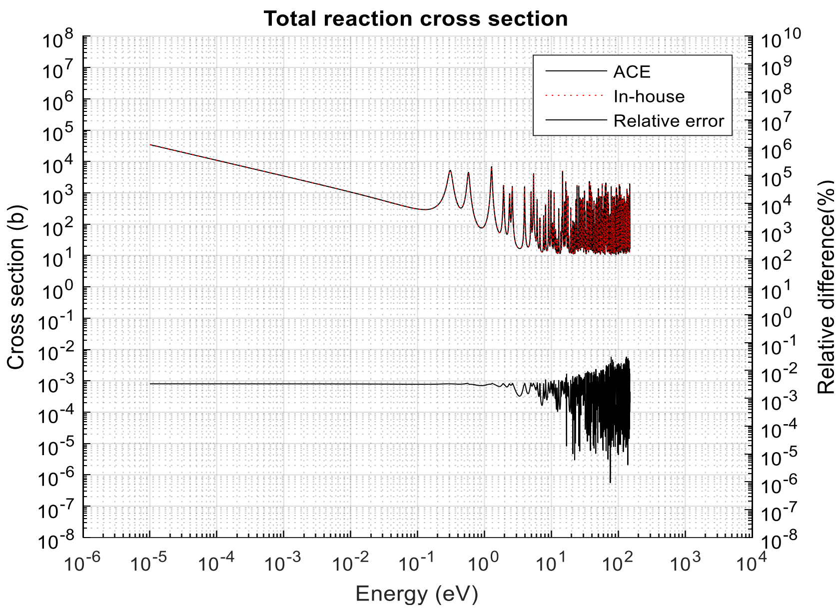


Table 1. Maximum relative difference (%)

Total	Scattering	Capture	Fission
0.030	0.033	0.035	0.035

Isotope: Pu^{239} (Reich – Moore)
Temperature: 0K
Energy range: 10^{-5}eV ~ 1keV

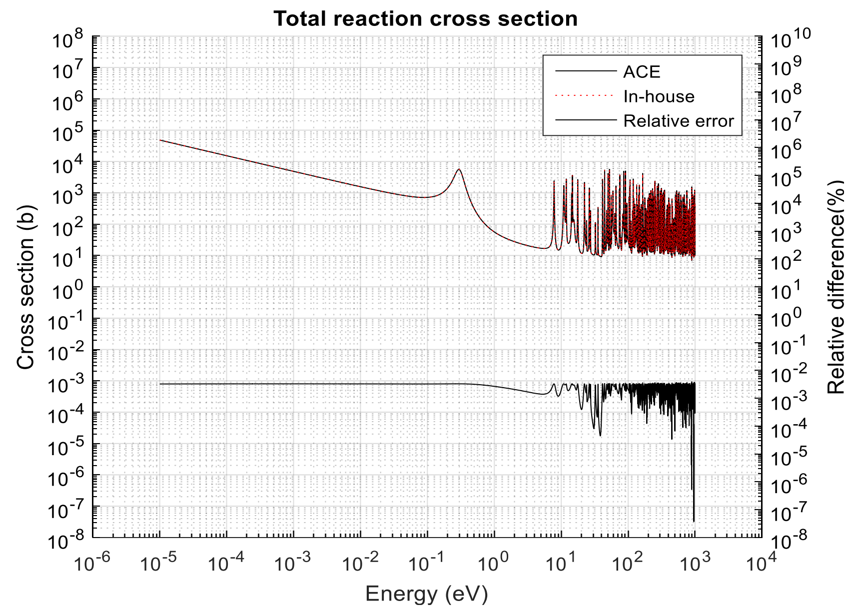


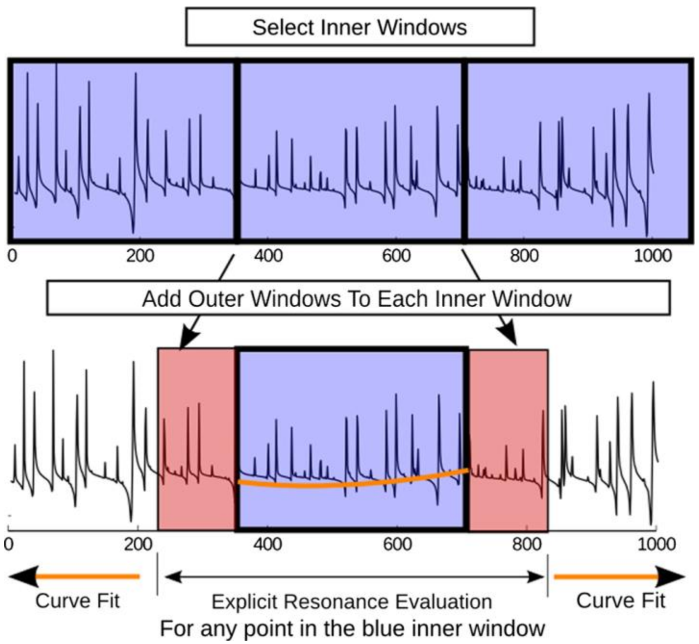
Table 2. Maximum relative difference (%)

Total	Scattering	Capture	Fission
0.0038	0.0056	0.0033	0.0033

Note: s-wave resonances case is working well.

Multi-pole Representation

- **Proposed by Hwang (ANL)**
- **Implemented into OpenMC (MIT)**
- **Window Concept: Inner and Outer**



$$\sigma_t(E,T) = \sigma_p(E) + p(E)_{poles \notin \Omega_{outer}} + \frac{1}{E}\sum_{l,J}\sum_{poles \in \Omega_{outer}} \frac{\mathrm{Re}\left[R^{(t)}_{l,J,\lambda,j}\sqrt{\pi}W\left(z_0(T)\right)\right]}{2\sqrt{\xi}}$$

- E **energy point of interest within** Ω_{inner} **window;**
- Ω_{inner} **and** Ω_{outer} **are inner and outer window ranges;**
- $p(E)_{poles \notin \Omega_{outer}}$ **is the polynomial fitting of the all poles outside the outer window;**
- $\sigma_p(E)$ **potential scattering cross section**

C. Josey et al., Windowed multipole for cross section Doppler broadening, J. Comput. Phys (2015).

Multi-pole representation

- **Converting resonance parameters into Multi-poles**
  - ***Simultaneous Root finding***
  - ***Restart Capability***
  - ***Arbitrary Precision***
  - ***Higher orbital angular momenta resonances***

- **On the fly Doppler broadening for in-house Monte Carlo code**
  - ***Reducing the number of poles***
  - ***Polynomial fitting***
  - ***Window energy concept***

ON-THE-FLY DOPPLER BROADENING

- **Multipole representation**
  - **OpenW module is implemented**

- **Benchmark problem : BEAVRS Full core**
- **Temperature : 293.6K**
- **Simulation specifications**
  - **# of inactive cycles : 200**
  - **# of active cycles : 2,000**
  - **# of histories per cycle : 100,000**
  - **# of cores : 20**

Cross section	Eigenvalue	STD	N/s inactive	N/s Active
ACE	1.01860	0.00005	22,870	23,705
OTF DB	1.01873	0.00005	20,409	21,204

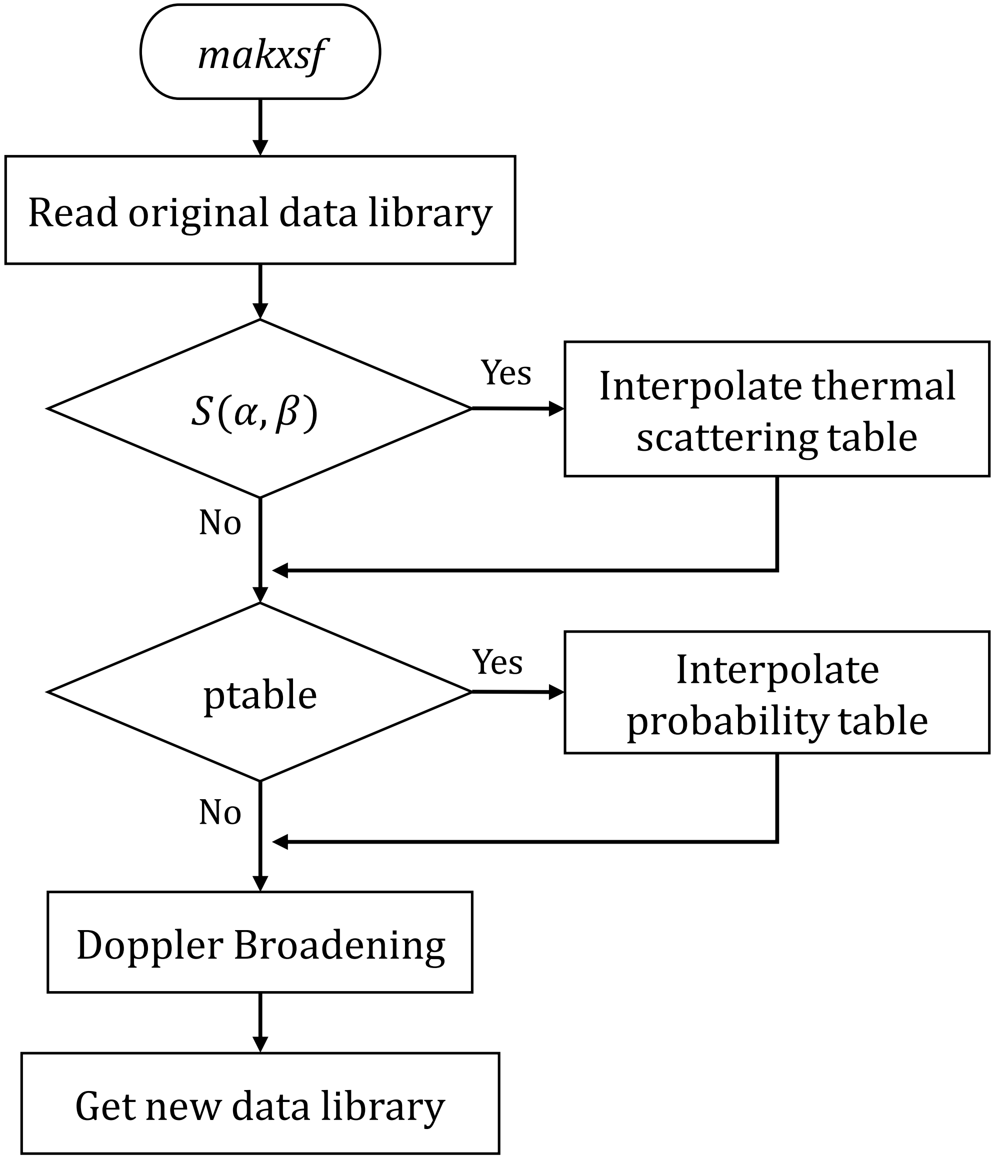
FUNCTIONS

SIGMA1 Kernel (Makxsf)

INTRODUCTION

- **The *makxsf* code is a utility program for manipulating cross-section library files for the *MCNP5* Monte Carlo code.**
  - ***makxsf* can be used to**
    - **convert ACE data files between ASCII and binary formats and to make customized libraries containing selected datasets.**
    - **Doppler broaden the resolved data to any higher temperature with using several routines from the *NJOY* and *DOPPLER*.**
    - **interpolate $S(\alpha, \beta)$ thermal scattering kernels and probability tables for unresolved resonance data between two bracketing temperature with using several routines from the *NJOY* and *DOPPLER*.**

makxsf FLOW CHART IN MCS



$$f = \frac{T_{\text{target}} - T_{\text{lower}}}{T_{\text{higher}} - T_{\text{lower}}}$$

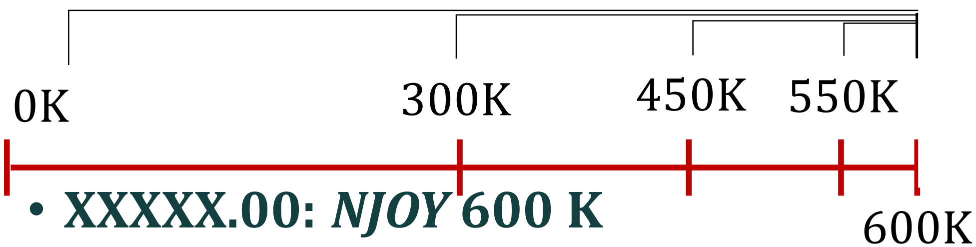
$$S(T_{\text{target}}) = (1-f) * S(T_{\text{lower}}) + f * S(T_{\text{higher}})$$

$$f = \frac{\log(T_{\text{target}}) - \log(T_{\text{lower}})}{\log(T_{\text{higher}}) - \log(T_{\text{lower}})}$$

$$P(T_{\text{target}}) = (1-f) * P(T_{\text{lower}}) + f * P(T_{\text{higher}})$$

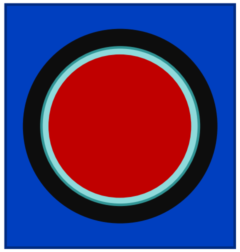
CROSS SECTION LIBRARY GENERATION

- **Cross section libraries are generated by *NJOY* at different temperatures (0, 300, 450, 550, 600, 650, 750, 900, 1200 K).**
- **Different 600K Cross section libraries are generated by *makxsf*.**



- **XXXXX.00: *NJOY* 600 K**
- **XXXXX.01: *makxsf* from *NJOY* 550 K**
- **XXXXX.02: *makxsf* from *NJOY* 450 K**
- **XXXXX.03: *makxsf* from *NJOY* 300 K**
- **XXXXX.04: *makxsf* from *NJOY* 0 K**

TEST PROBLEM – UO2 PINCELL



- **UO2 pin cell geometry with reflective boundary**
  - R1~R4 = 0.98 cm, 1.10 cm, 1.34 cm, 1.47 cm / Z = 40cm
  - M1~M4 = UO2, Air, Zr, Coolant
- **Material composition**
  - Fuel density (900 K) = 10.176 g/cm3
    - ^{234}U (0.03%) + ^{235}U (2.96%) + ^{238}U (85.16%) + ^{16}O (11.85%)
  - Air density (600 K) = 0.001 g/cm3
    - ^{16}O (100%)
  - Zr density (600 K) = 6.55 g/cm3
    - ^{90}Zr (100%)
  - Coolant density (600 K) = 0.7 g/cm3
    - ^{1}H (11.19%) + ^{16}O (88.81%) + ^{10}B (0.01%)
- **MCS is used for calculation.**
  - 100,000 neutron histories per a cycle,
    50 inactive cycle and 500 active cycle

Library	MCS_k_{eff}	Cross section generation time
NJOY 900K, *NJOY* 600K	1.24234 ± 0.00013	-
makxsf from '*NJOY* 566.6K'	1.24210 ± 0.00010	6.85 sec
makxsf from '*NJOY* 293.6K'	1.24227 ± 0.00012	12.43 sec
makxsf from '*NJOY* 0K'	1.24201 ± 0.00013	40.28 sec

FUNCTIONS

Image

Input Visualization Module

▪ Format

- PPM (Portable Pixmap Format)

▪ Advantage

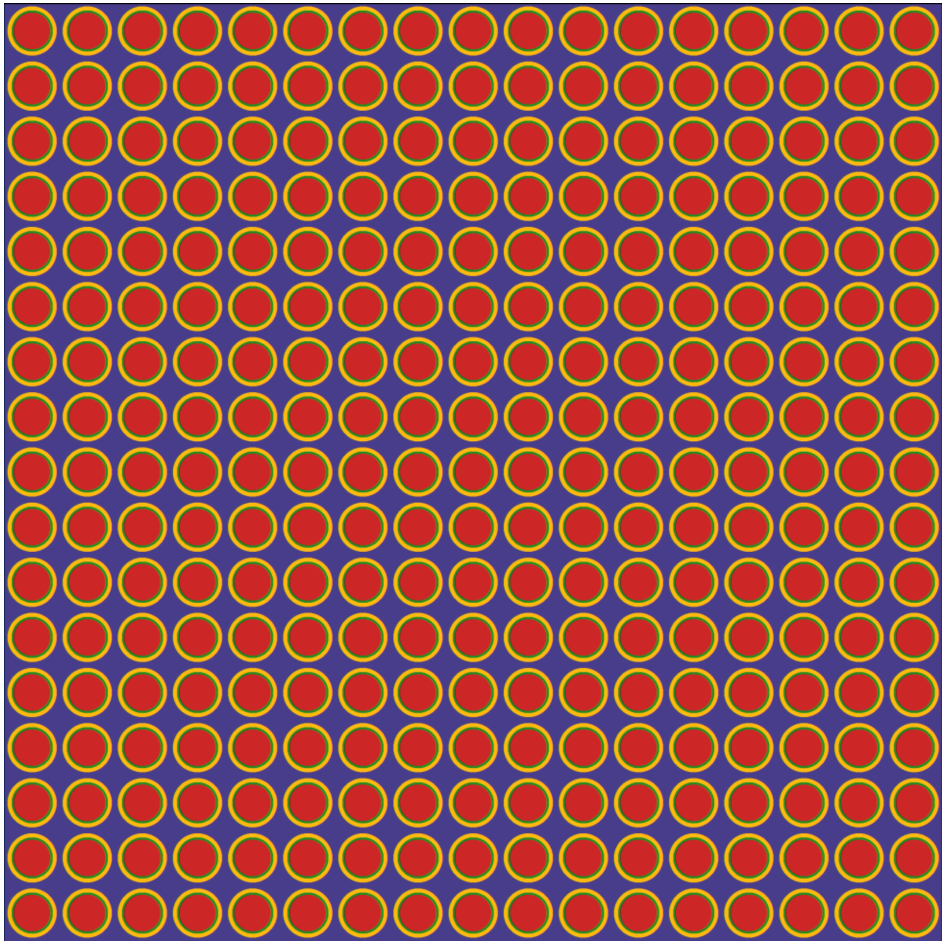
- Format is very easy
- Processing speed is faster than others
  (since it does not compress the image files)

▪ Disadvantage

- The file size is huge
  (100 times than PNG format, 50 times larger than JPG format)

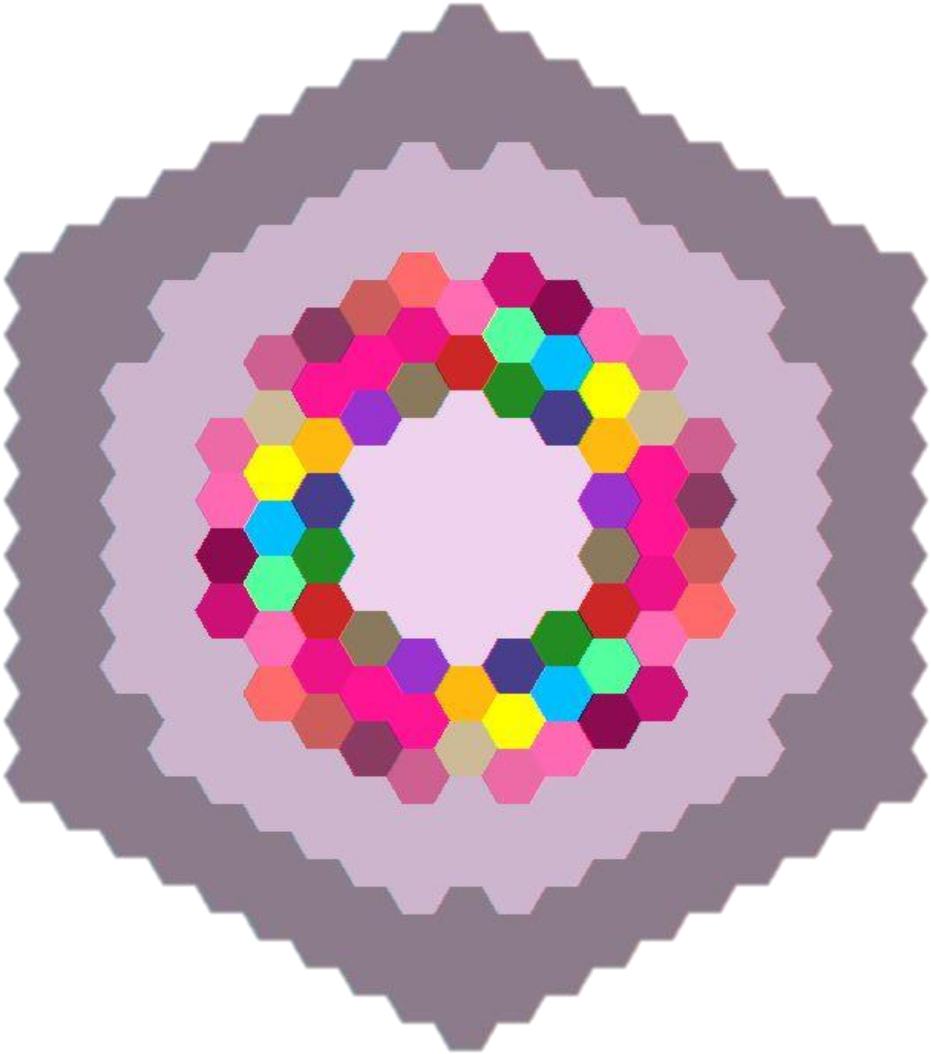
Input Visualization Module

- **PWR assembly**



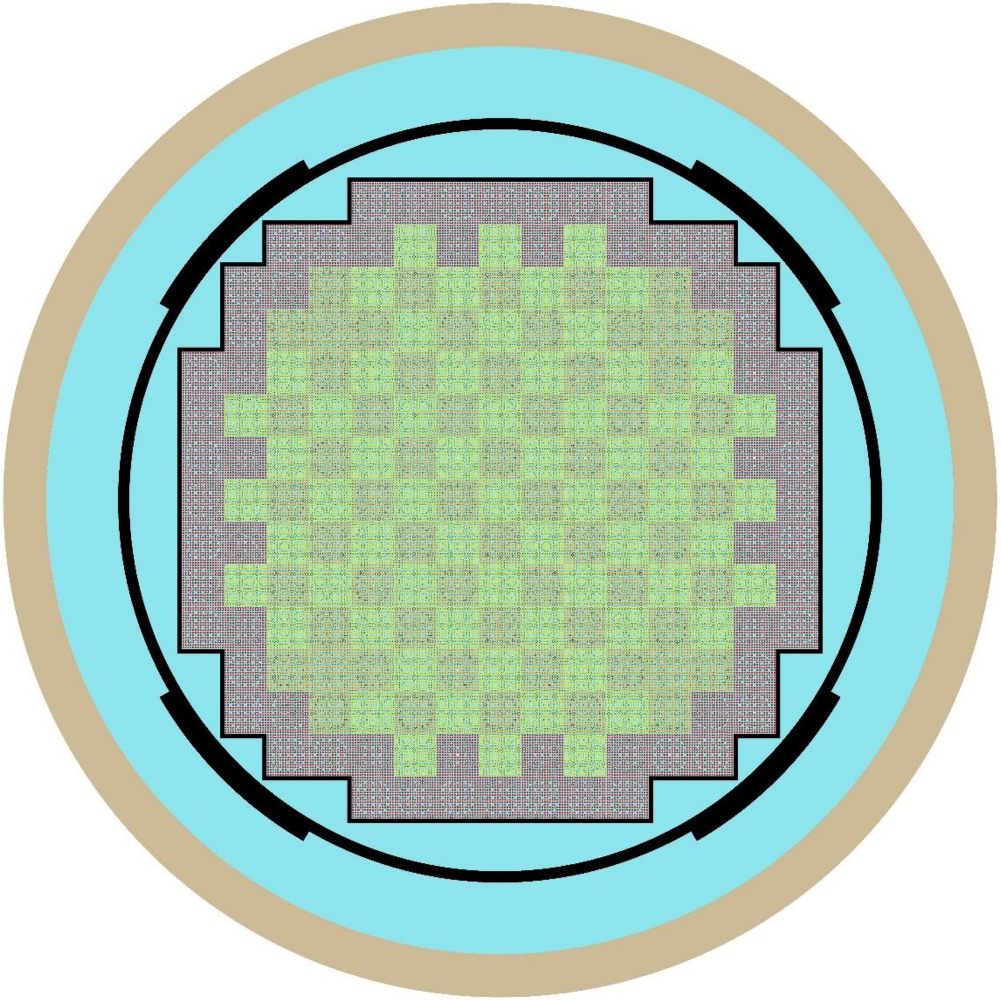
Input Visualization Module

- **MHTGR-350**

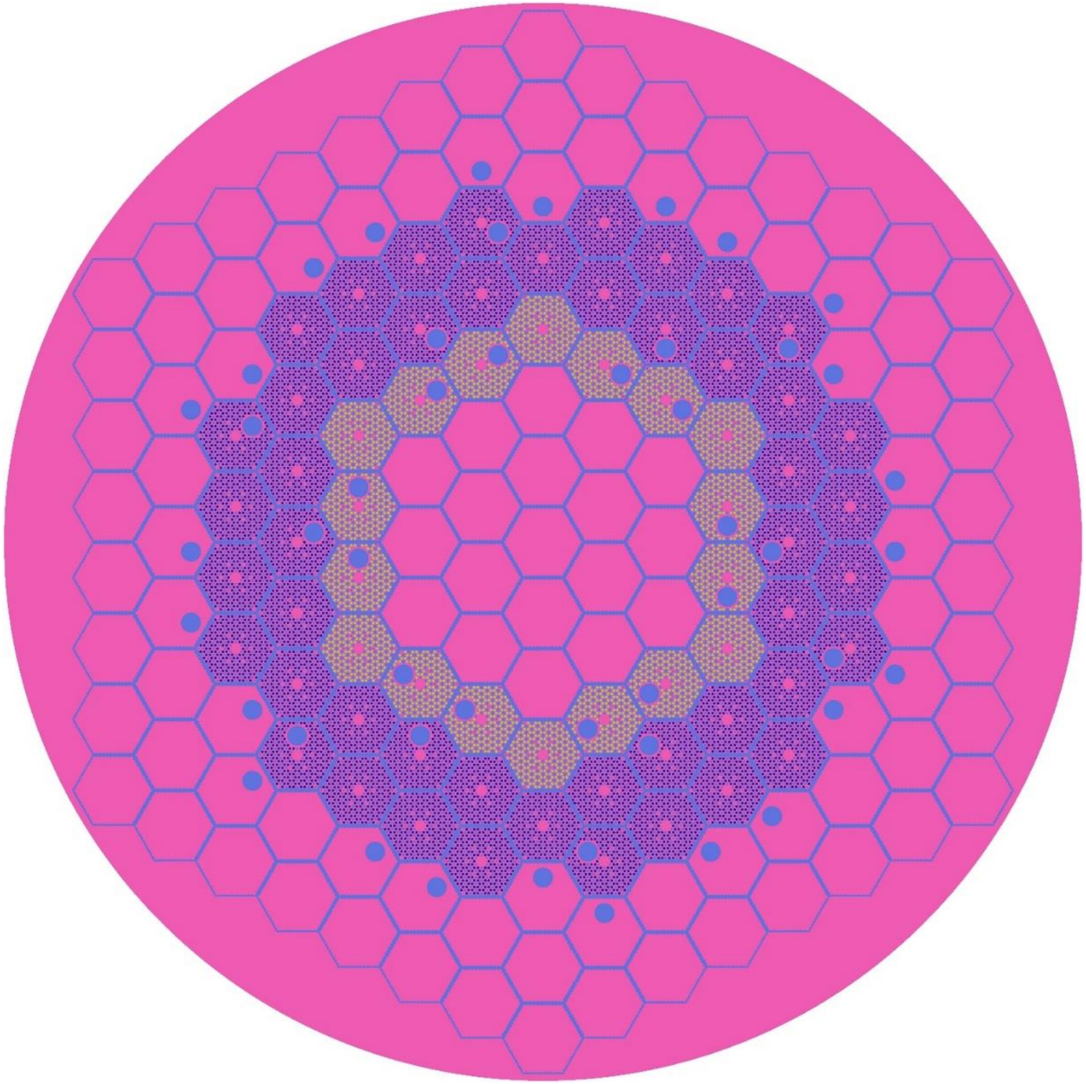


Input Visualization Module

- **BEAVRS**



- **PMR-200**



FUNCTIONS

Gamma Transport

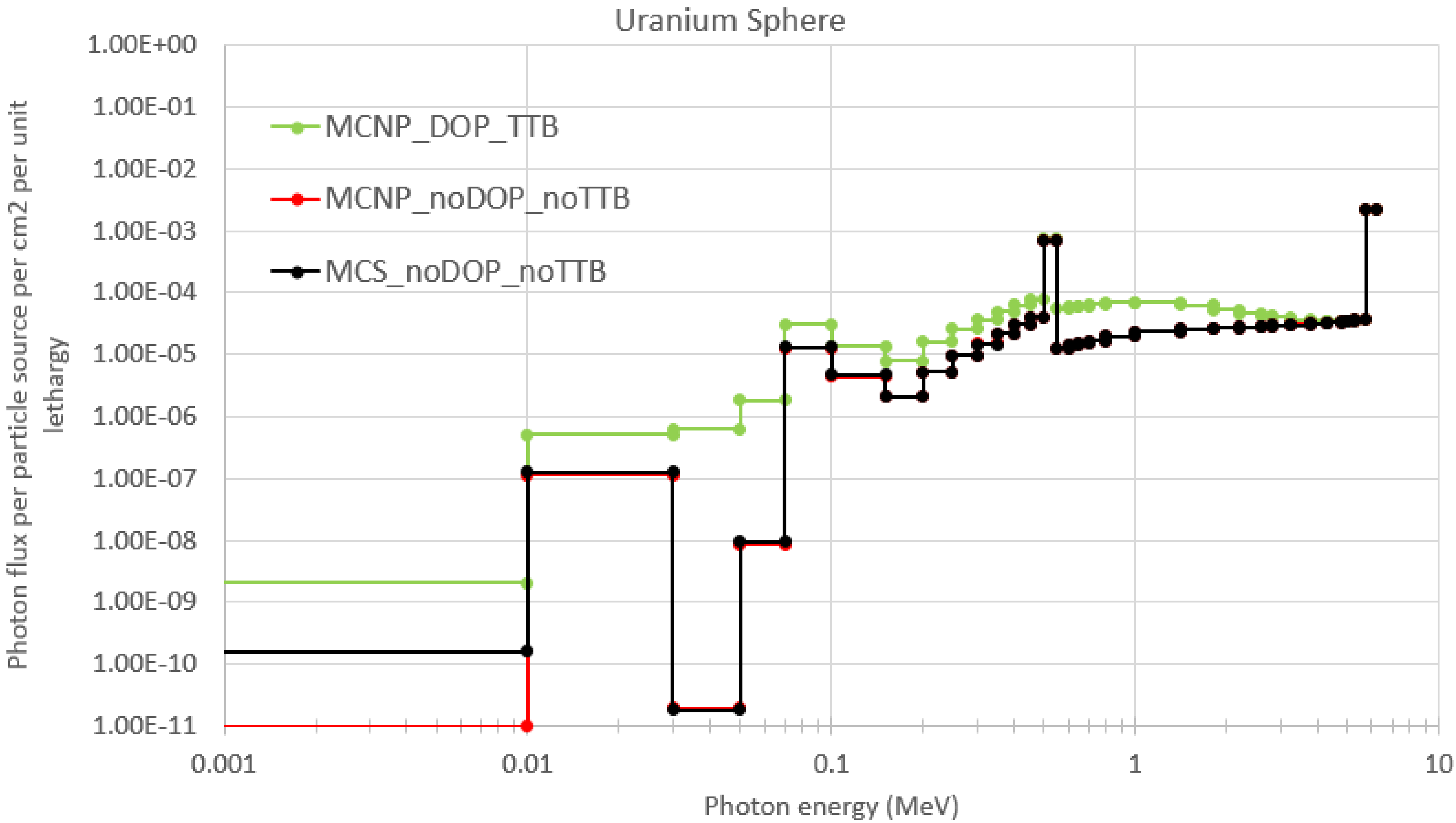
Status of photon transport in MCS

- **Photoatomic XS from ACE files (ENDF/B-VII.1)**
- **Additional photon data files from SERPENT2 library**
- **Photoelectric effect:**
  - Sampling of electron subshell using subshell photoelectric XS
  - Atomic relaxation simulated for all subshells with binding energy > 1 keV
- **Rayleigh (coherent) scattering**
  - Sampling from Thomson differential XS with coherent form factors
- **Compton (incoherent) scattering**
  - Sampling from Klein-Nishina differential XS with incoherent scattering factors
  - Kahn's method below 1.4 MeV and Koblinger's method above 1.4 MeV
- **Pair production**
  - Positron/electron annihilation at rest and production of two 511 keV photons
- **Ongoing implementation:**
  - Doppler broadening during Compton scattering
  - Bremsstrahlung (use of thick-target bremsstrahlung approximation)
  - Photon KERMA tally

Preliminary MCNP6 / MCS photon flux comparison

Uranium sphere (20 cm radius) surrounded by water

Isotropic 6-MeV monokinetic point source in the center of the sphere



DOP: Doppler broadening during Compton scattering

TTB: thick-target bremsstrahlung

FUNCTIONS

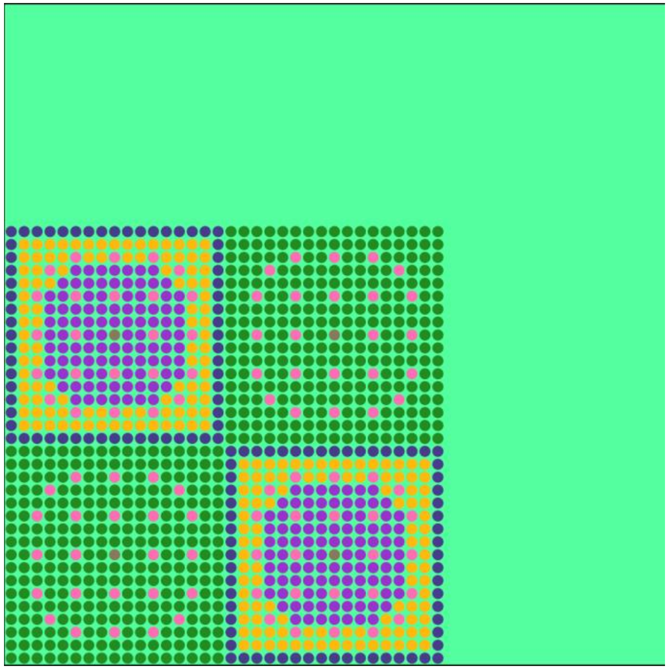
Indexing

TALLY INDEXING

Cell indexing for massive tallies

- Direct calculation (hash-table algorithm)
- Every cell have unique index (default index)
- Easy to make index

Default index	Index for fuel cell	Index for coolant
1	1	NONE
2	NONE	1
3	2	NONE
4	NONE	2
5	3	NONE
6	NONE	3
7	4	NONE



▪ Pin-wise tally of McCARD

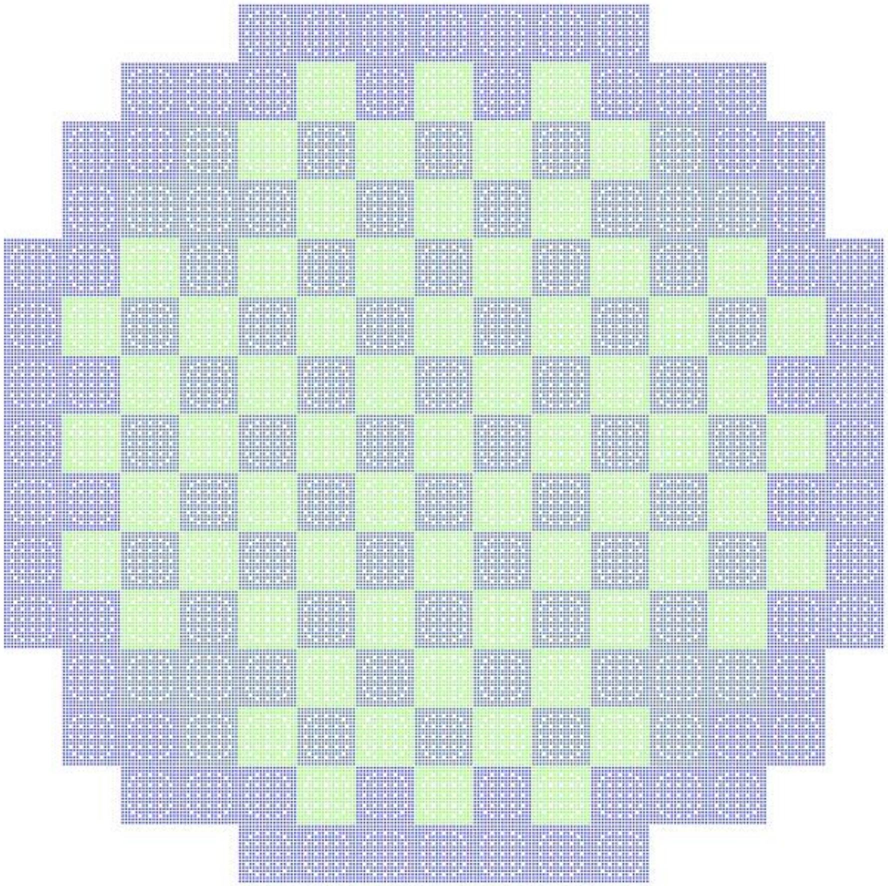
```
Tally (
[
if FLAG_TALLY>=1 :
   out.write('    Flux\n')
   for k in range(FLAG_TALLY):
      for j in range(ASM_NUM):
         for i in range(ASM_NUM):
            if (compBB[j][i] != 0):
               for q in range(PIN_NUM):
                  for p in range(PIN_NUM):
                     if (compAA[q][p] == 0):
                        if NUM_AXIAL==1:
                           for m in range(1,NUM_RADIAL+1):
                              out.write('      asm%02d_%02d>pin%02d_%02d>Pellet_%04d \n' % (j+1, i+1, q+1, p+1, m) )
                        else :
                           for n in range(1,NUM_AXIAL+1):
                              for m in range(1,NUM_RADIAL+1):
                                 out.write('      asm%02d_%02d>pin%02d_%02d>Pellet_%04d \n' % (j+1, i+1, q+1, p+1, ((n-1)*NUM_RADIAL+m)) )
]
);
```

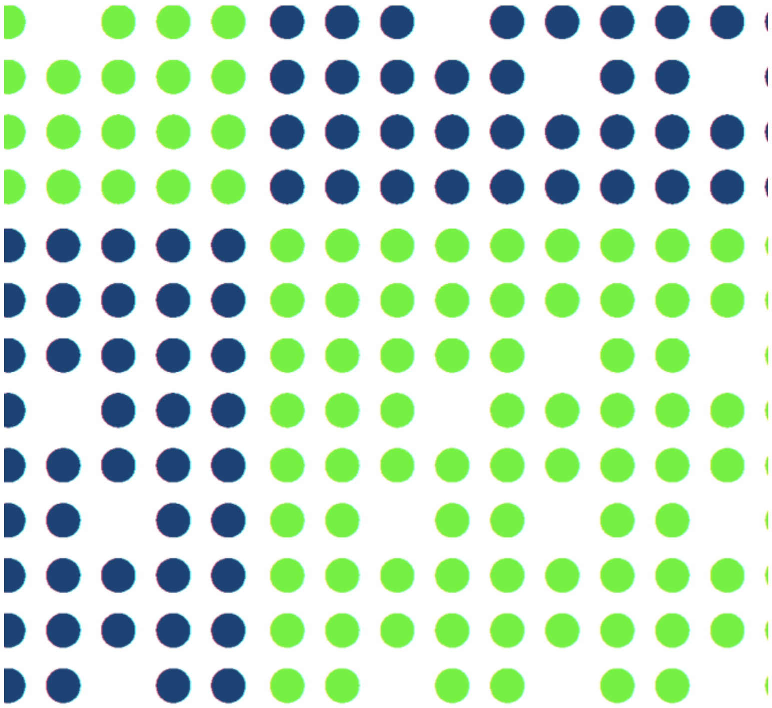
▪ Pin-wise index of MCS

```
<indices>
    <name> tempname </name>
    <cell-wise> fuel-1.6% fuel-2.4% fuel-3.1%  </cell-wise>
</indices>
```

▪ Material-wise option

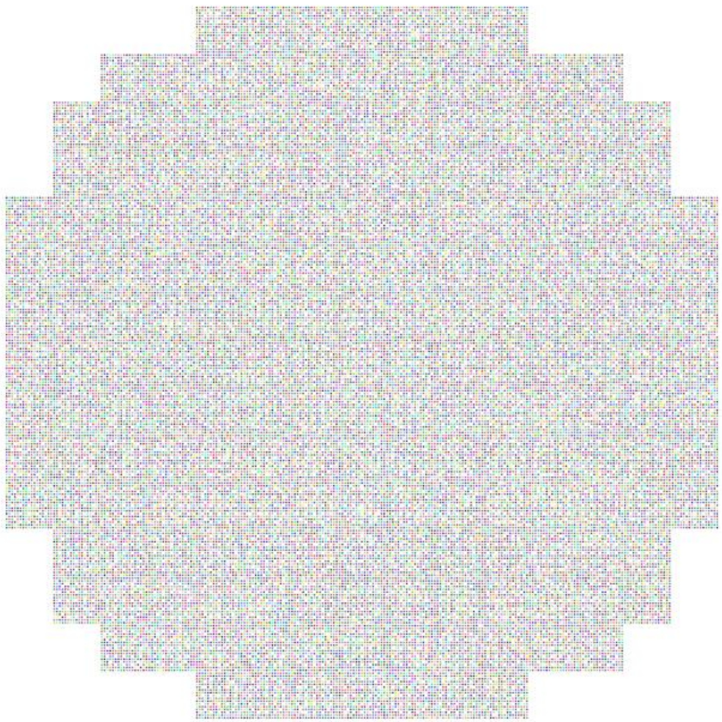
```
<indices>
    <name> tempname </name>
    <material-wise> fuel-1.6% fuel-2.4% fuel-3.1%  </material-wise>
</indices>
```

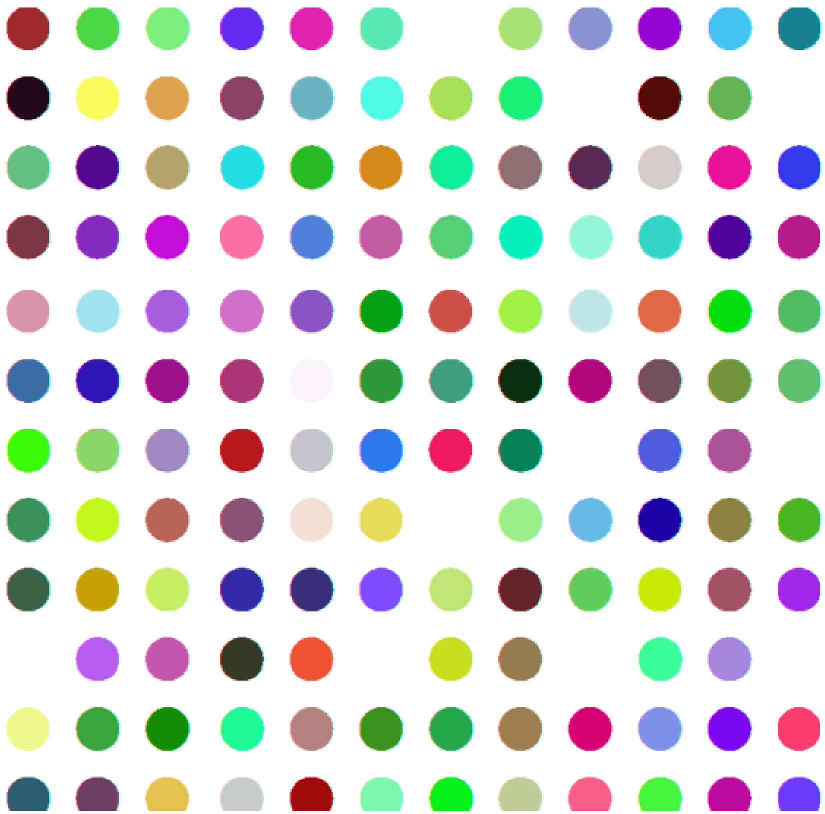




▪ Cell-wise option

```
<indices>
    <name> tempname </name>
    <cell-wise> fuel-1.6% fuel-2.4% fuel-3.1%  </cell-wise>
</indices>
```

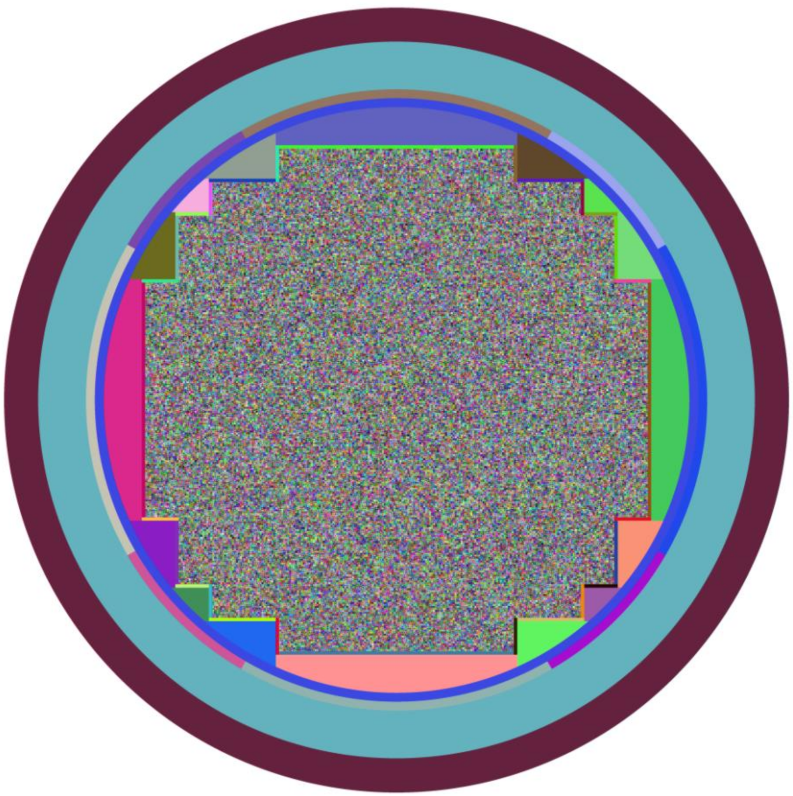


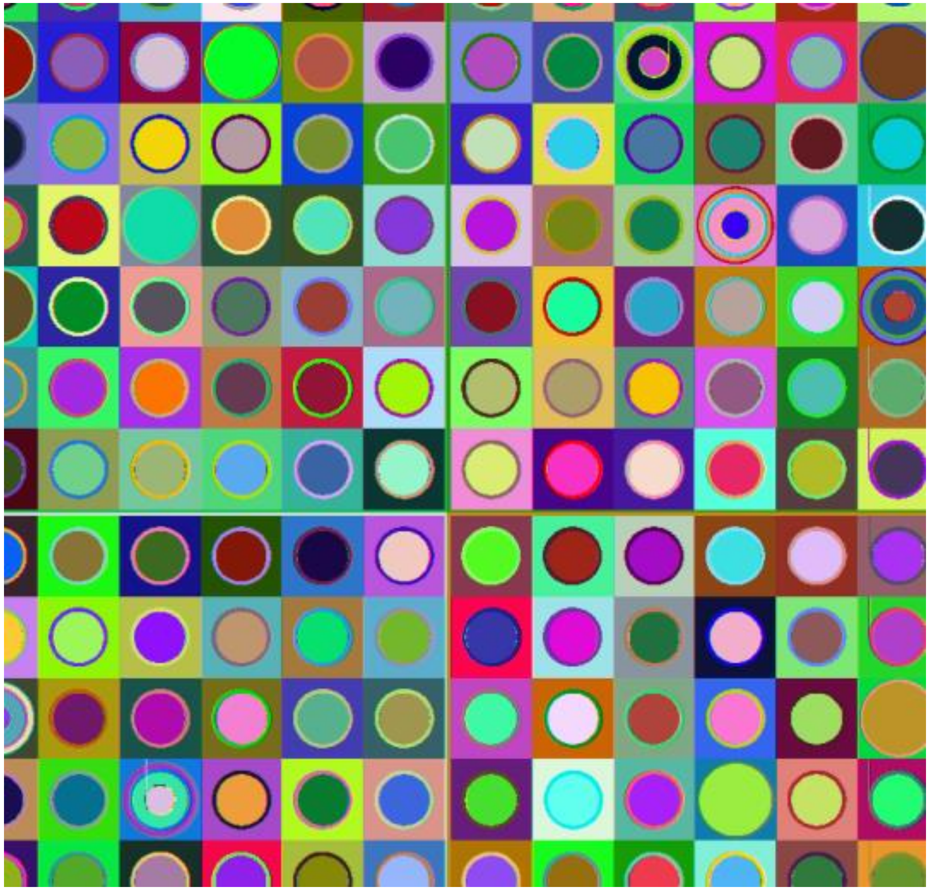


INDEX MAP FOR DEPLETION

▪ Cell-wise option

```
<indices>
    <name> tempname </name>
    <cell-wise> air bg fuel-1.6% fuel-2.4% fuel-3.1% he inconel
    ss304 clad water carbon-steel cr  </cell-wise>
</indices>
```





▪ Efficiency test with BEAVRS 3D core

- Case1: # of tally cell=0
- Case2: # of tally cell=781,662, # of tally quantity=1
- Case3: # of tally cell=781,662, # of tally quantity=10

# cells: 781,662	Case1	case2		case3	
	Time	Time	Ratio (case2/case1)	Time	Ratio (case3/case1)
MCS	1.000	1.010	1.014	1.090	1.088
MCNP6	2.430	349.0	144.0	3420	1412
Ratio (MCNP/MCS)	2.4	**344**	-	**3,148**	-

- **Efficiency test with H-M core**
  - **# of neutrons used: 10,000,000**

	Time [sec]			
# pinwise tallies	MCS	McCARD	Serpent	Serpent (w/o woodcock)
0	2,678	3,839	1,576	3,602
1	2,715	9,124	Inf.	-
5	3,131	49,651	Inf.	-

INDEXING SYSTEM

- **This index is used for**
  - **Tallies**
  - **Burnup**
  - **TH feedback**
  - **Etc..**

```
    <scoring> power </scoring>
    <estimator> track-length </estimator>
</detector>
<cell indices="pins" detector="power" /> @ pin-wise power tally
<cell indices="assms" detector="power" /> @ assembly-wise power tally
@======================

@----------------------
```

```
<burnup>
   <power> 852.75 </power>
   <indices> dep </indices>
   <eq-xe> on </eq-xe>
   <pc> semi </pc>
   <time>
                  2.3369E-04  9.0437E-01  3.4913E+00  4.0000E+00  6.0000E+00
      6.2675E+00  7.6299E+00  1.1000E+01  1.5068E+01  1.5641E+01  1.6000E+01
      2.0534E+01  2.1000E+01  2.2000E+01  2.3913E+01  2.5000E+01  3.0274E+01
      3.1000E+01  3.5212E+01  3.6000E+01  5.0535E+01  5.2000E+01  6.9000E+01
      7.7049E+01  8.0000E+01  8.5000E+01  9.6000E+01  1.0781E+02  1.1000E+02
      1.2400E+02  1.4000E+02  1.4050E+02  1.4100E+02  1.4400E+02  1.5000E+02
      1.5167E+02  1.5200E+02  1.5600E+02  1.6400E+02  1.7400E+02  1.7545E+02
      1.7700E+02  1.8000E+02  1.9000E+02  2.0333E+02  2.0400E+02  2.1400E+02
      2.1900E+02  2.2000E+02  2.2500E+02  2.2800E+02  2.2908E+02  2.3500E+02
      2.4800E+02  2.5902E+02  2.6600E+02  2.7100E+02  2.8840E+02  2.9500E+02
      2.9600E+02  3.0181E+02  3.1000E+02  3.1790E+02  3.2600E+02  3.2700E+02
   </time>

   @ ======================================
   @ print options
   <print-mat> on </print-mat>
   <print-matlab> on </print-matlab>
   <print-eq-xe> off </print-eq-xe>
   <print-dep> off </print-dep>
   @ ======================================
</burnup>
```

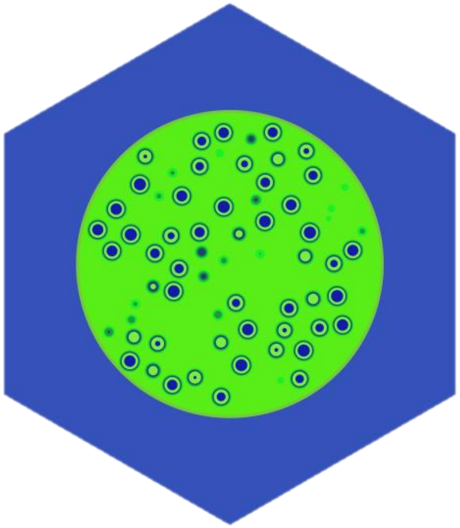
```
<th1d>
   <switch> on </switch>
   <n-axial-meshes> 10 </n-axial-meshes>
   <period> 1 </period>
   <power> 852.75 </power>
   <temperature-inlet> 293.6 </temperature-inlet>
   <radii>
      3.9218e-01
      0.40005
      0.45720
   </radii>
   <pitch> 1.26 </pitch>
   <z-meshes> 10*36.5764 </z-meshes>
   <flow> 0.335276 </flow>
   <n-th-rings> 10 </n-th-rings>
   <n-pins> 14784 </n-pins>

   <print> off </print>
   <indices> fuels clad water </indices>
   <i-temperature>
      water        1
      carbon-steel 2
   </i-temperature>
</th1d>
```

FUNCTIONS

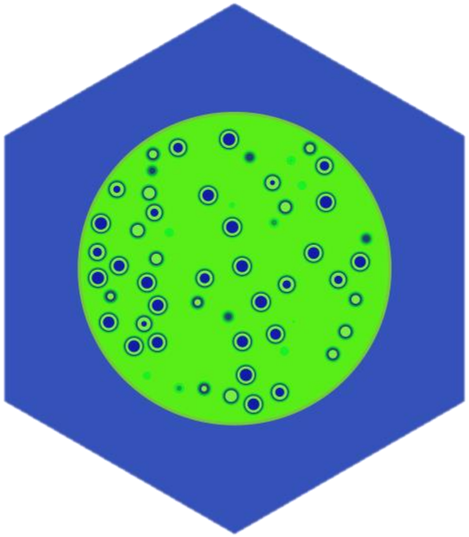
Triso Particle Random Sampling

▪ Random sampling of tris particle position

```
<universe name="triso">
    <compact type="cylinder" coeffs="0.6225 -0.5 0.5" matrix="CMP_m1">
        <triso fill="abc" radius="0.046500" pf="0.2350" />
    </compact>
    <cell name="matrix" material="CMP_m1" zone="-inf" />
    <cell name="kernel-1" fill="abc" zone="-inf" />
</universe>
```



MCS image / PF 27.5%



MCS image / PF 23.5%

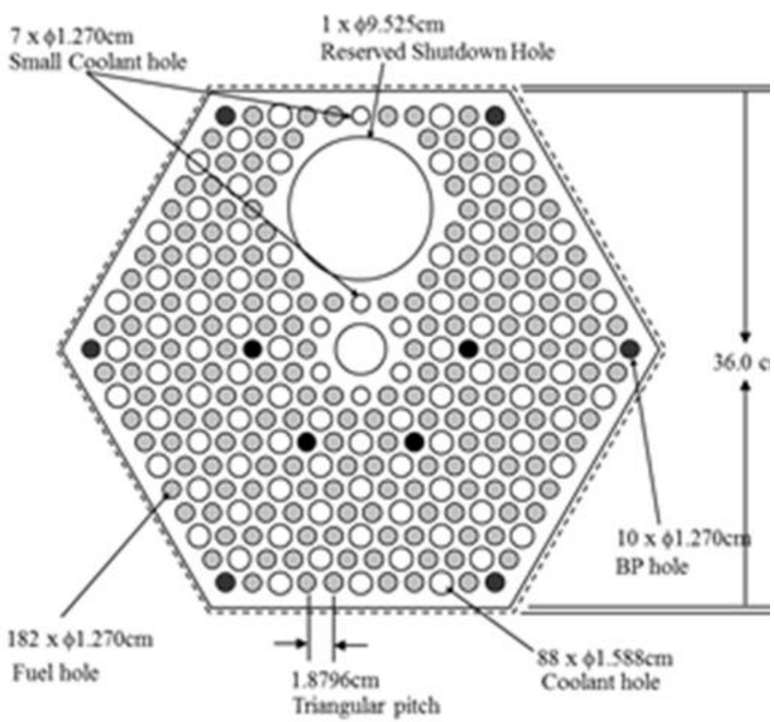
▪ PMR 200 compact

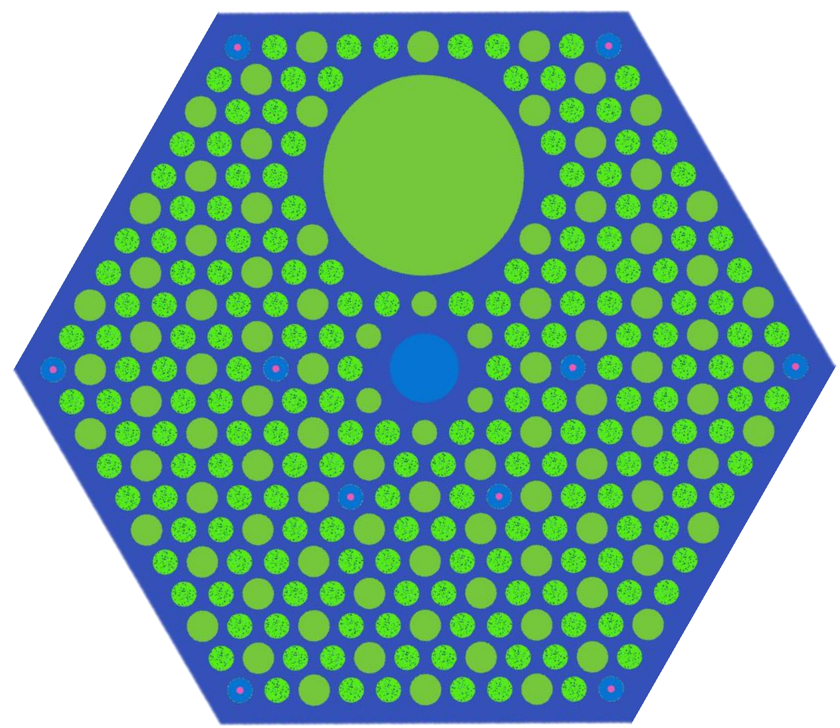
Problem	PMR 200 compact										
# of histories	2,200,000 (10 inactive / 100 active/ 20000 histories per cycle)										
# of process	1										
PF	MCS			McCARD				Serpent			
	keff	SD	Time [min]	keff	SD	Time [min]	Diff [pcm]	keff	SD	Time [min]	Diff [pcm]
0.1235	1.52746	0.00053	30.2	1.52817	0.00058	115.0	71.0	1.52638	0.00034	20.8	-108.0
0.2350	1.34252	0.00060	25.3	1.34469	0.00052	176.6	217.0	1.34385	0.00040	16.3	133.0
0.3235	1.24548	0.00053	23.6	1.24660	0.00051	239.1	112.0	1.24770	0.00038	16.0	222.0

PERFORMANCE EVALULATION

▪ PMR BLOCK

Block (PF=27.5)						
	McCARD (k-inf)	std (pcm)	Time (s)	MCS (k-inf)	std (pcm)	Time (s)
T=300	1.18823	29	**7876**	1.18531	26	**1347**
T=1500	1.00151	27	**8352**	0.99575	24	**1409**





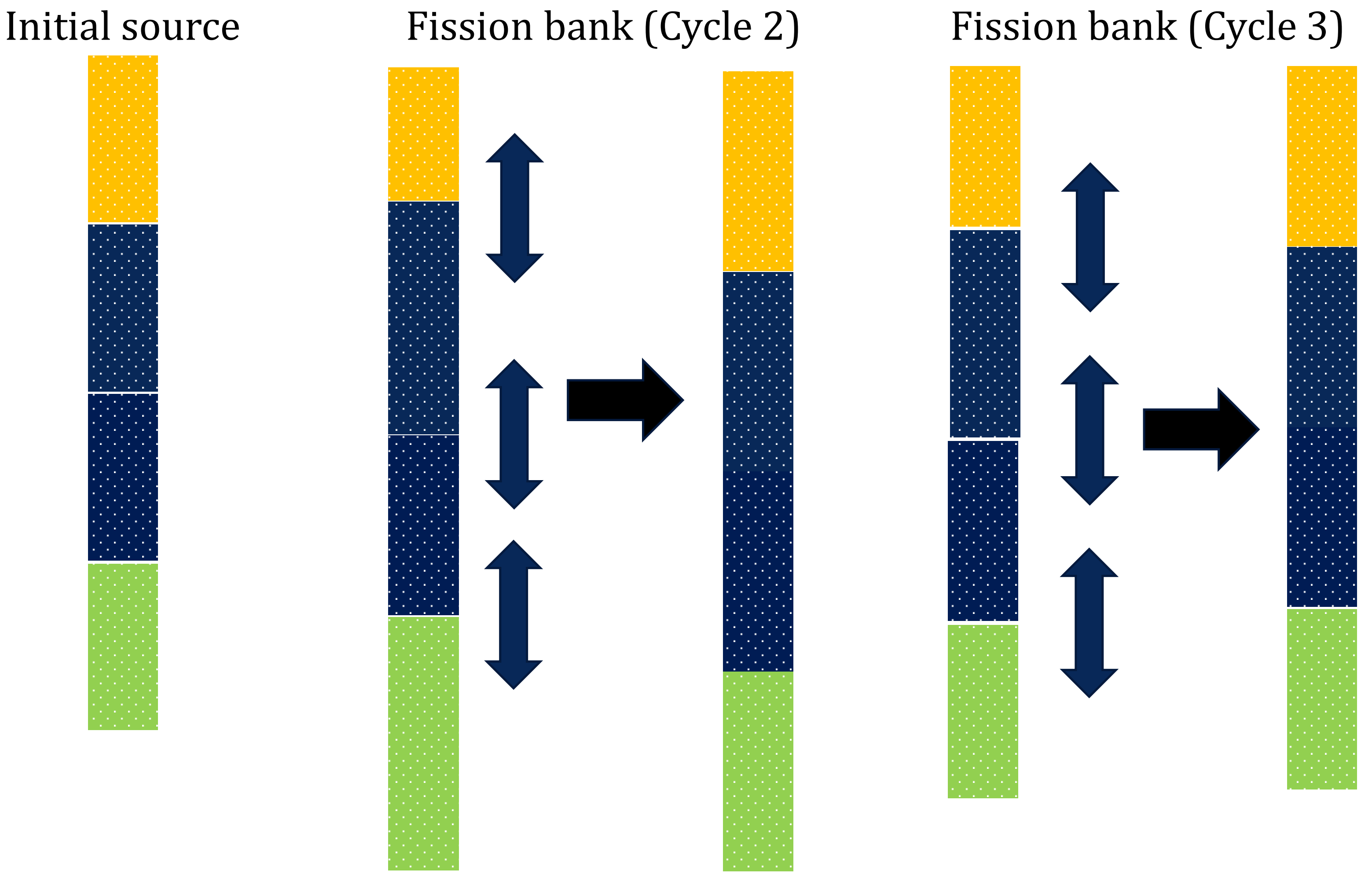
FUNCTIONS

Parallel Fission Bank

PARALLEL EFFICIENCY

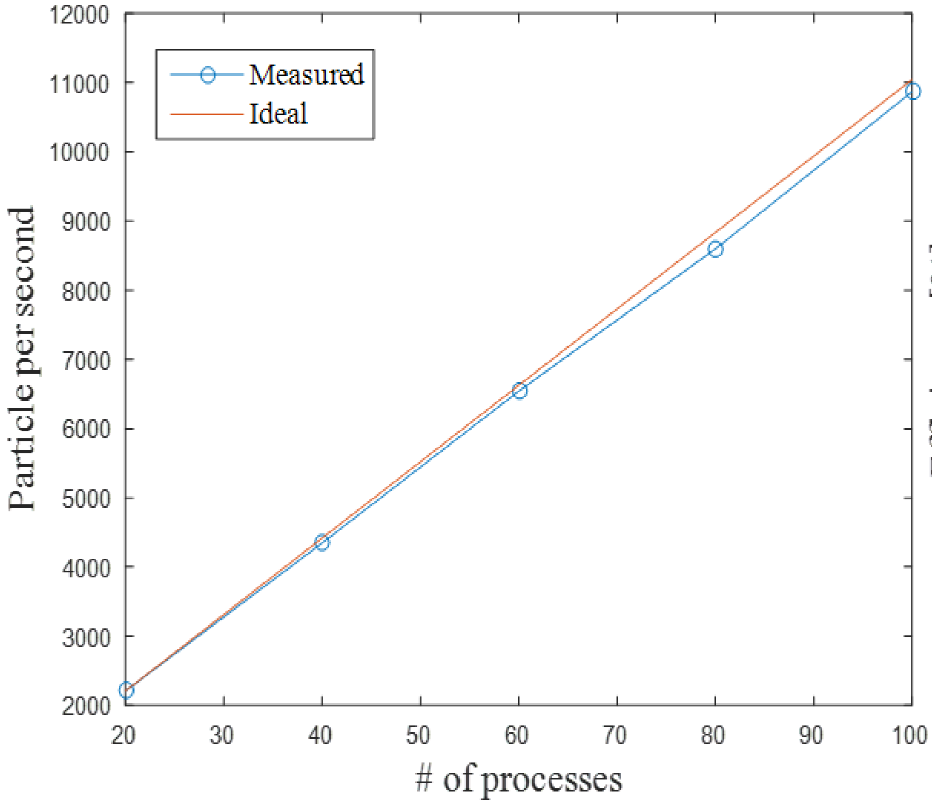
▪ Parallel fission bank

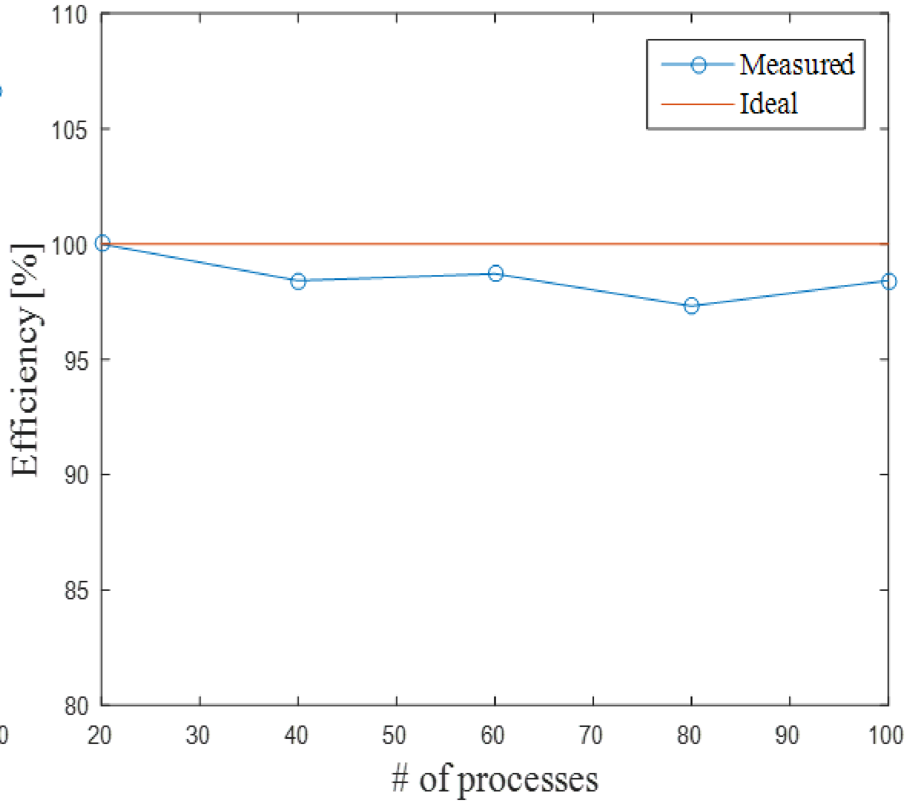
- Paul K. Romano "Parallel algorithm for Monte Carlo Particle Transport Simulation on Exascale Computing Architectures," Ph. D. thesis



PARALLEL EFFICIENCY

- **Test condition**
  - **BEAVRS benchmark**
  - **Parallel efficiency was tested with linux cluster (Intel Xeon CPUX5680)**





V&V

V&V

- **Criticality Safety Analysis (CSA) – ICSBEP**
- **VENUS-2**
- **Hoogenboom-Martin Benchmark**
- **BEAVRS benchmark**
- **KN-12 Cask**

V&V

Criticality Safety Analysis
ICSBEP

Criticality Safety Analysis

- **The purpose of the criticality safety analysis (CSA)**
  - **Spent fuel pools (SFPs) rack and Storage casks**
  - **Validation for 279 critical benchmark experiments selected from ICSBEP 2015**
  - **Verification through the comparison with proven reactor analysis codes (MCNP6 and SERPENT2)**
  - **Establishment of Upper Safety Limit (USL) for MCS code**
  - **Area of Applicability (AOA) is defined according to "NUREG/CR-6698 report[1)]" and "NET-300067-01[2)]"**
  - **279 critical benchmark selected cover all commercial LWR fuel storage rack or casks.**

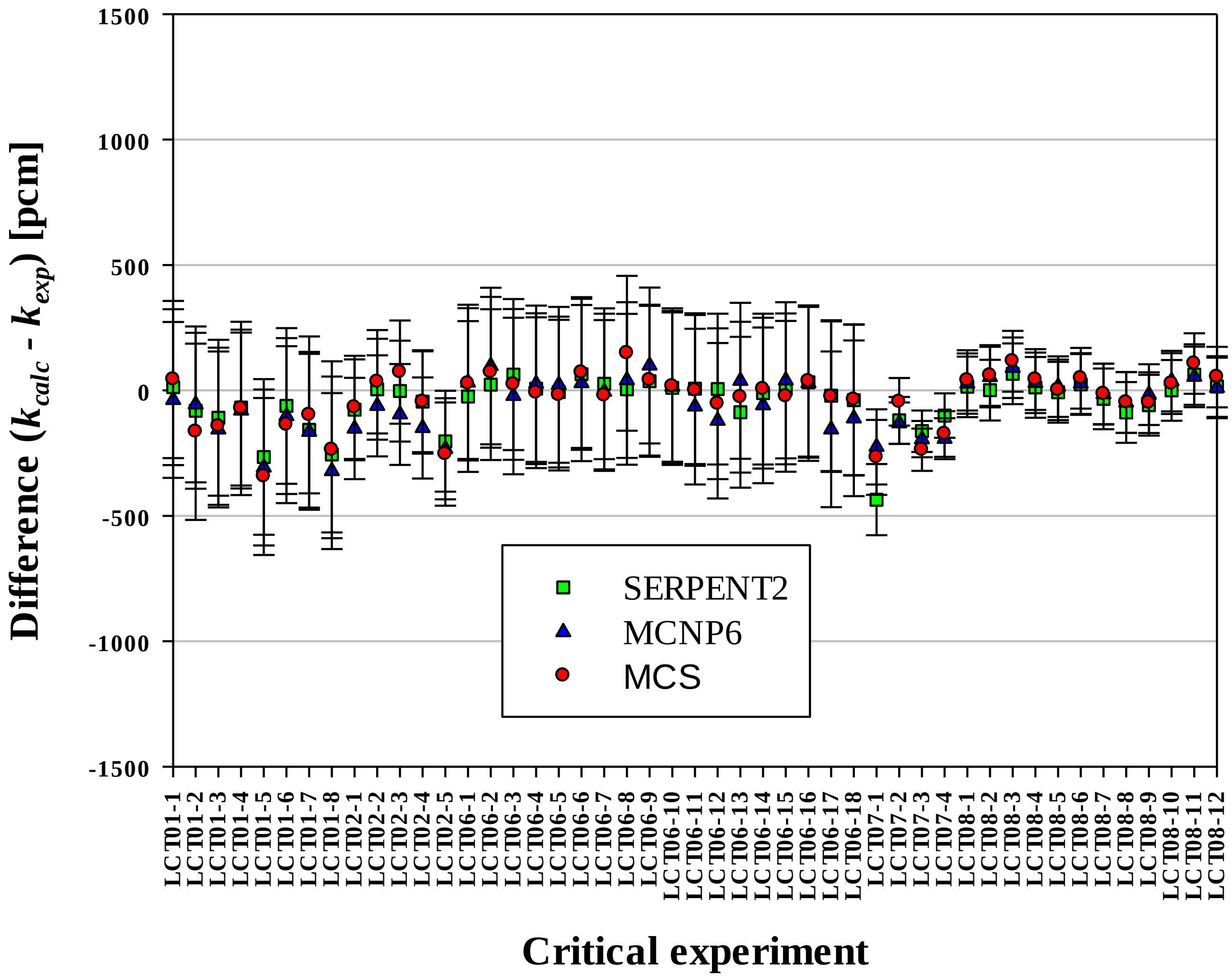
1) Guide for Validation of Nuclear Criticality Safety Calculational Methodology, NUREG/CR-6698, U.S. national Regulatory Commission, January 2001.
2) Criticality Safety Analysis of the Indian Point Unit 2 Spent Fuel Pool with Credit for Inserted Neutron Absorber Panels, NETCO Report NET-300067-01, Rev. 1.

Area of Applicability (AOA)

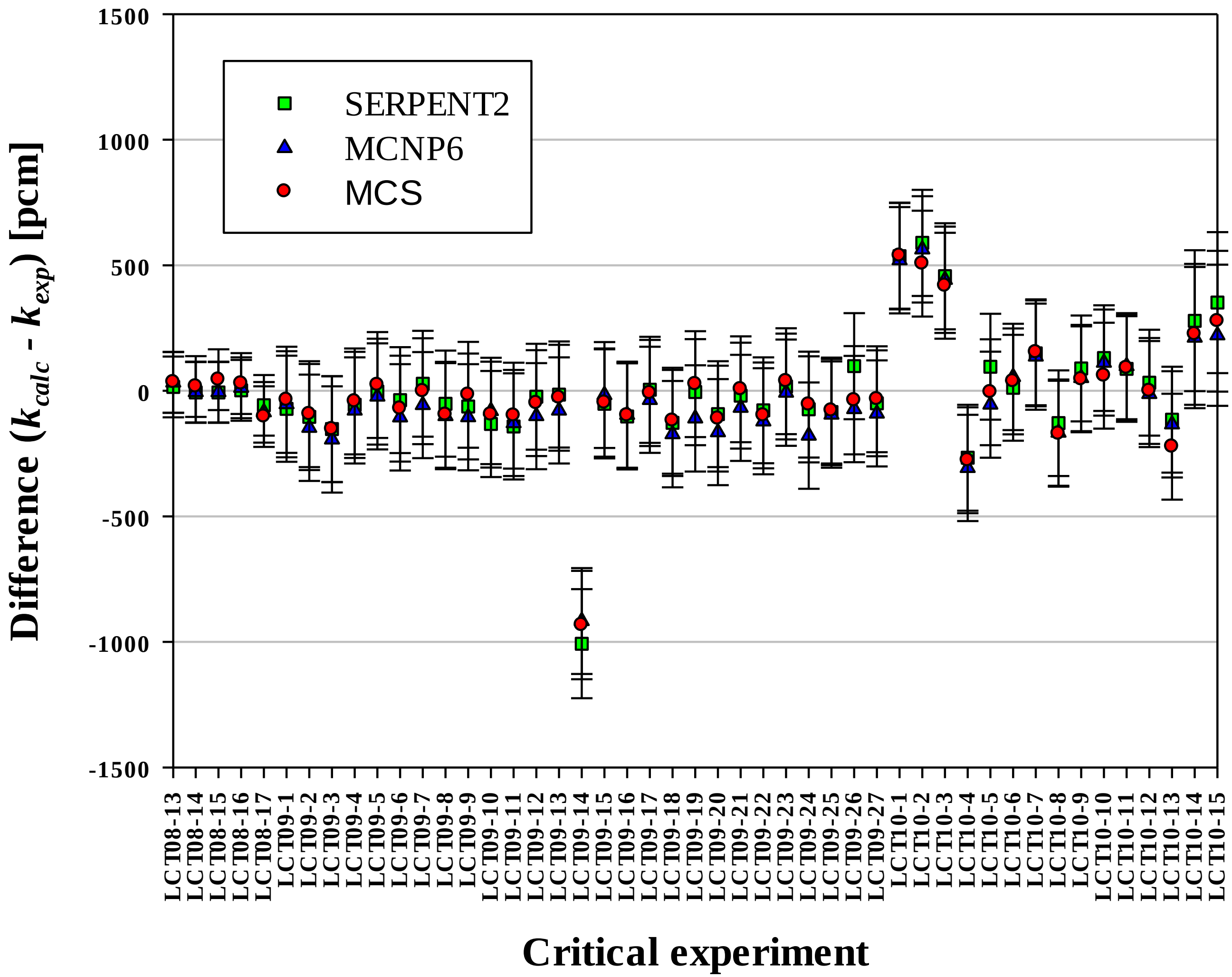
- **Representative of the usual range of physical conditions met in LWR spent fuel pools and storage casks**

Parameter	Range	Comments
Fissionable material	UO_2	The fuel is the same than in the benchmark experiments
Enrichment (wt% ^{235}U)	2.35 to 4.74	
Lattice type	Square	
H/U	0.4683 to 11.5398	
Lattice pin pitch (cm)	1.075 to 2.540	
Temperature (K)	289 to 298	Room temperature
Soluble boron concentration (g/L)	0.015 to 5.030	41 cases (LCT-008, LCT-011, LCT-035, LCT-050, LCT-051)
Reflector	Water, Lead, Depleted Uranium, Carbon Steel	
Moderating material	Water	The moderator in all the validation cases is water

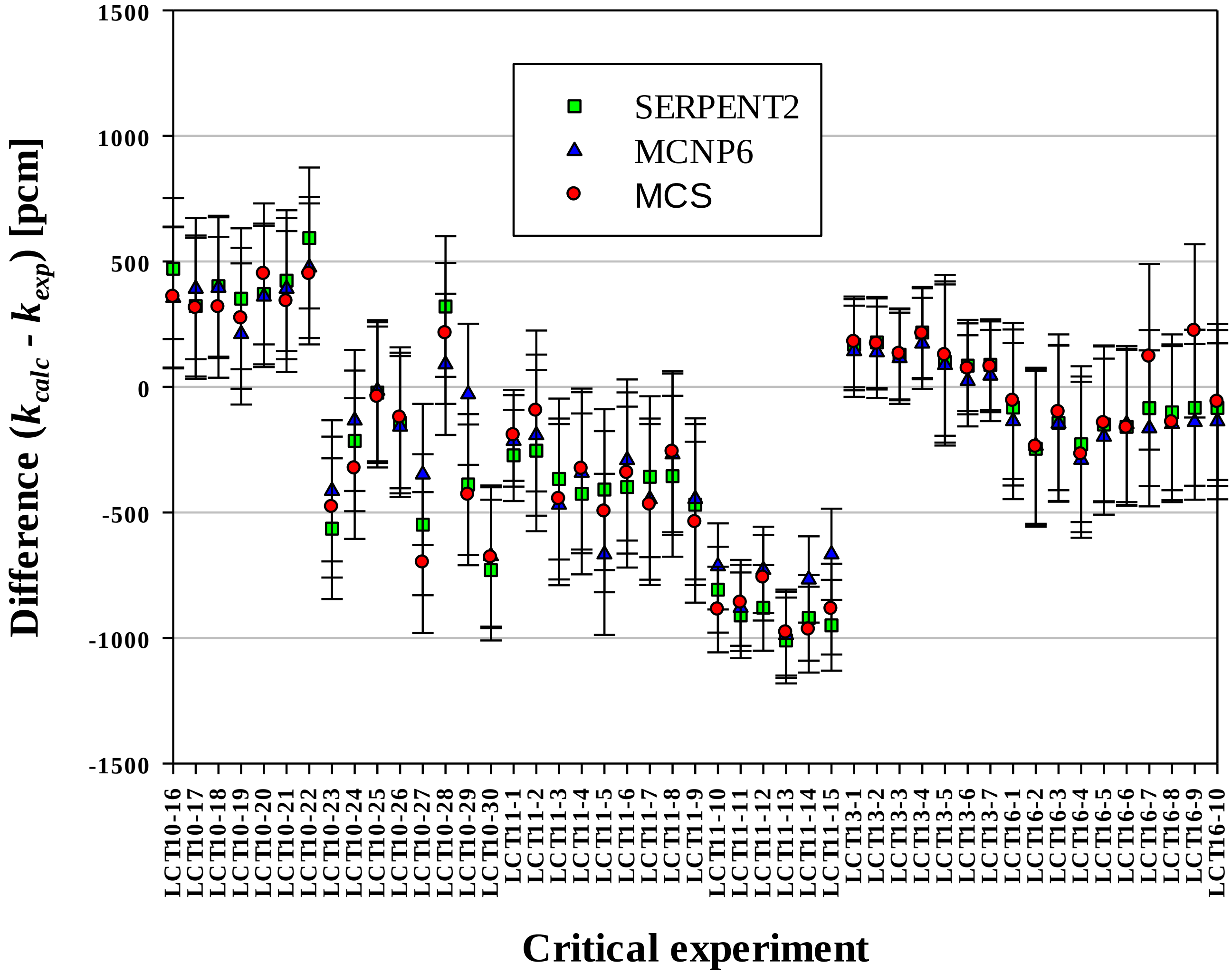
Biases on the k_{eff} for validation cases(1/6)



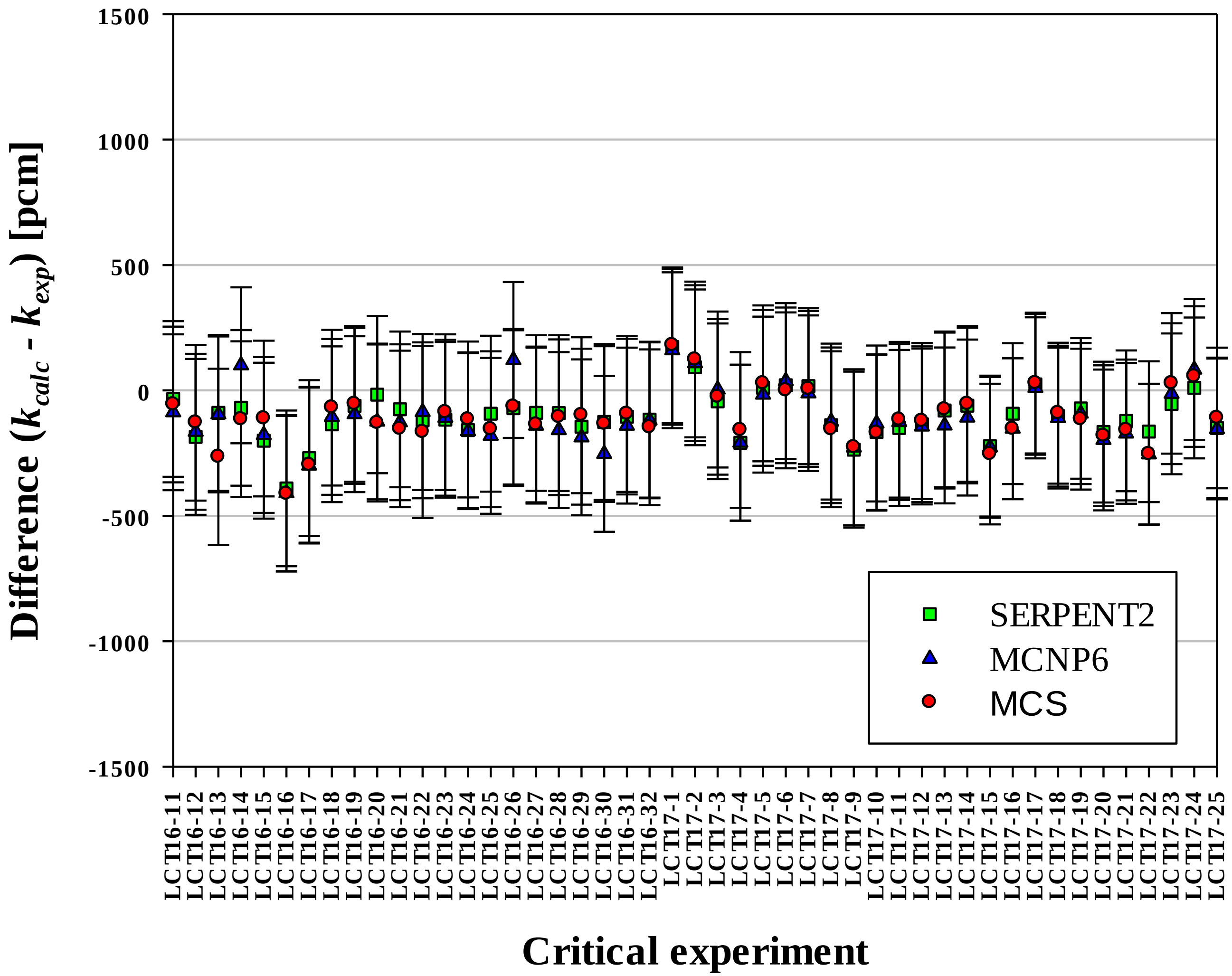
Biases on the k_{eff} for validation cases(2/6)



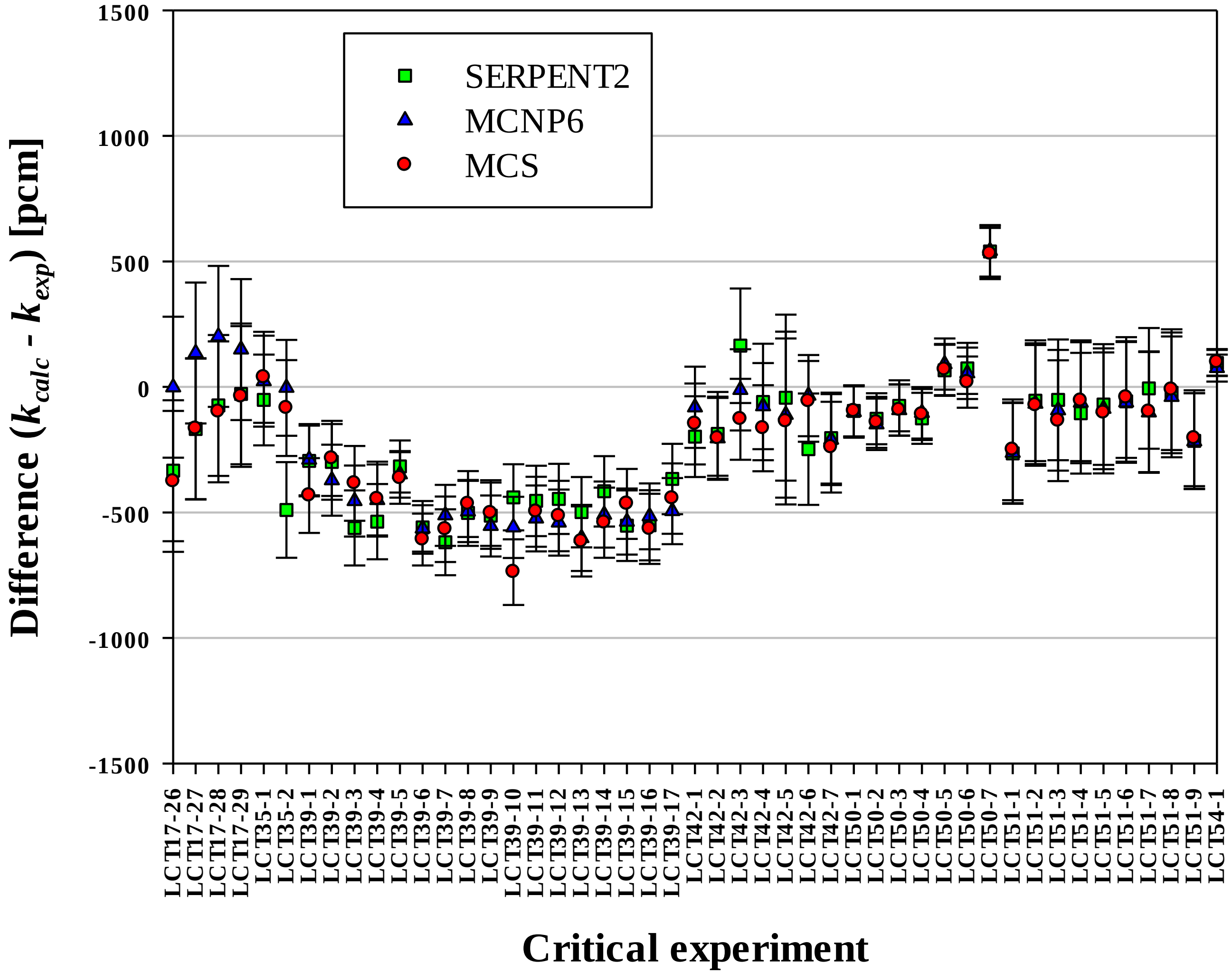
Biases on the k_{eff} for validation cases(3/6)



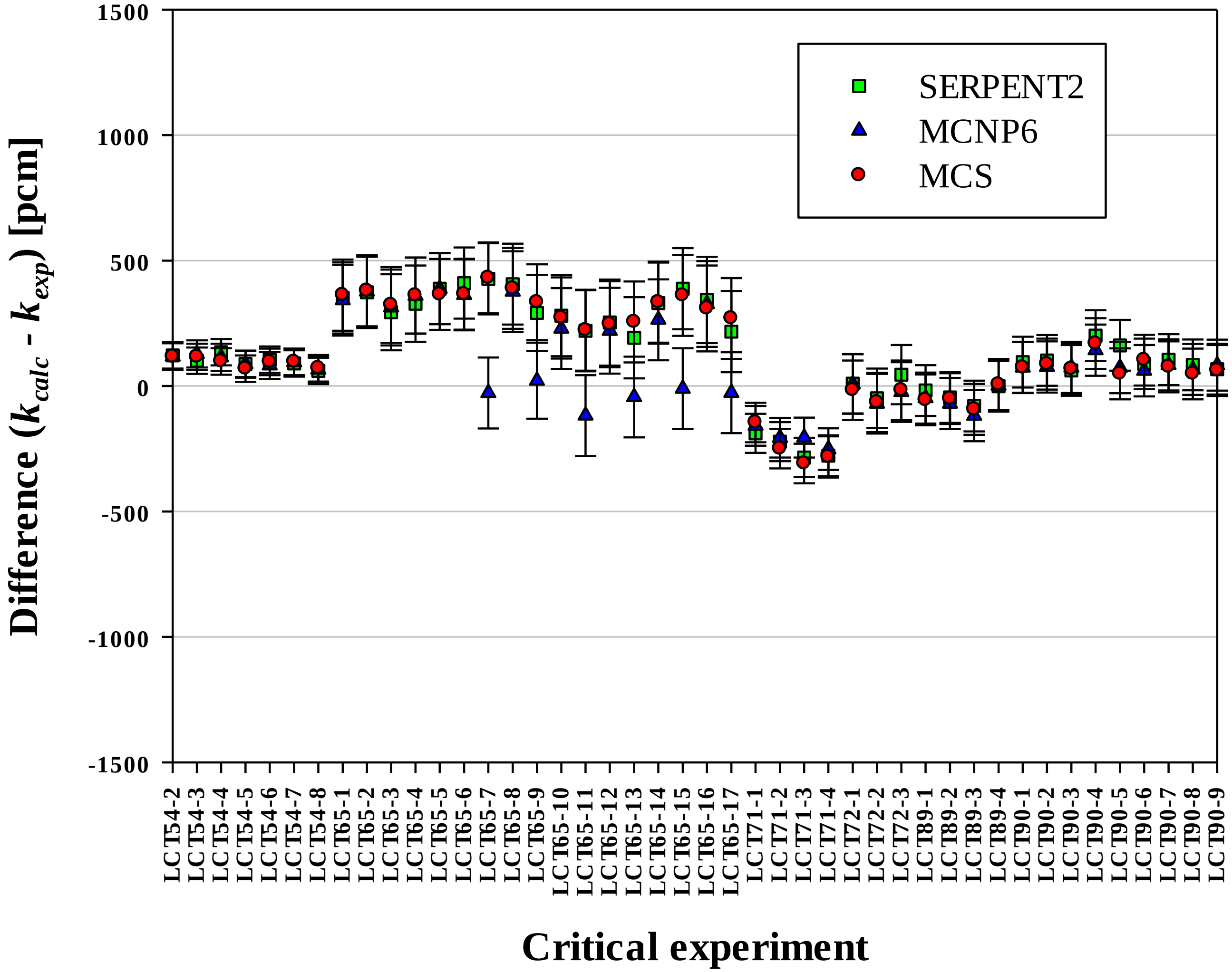
Biases on the k_{eff} for validation cases(4/6)



Biases on the k_{eff} for validation cases(5/6)



Biases on the k_{eff} for validation cases(6/6)



Summary of k_{eff}

- **Mean and standard deviation of experimental and calculated k_{eff} for all validation cases devided by all validation cases**

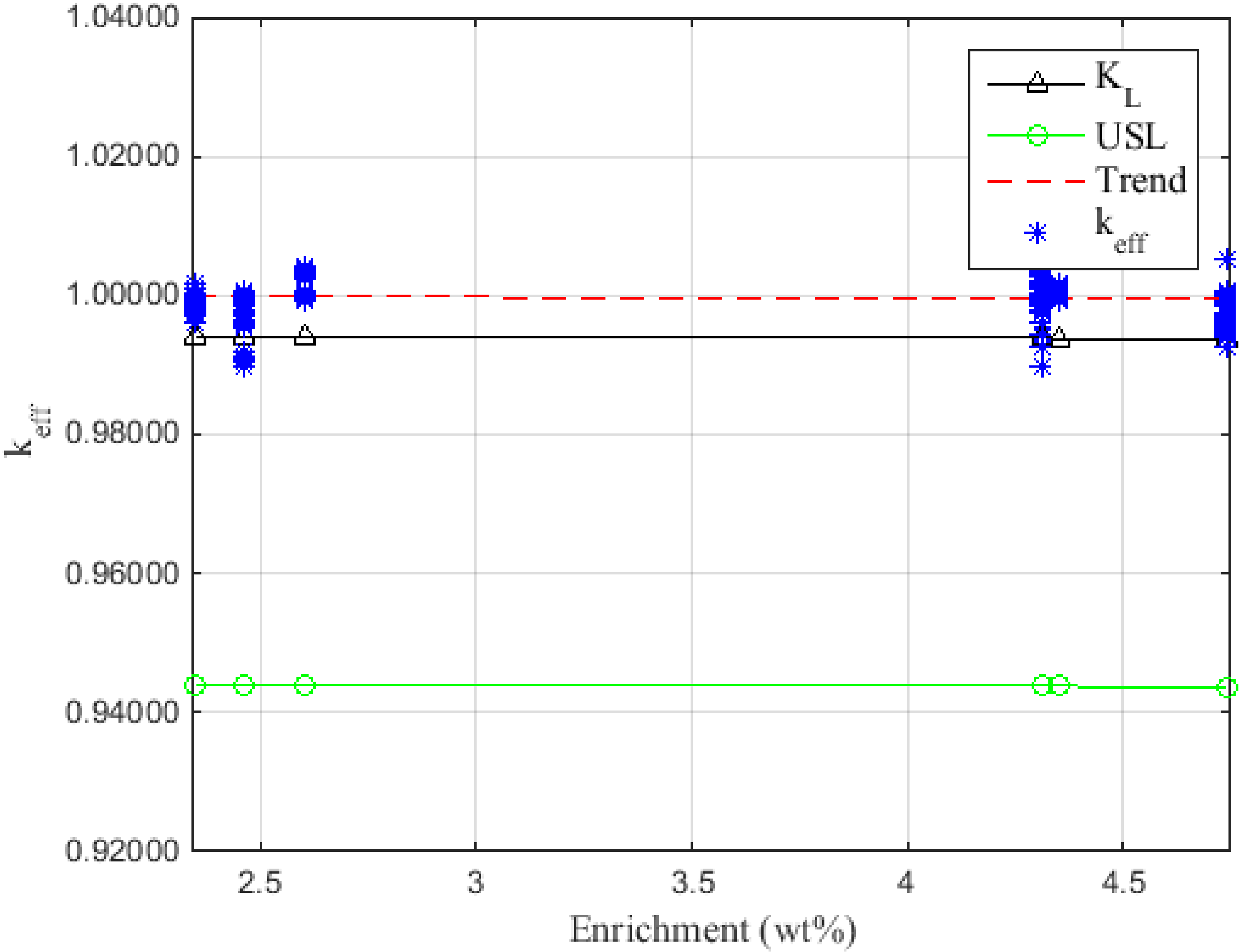
Category	Mean		$\Delta_{(calc-exp)} \pm \sigma$ (pcm)[1)]	$\Delta_{(calc-MCNP)} \pm \sigma$ (pcm)[2)]
	k_{eff}	Std.		
Experiment	1.00015	0.00214		
MCNP6	0.99944	0.00027	-72 ± 258	
MCS	0.99941	0.00021	-74 ± 263	-3 ± 69
SERPENT2	0.99932	0.00025	-83 ± 240	-12 ± 98

1) $\left(\sum_{i=1}^{\#\ of\ cases}\left(k_{eff}^{calc}-k_{eff}^{exp}\right)\right)/(\#\ of\ cases)\ \pm\left(\sum_{i=1}^{\#\ of\ cases}\left(\sqrt{\left(\sigma_{eff}^{calc}\right)^2+\left(\sigma_{eff}^{exp}\right)^2}\right)\right)/(\#\ of\ cases)$

2) $\left(\sum_{i=1}^{\#\ of\ cases}\left(k_{eff}^{calc}-k_{eff}^{MCNP6}\right)\right)/(\#\ of\ cases)\ \pm\left(\sum_{i=1}^{\#\ of\ cases}\left(\sqrt{\left(\sigma_{eff}^{calc}\right)^2+\left(\sigma_{eff}^{MCNP6}\right)^2}\right)\right)/(\#\ of\ cases)$

- **Table shows statistical of k_{eff} and the standard deviation for all critical e xperiment benchmarks, which is sum of experiment or calculated k_{eff} va lues**

USL as function of fuel enrichment

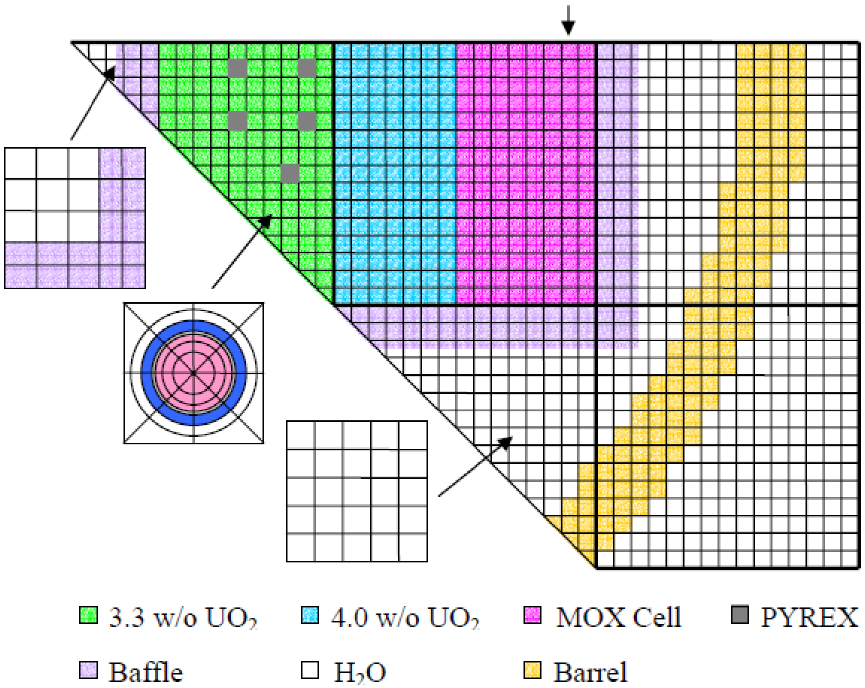


V&V

VENUS-2

▪ VENUS -2 core benchmark

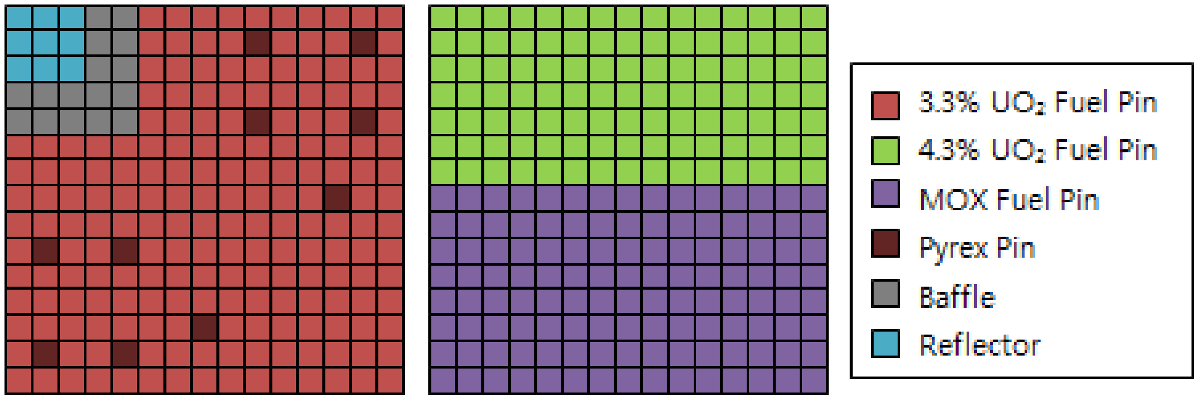
- **MOX fuel benchmark problem for validation**



Z. Zhong, T.J. Downar, H.G. Joo, J.Y. Cho, "Benchmark Analysis of the DeCART MOC Code with the VENUS-2 Critical Experiment," PHYSOR 200 4, Chicago, Illinois, April 25-29 (2004)

B.C. Na, "Benchmark on the VENUS-2 MOX Core Measurements," OECD/NEA Report, NEA/NSC/DOC (2000)7, (2000)

Verification – VENUS-2



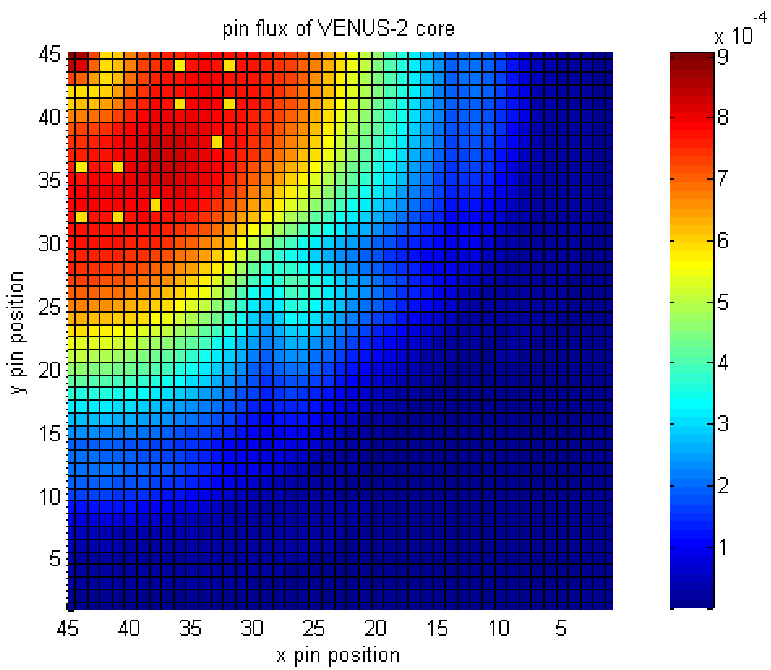
UOX Assembly　　MOX Assembly

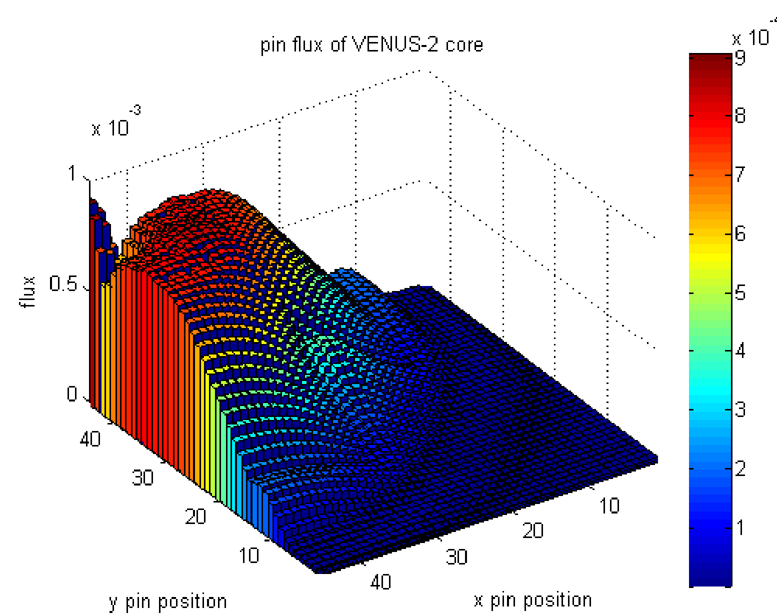
Benchmark		MCNP	MCS	Diff.
VENUS-2 Pin Cell	3.3% UO_2	1.41209	1.41182	27
		0.00008	0.00010	
	4.0% UO_2	1.34236	1.34211	25
		0.00009	0.00011	
	MOX	1.26573	1.26553	20
		0.00009	0.00010	
VENUS-2 Assembly	UOX	1.17862	1.17843	19
		0.00010	0.00010	
	MOX	1.30169	1.30155	14
		0.00009	0.00010	

Verification – VENUS-2

▪ 2D core result

codes	keff (stdev.)	library
DeCART-45g	1.08209	ENDF-B-VI
MCNP 4B	1.08277	ENDF-B-VI
MCS	1.08526 (0.00011)	ENDF-B-VII





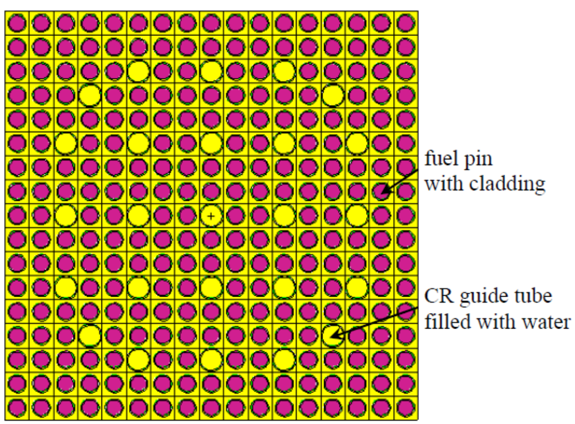
V&V

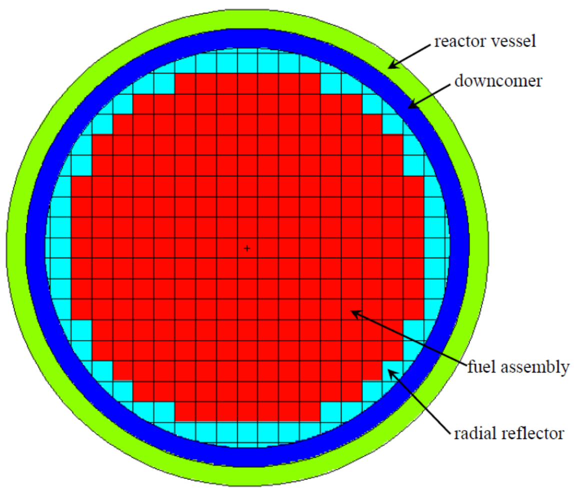
Hoogenboom Martin

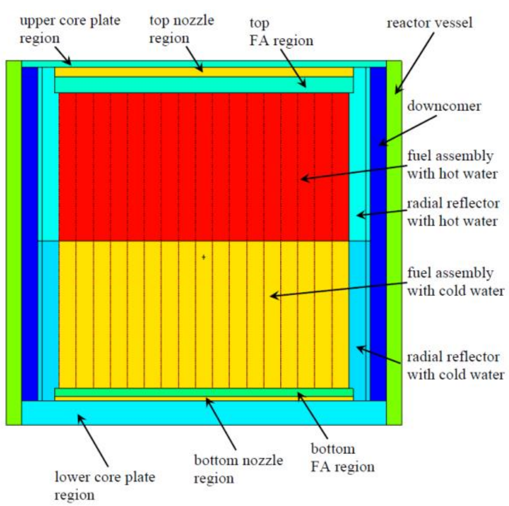
Verification - Hoogenboom

▪ Hoogenboom benchmark

- 200/450/100,000 : inactive/active/history per cycle
- Flux tally: 357x357 = 127449
- Fission rate tally: 357x357 = 127449





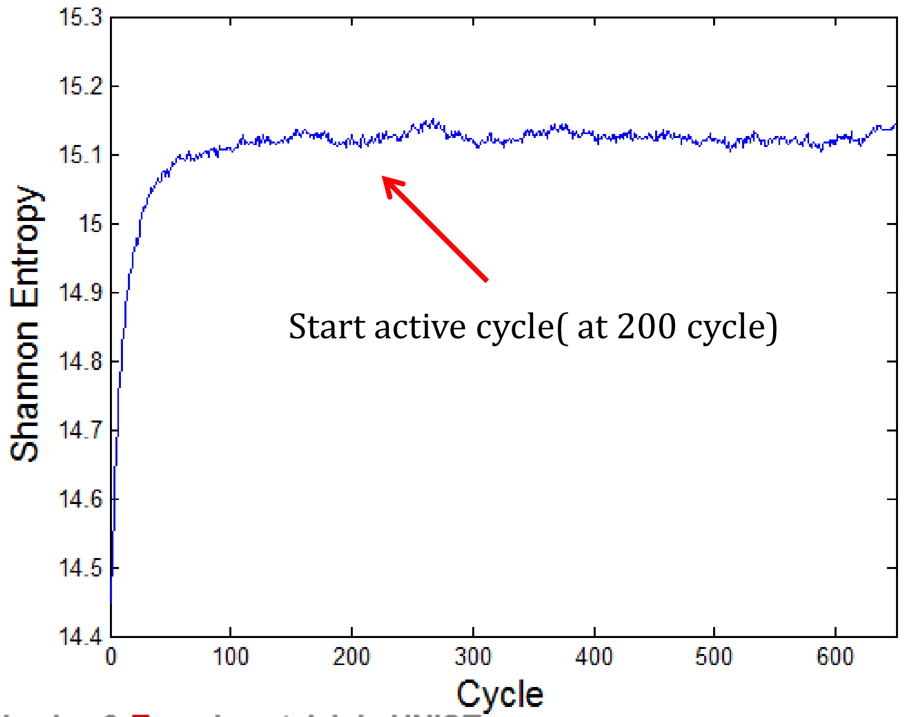


Verification – Hoogenboom-Martin

▪ Hoogenboom benchmark

- 200/450/100,000 : inactive/active/history per cycle

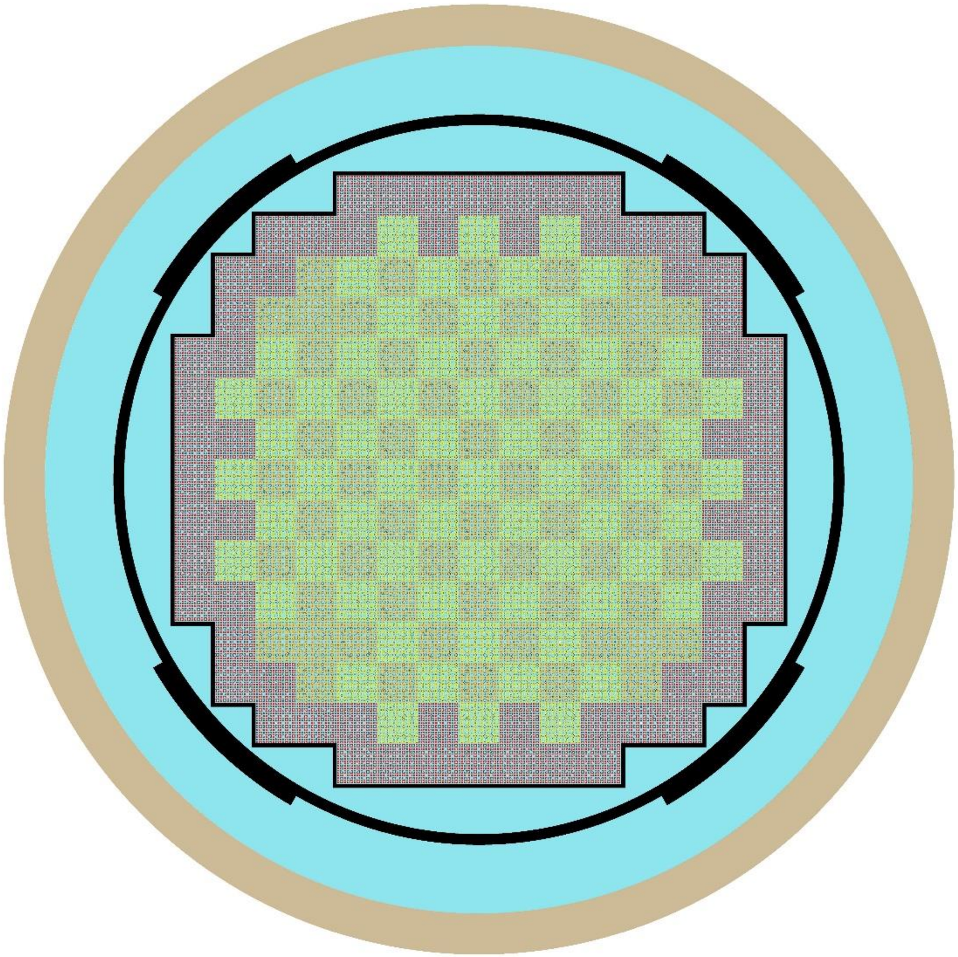
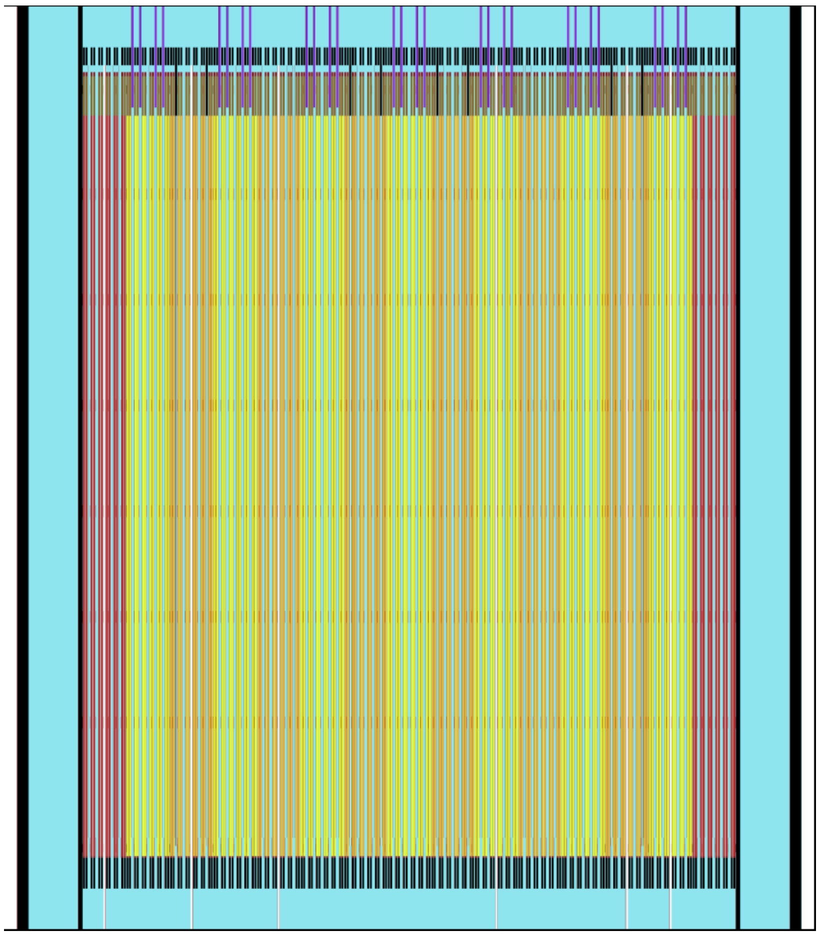
code	keff	stdev.
MCNP	1.00023	0.00006
OPENMC	1.00002	0.00006
MCS	1.00090	0.00010



V&V

BEAVRS

- **BEAVRS geometry generated by SCORE**

▪ Rod worth and keff

	MCS		Rod worth			
	keff	STD	MCS	measured	OpenMC	nTRACER
ARO	0.99819	0.00007		-	-	-
D in	0.99060	0.00006	786	788	776	771
C in	0.97856	0.00007	1249	1203	1210	1234
B in	0.96652	0.00007	1221	1171	1230	1197
A in	0.96224	0.00007	545	548	535	556
SE in	0.95872	0.00007	492	461	455	501
SD in	0.95155	0.00007	811	772	-	-
SC in	0.94164	0.00007	1102	1099	-	-

ITC

- 566.6K and 580K were used
- ACE cross section data were generated at exact temperature
- Thermal expansion of water was considered (water only)
- Density at 580K was calculated with STEAM TABLE and MCS uses the density with red color

	STEAM TABLE		BEAVRS	
T [K]	Pressure [psia]	Density [g/cm3]	Density w/o B [g/cm3]	Density w/ B [g/cm3]
566.6	2250	0.73980	0.73979	0.74058
580	2250	0.71156	0.71155	**0.71231**

- **DBRC for all nuclide which has more than 200 atomic weight**

Condition		Keff at 566.6K		Keff at 580K		ITC	STD	Measured	Diff [%]
ARO	No Upscattering	0.99818	6.42E-06	0.99783	9.22E-06	-1.46	0.05	-1.75	17%
	DBRC	0.99774	9.30E-06	0.99735	8.86E-06	-1.62	0.05	-1.75	7%
D in	No Upscattering	0.99974	1.26E-05	0.99907	1.26E-05	-2.78	0.07	-2.75	-1%
	DBRC	0.99933	1.29E-05	0.99859	1.27E-05	-3.07	0.08	-2.75	-12%
C in	No Upscattering	0.99891	1.29E-05	0.99699	1.32E-05	-7.99	0.08	-8.01	0%
	DBRC	0.99844	1.27E-05	0.99653	1.29E-05	-7.96	0.08	-8.01	1%

Detector Signal

▪ Fission chambers in IT

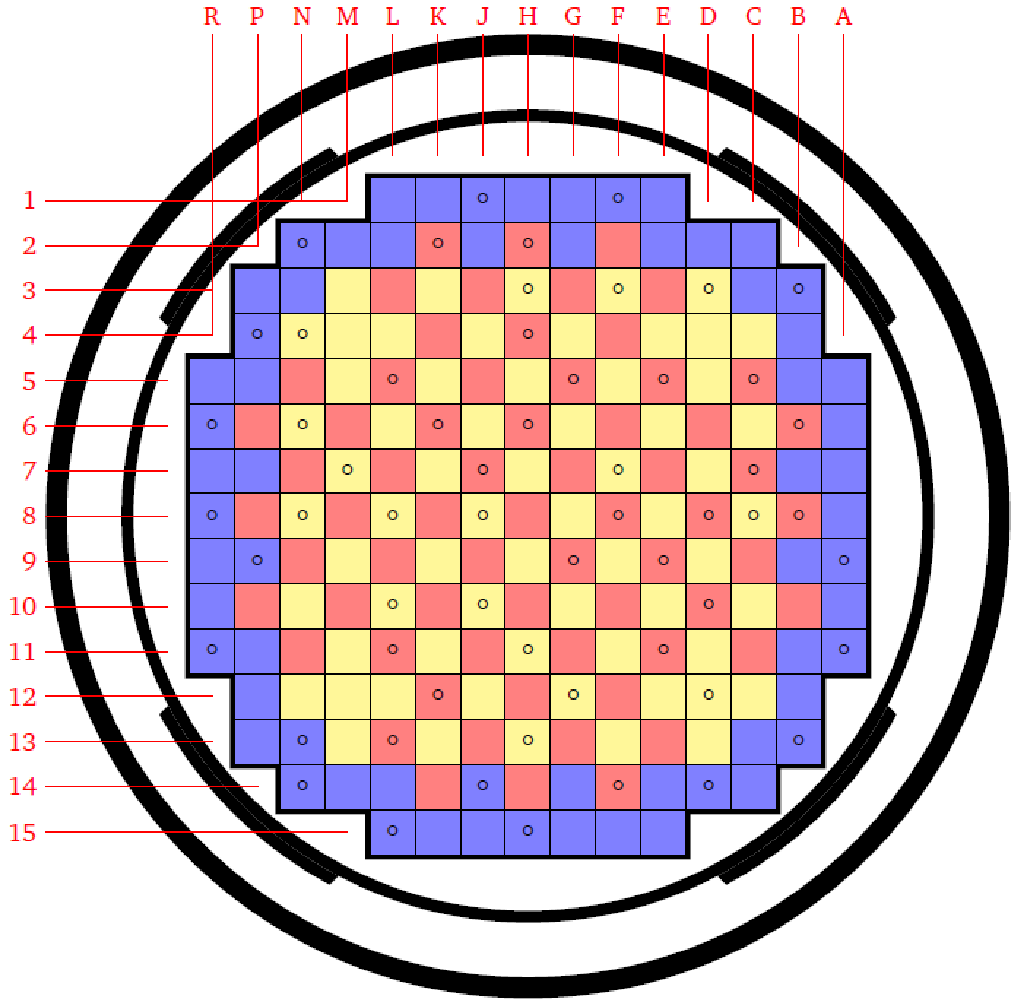


Figure 28: Instrument tube positions. Source: 43

Detector Signal

- **Statistical error is < 0.2 %**
- **Rms: 4.85%**

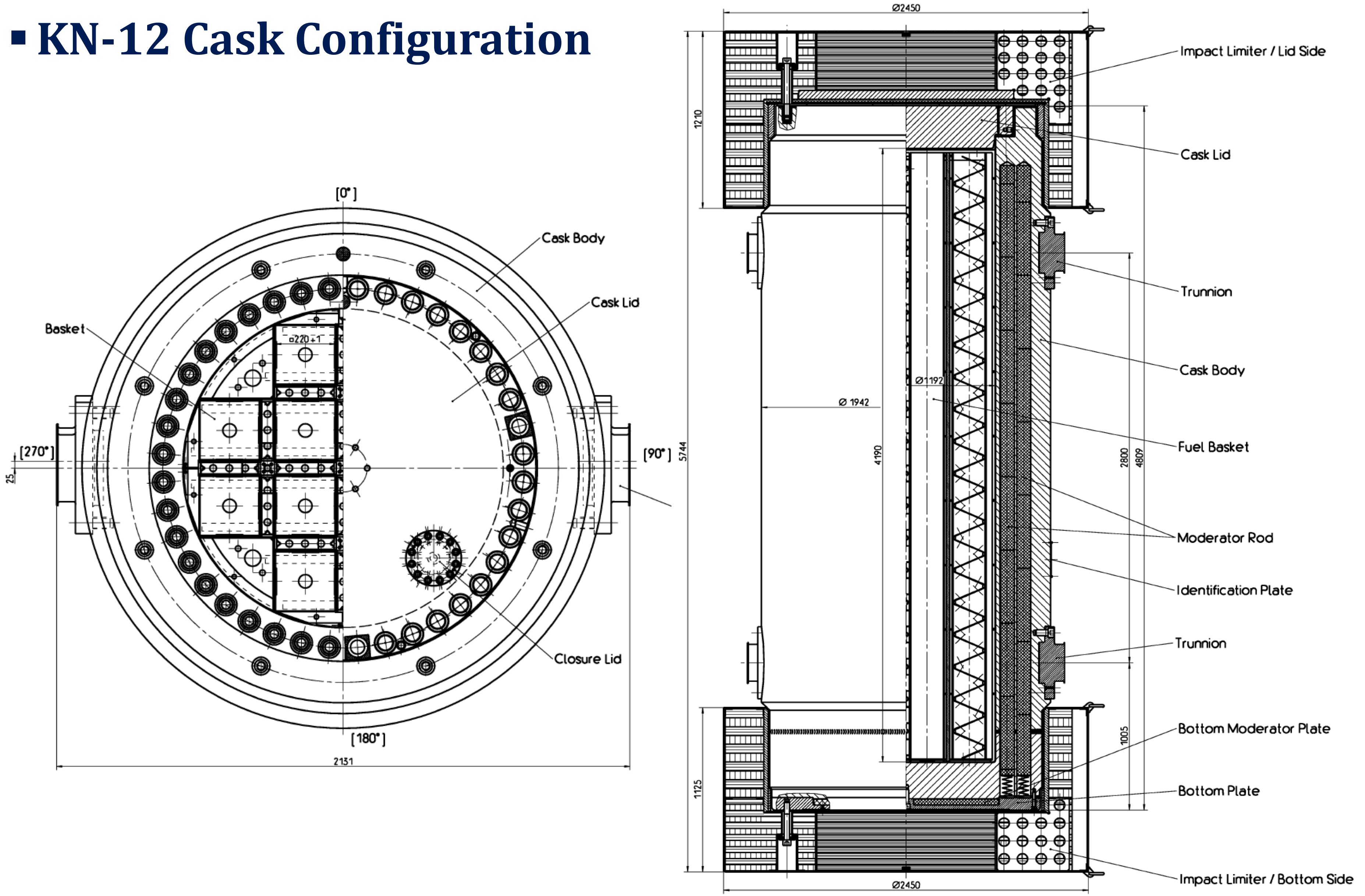
	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1	Tallied Measured C/E-1 [%]				- - -	- - -	0.789 0.777 1.462	- - -	- - -	0.710 0.699 1.547	- - -				
2			0.692 0.645 6.770	- - -	- - -	1.256 1.171 6.731	- - -	1.255 1.223 2.577	- - -	- - -	- - -	- - -	- - -		
3		- - -	- - -	- - -	- - -	- - -	- - -	0.933 0.898 3.766	- - -	0.975 0.965 0.990	- - -	1.193 1.171 1.856	- - -	0.694 0.689 0.733	
4		0.928 0.845 8.920	1.184 1.115 5.791	- - -	- - -	- - -	- - -	1.162 1.115 4.017	- - -	- - -	- - -	- - -	- - -	- - -	
5	- - -	- - -	- - -	- - -	1.263 1.165 7.734	- - -	- - -	- - -	1.167 1.129 3.287	- - -	1.276 1.247 2.293	- - -	1.363 1.320 3.130	- - -	- - -
6	0.702 0.670 4.604	- - -	0.966 0.920 4.780	- - -	- - -	1.156 1.102 4.682	- - -	1.085 1.042 3.971	- - -	- - -	- - -	- - -	- - -	1.264 1.239 1.981	- - -
7	- - -	- - -	- - -	0.959 0.924 3.685	- - -	- - -	1.036 1.008 2.726	- - -	- - -	0.912 0.892 2.210	- - -	- - -	1.207 1.204 0.275	- - -	- - -
8	0.752 0.730 2.975	- - -	0.928 0.899 3.111	- - -	0.933 0.918 1.585	- - -	0.788 0.774 1.791	- - -	- - -	1.087 1.088 -0.073	- - -	1.172 1.185 -1.108	0.941 0.966 -2.647	1.266 1.295 -2.290	- - -
9	- - -	0.850 0.837 1.505	- - -	- - -	- - -	- - -	- - -	- - -	1.044 1.071 -2.617	- - -	1.171 1.175 -0.320	- - -	- - -	- - -	0.798 0.846 -6.037
10	- - -	- - -	- - -	- - -	0.979 0.964 1.519	- - -	0.909 0.920 -1.212	- - -	- - -	- - -	- - -	1.224 1.291 -5.486	- - -	- - -	- - -
11	0.572 0.576 -0.672	- - -	- - -	- - -	1.268 1.263 0.400	- - -	- - -	0.939 0.968 -3.128	- - -	- - -	1.276 1.330 -4.271	- - -	- - -	- - -	0.582 0.631 -8.471
12		- - -	- - -	- - -	- - -	1.214 1.223 -0.732	- - -	- - -	0.968 1.034 -6.805	- - -	- - -	1.338 1.438 -7.494	- - -	- - -	
13		- - -	0.840 0.857 -2.059	- - -	1.355 1.339 1.154	- - -	- - -	0.939 0.984 -4.799	- - -	- - -	- - -	- - -	- - -	0.695 0.792 -13.916	
14			0.686 0.700 -2.005	- - -	- - -	- - -	0.858 0.919 -7.048	- - -	- - -	1.260 1.357 -7.722	- - -	0.940 1.050 -11.657	- - -		
15					0.577 0.602 -4.392	- - -	- - -	0.759 0.837 -10.262	- - -	- - -	- - -				

V&V

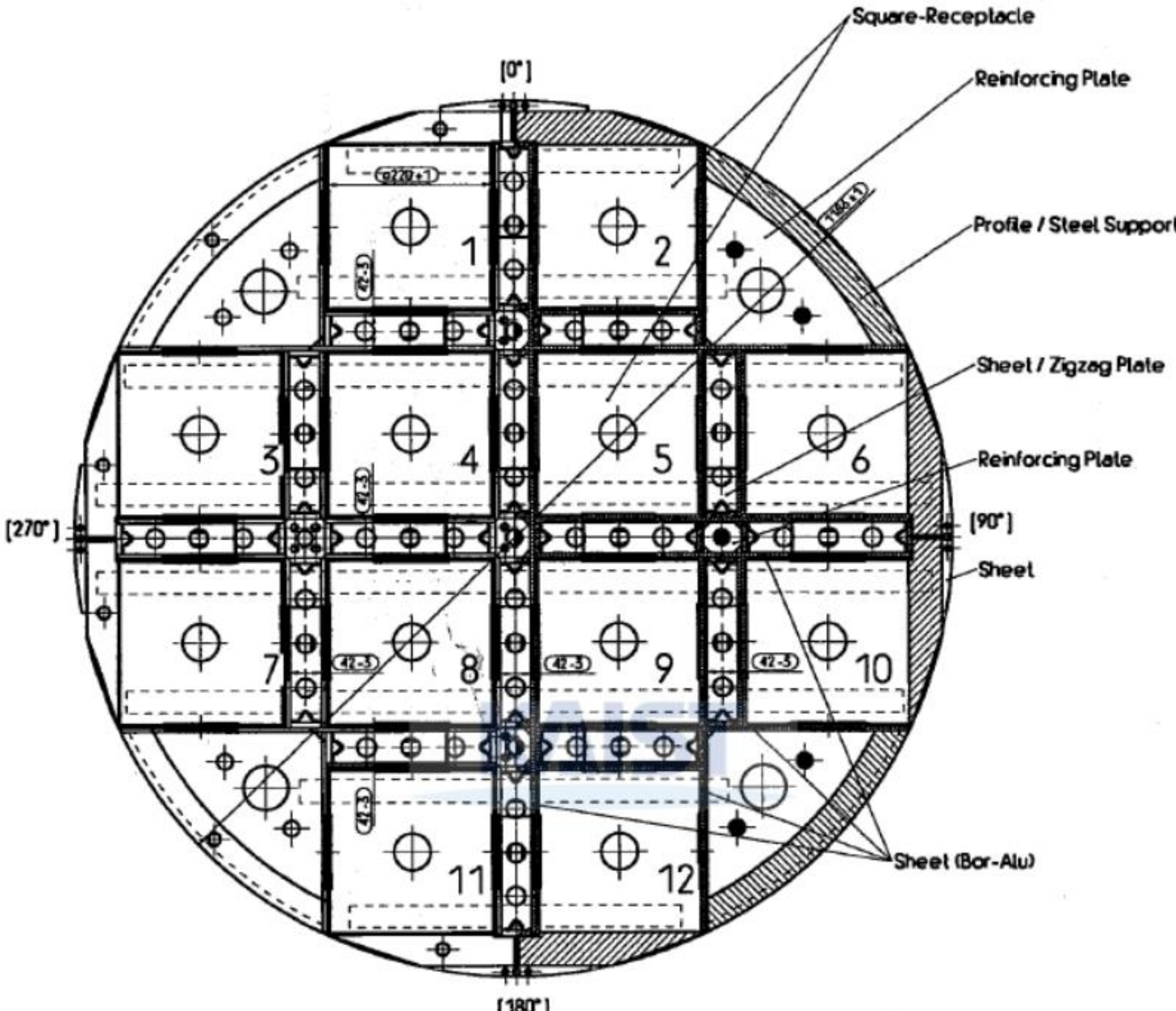
KN-12

KN-12 Transport Cask Configuration

- **KN-12 Cask Configuration**

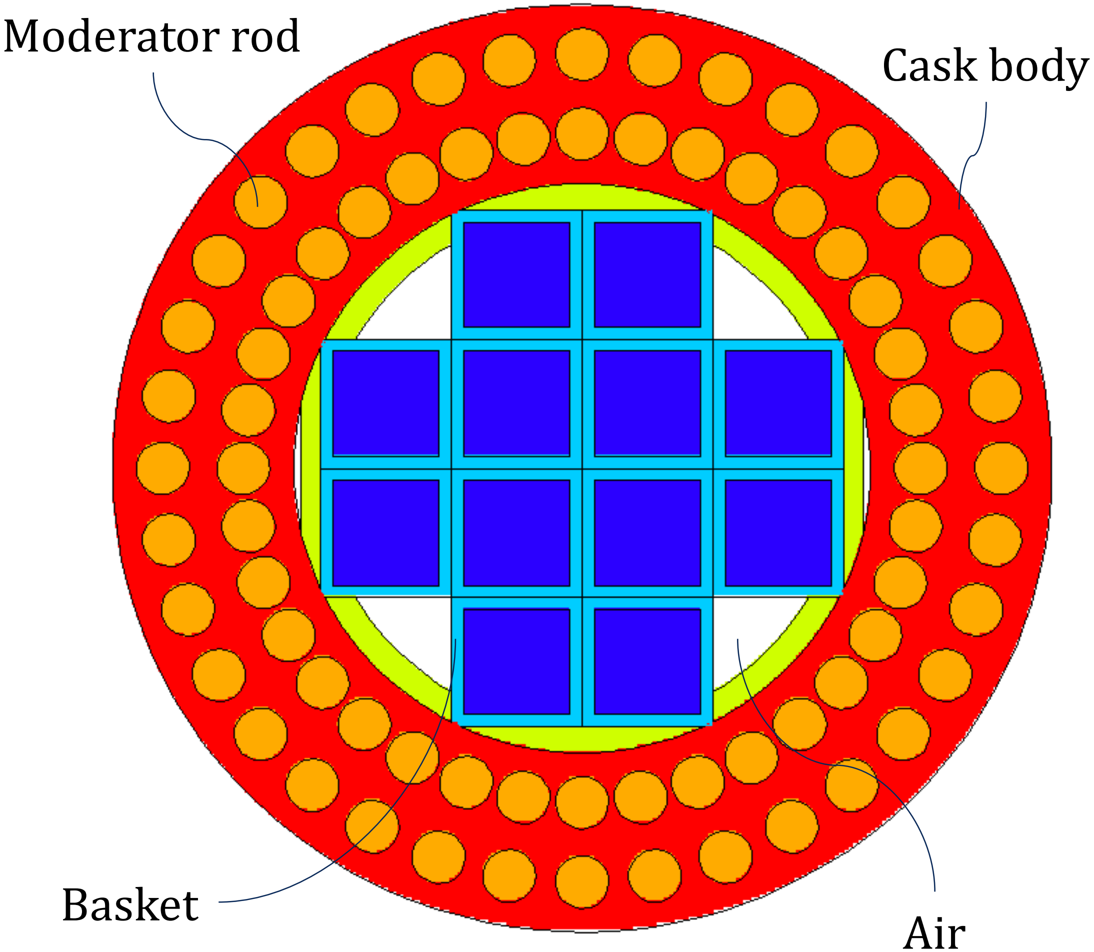


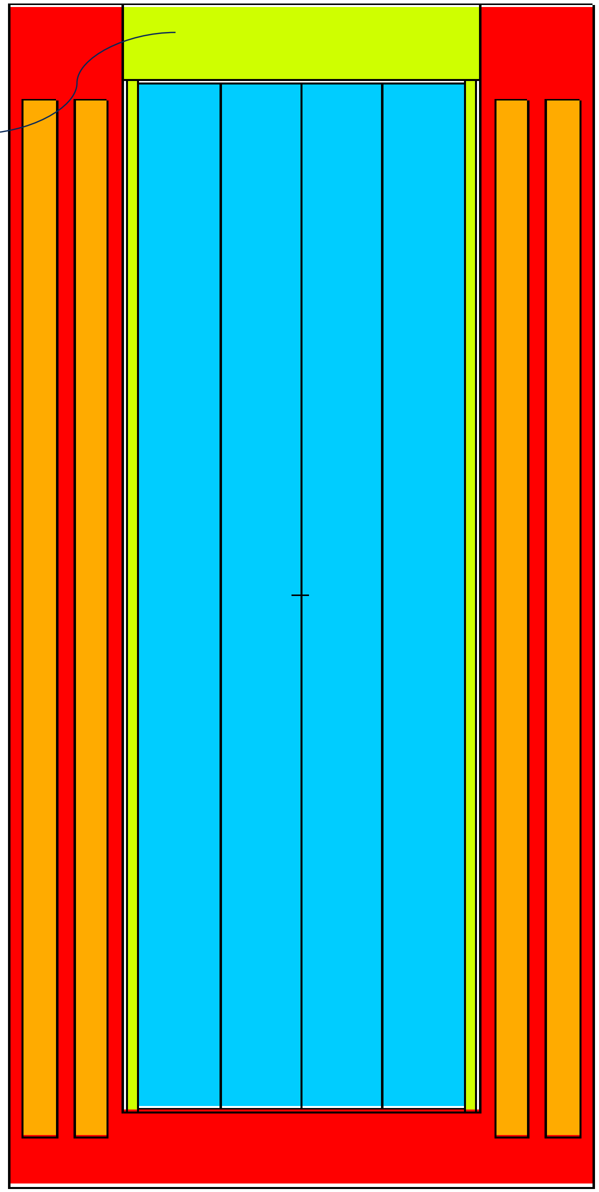
KN-12 Transport Cask Configuration



KN-12 Configuration by MCNP Visual Editor

- **KN-12 Cask Configuration**





KN-12 Transport Cask Modeling

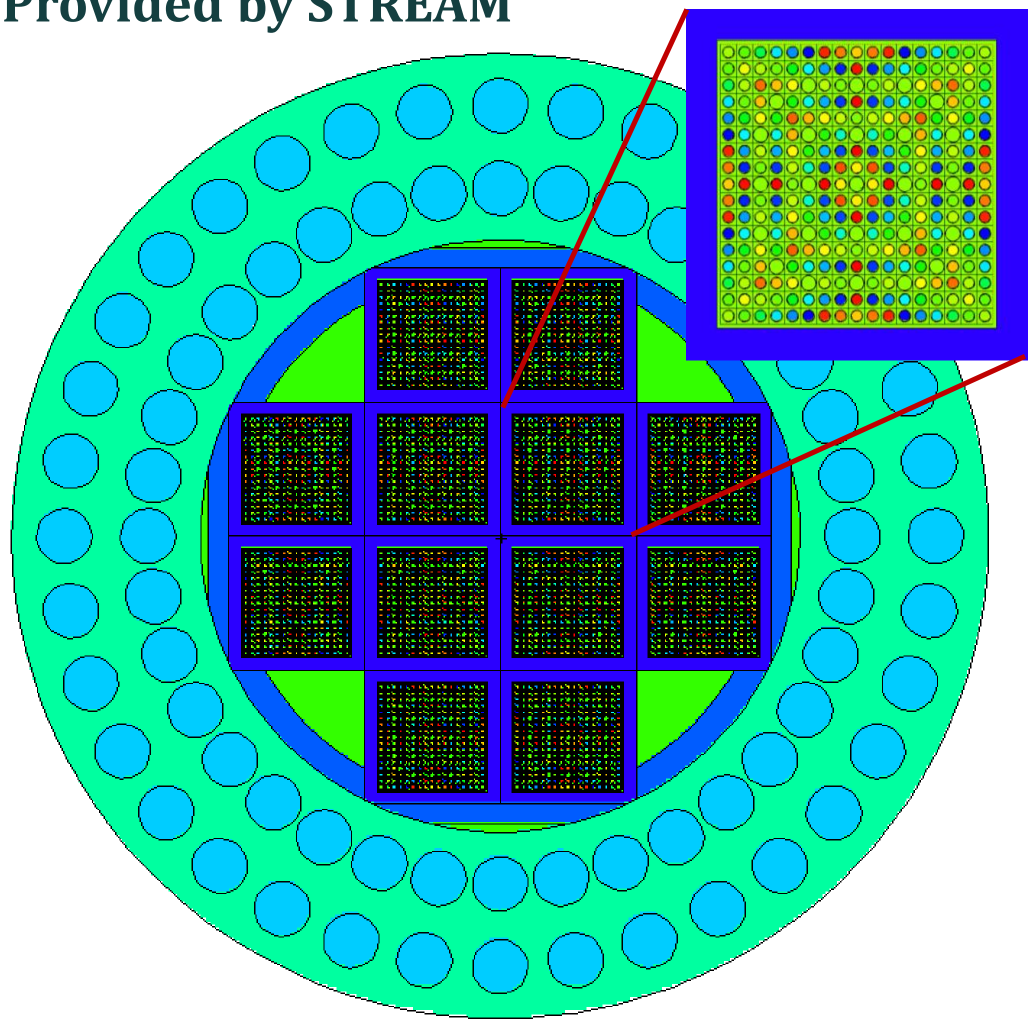
▪ KN-12 Cask Components and Materials

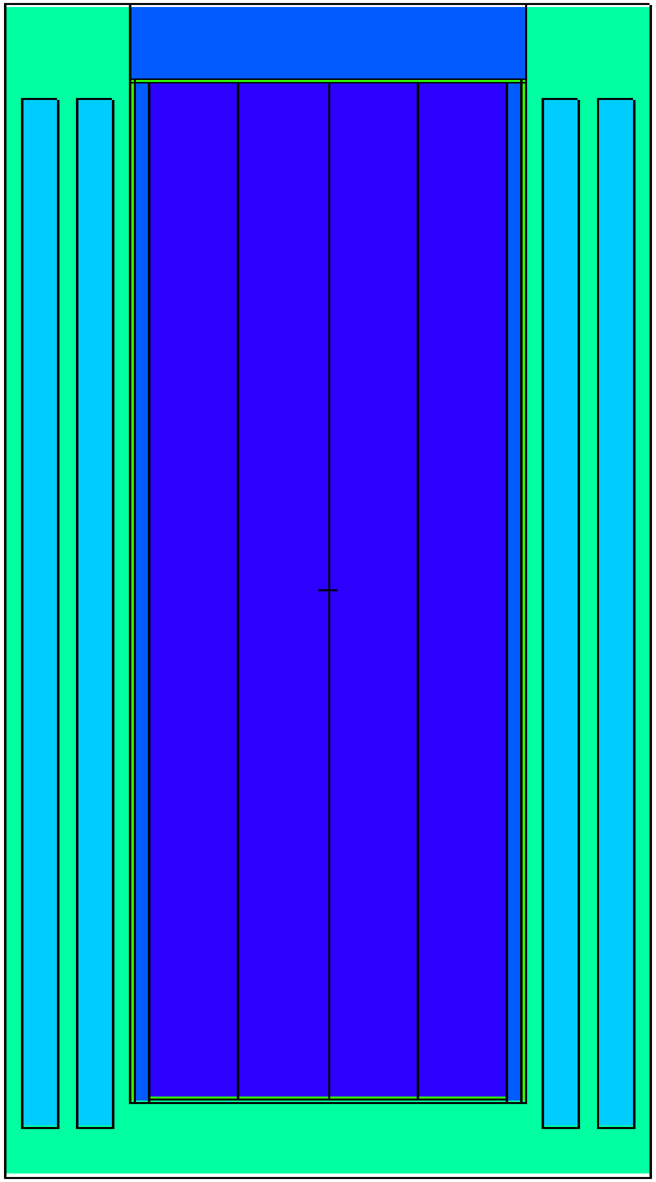
Component	#/cask	Material	Density [g/cm^3]	Isotope Abundance [%]
Cask body	1	Carbon steel	7.85	Si (0.021%), Mn (0.55%), C (0.7%), P (0.014%), S (0.3%), Fe (98.415%)
Cask lid	1	Stainless steel	8.03	Ni (9%), Cr (19%), Si (1%), Mn (2%), C (0.08%), P (0.045%), S (0.03%), Fe (68.845%)
Fuel assembly	12	Fuel rod, cladding, air, water	-	STREAM provides
Basket	12	Borated stainless steel	7.8	Stainless steel (99%) Boron (1%)
Moderator rod	72	Polyethylene	0.94	C (33.33%), H (66.67%)

KN-12 Configuration by MCNP Visual Editor

▪ MCNP6 Visual Editor Plot (KN-12 Cask with FA's)

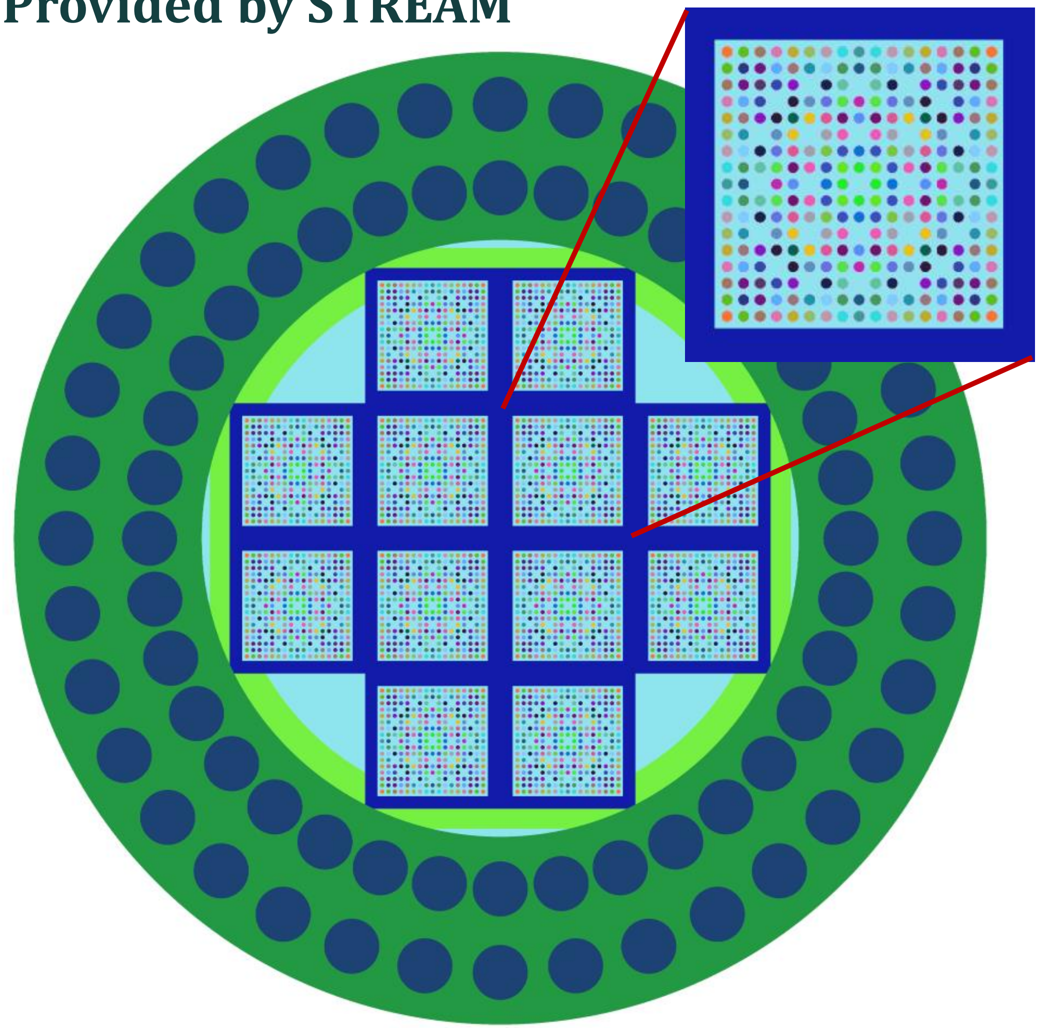
- 60,000 MWd/MTU Burned Fuel Assemblies
- Provided by STREAM

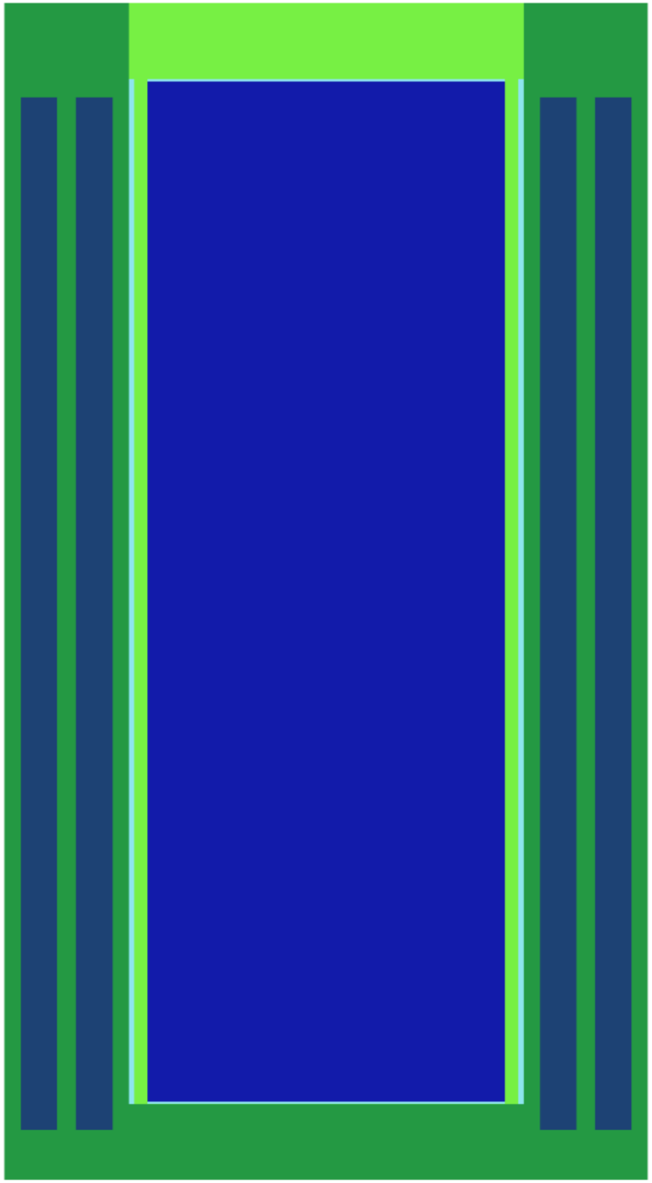




KN-12 Configuration by MCS

- **MCS Plot (KN-12 Cask with FA's)**
  - 60,000 MWd/MTU Burned Fuel Assemblies
  - Provided by STREAM





Criticality Calculation (MCNP6 vs MCS)

▪ Criticality Calculation and Computing Performance

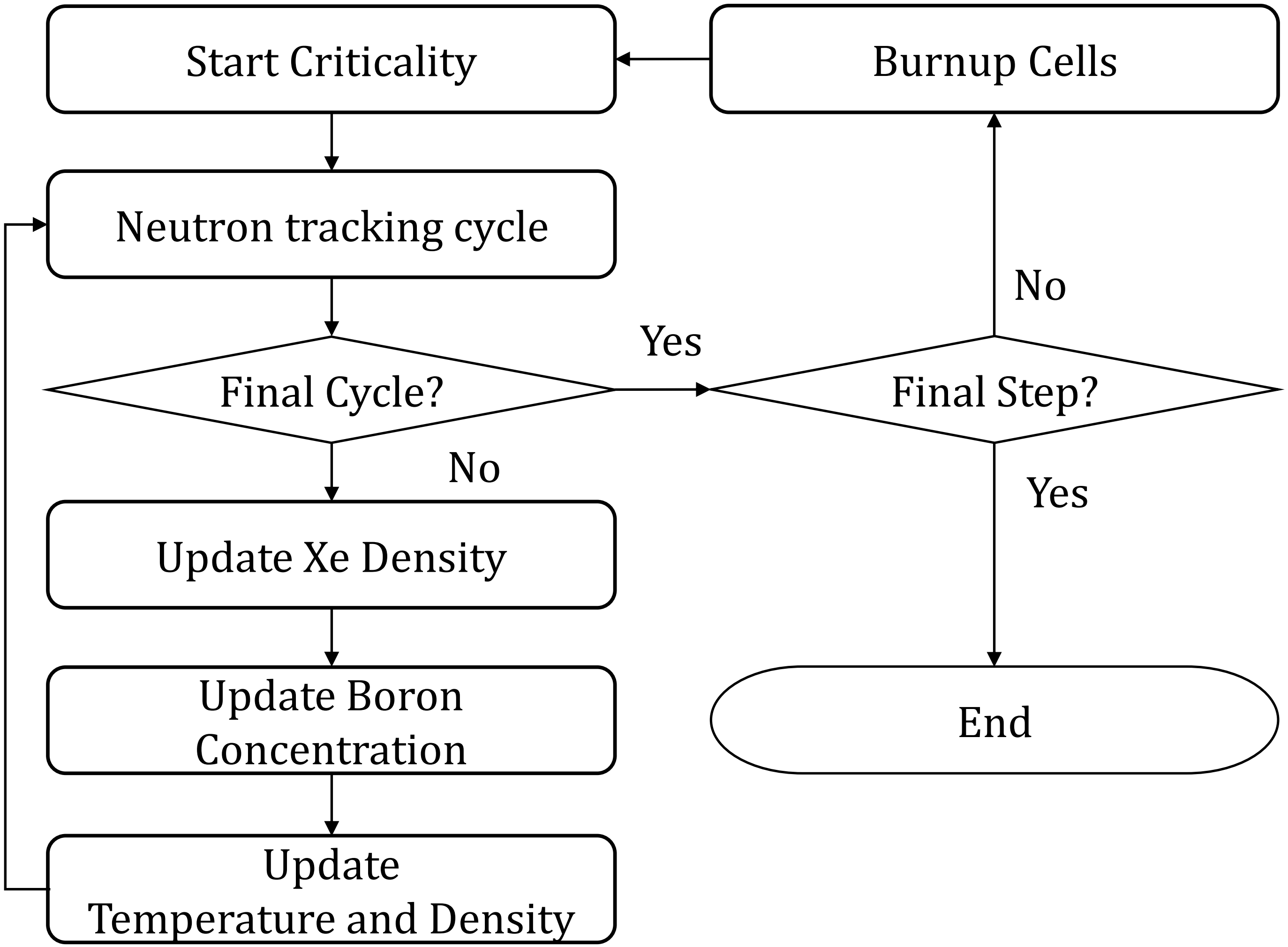
- History 30,000 / inactive cycle 50 / active cycle 500
- Parallel process using 32 cores
- k_{eff} difference = 12 pcm (Standard deviation = 14 pcm)

	MCNP6	MCS (Double indexing off)
k_{eff}	0.64736 (0.00014)	0.64724 (0.00014)
Computing time [sec]	2098	1261

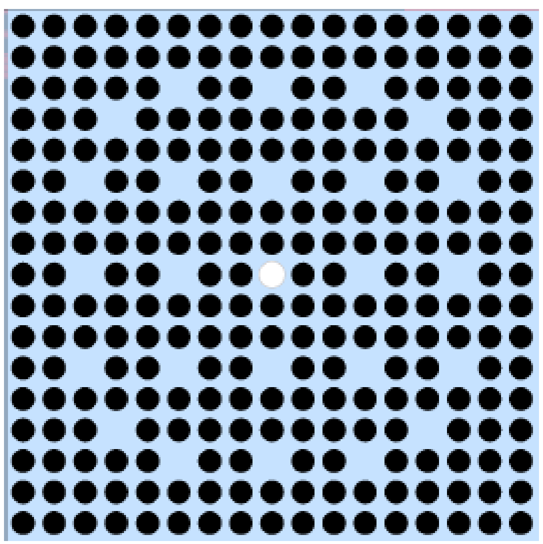
- Double-indexing ON → MCS computing time ↓

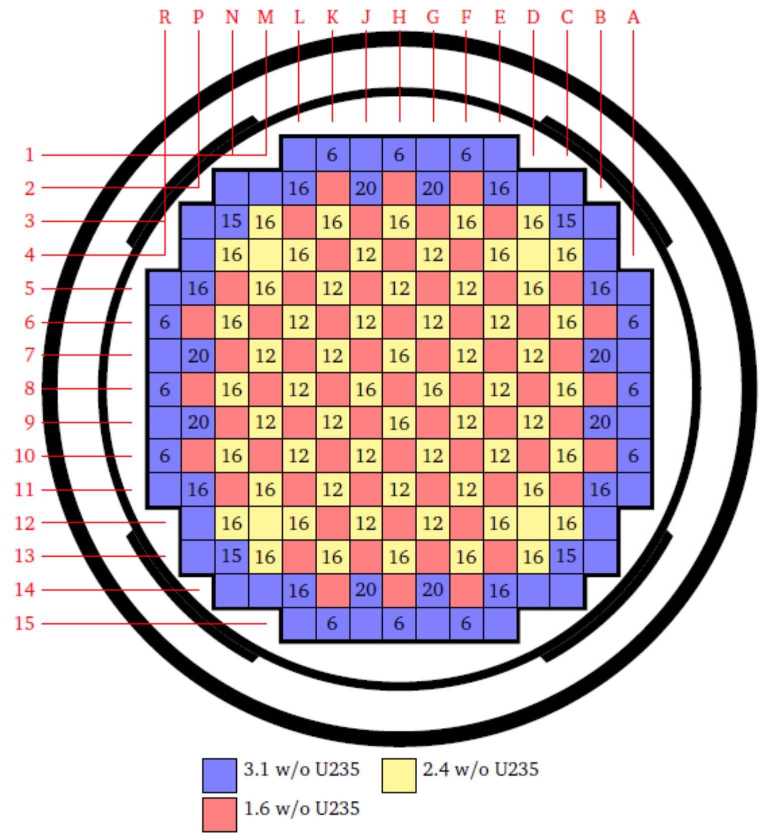
BEAVRS CYCLE 1

FLOW CHART


Start Criticality
Burnup Cells
Neutron tracking cycle
No
Yes
Final Cycle?
Final Step?
No
Yes
Update Xe Density
Update Boron Concentration
End
Update Temperature and Density

- **BEAVRS benchmark (2013)**
  - **Published by MIT reactor physics group**
  - **Updated reactor challenge problem to replace the H-M benchmark**
  - **4 Contains detailed description of most reactor core components**
  - **loop Westinghouse PWR**





BEAVRS TH CALCULATION

▪ BEAVRS CORE

- # of fuel cells : 50952
- # of axial meshes : 20
- # of radial meshes : 3

- Cell tallies : Fission (collision and track-length), absorption, flux

- Library : ENDF-B/VII.1
- OpenW : On
- Equilibrium Xenon : On
- TH feedback : On
- Critical Boron Search : On
- Tempdiff : 30 K

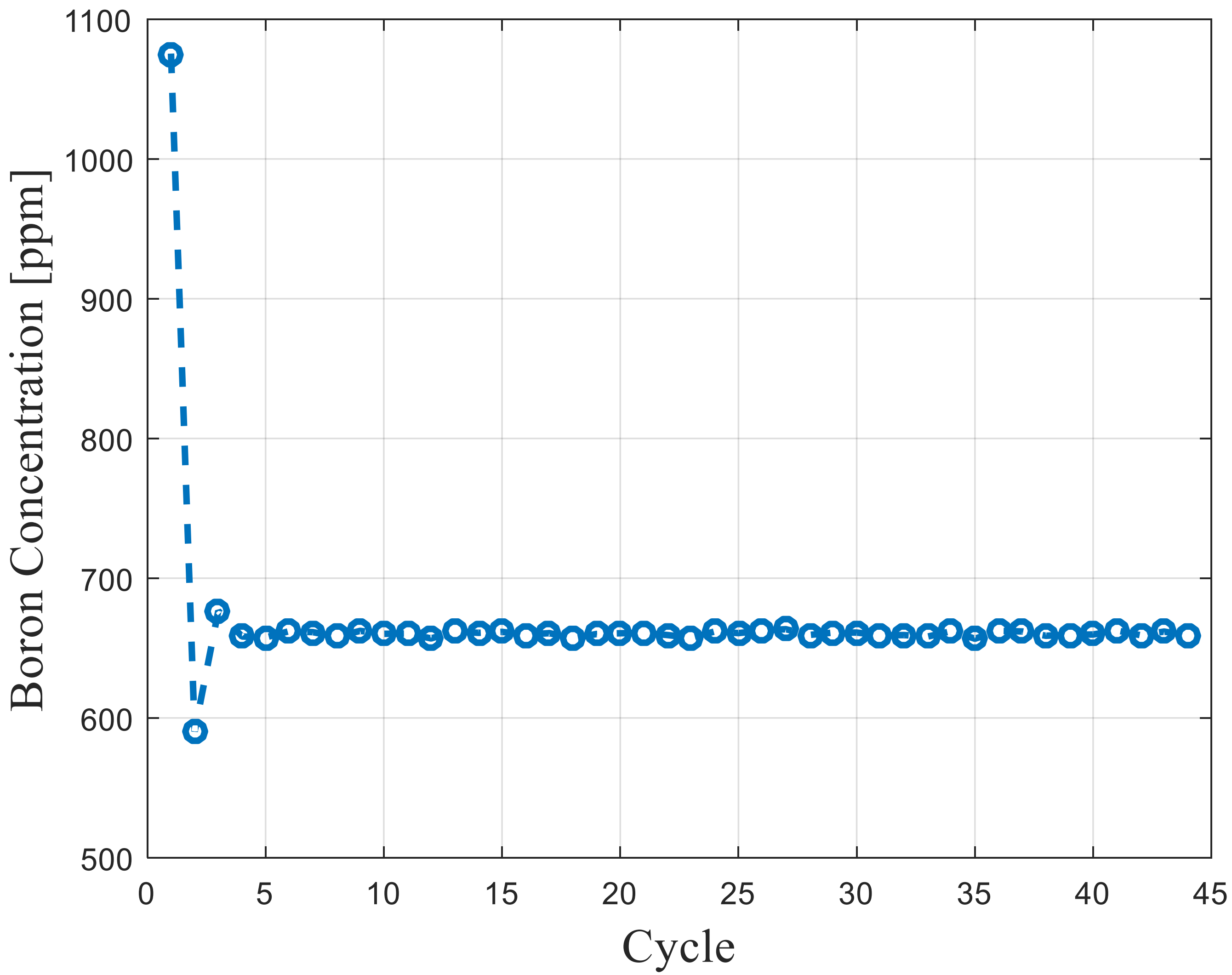
- Active : 40
- Inactive : 4
- Multicycle : 300
- Histories : 100,000

BEAVRS TH CALCULATION

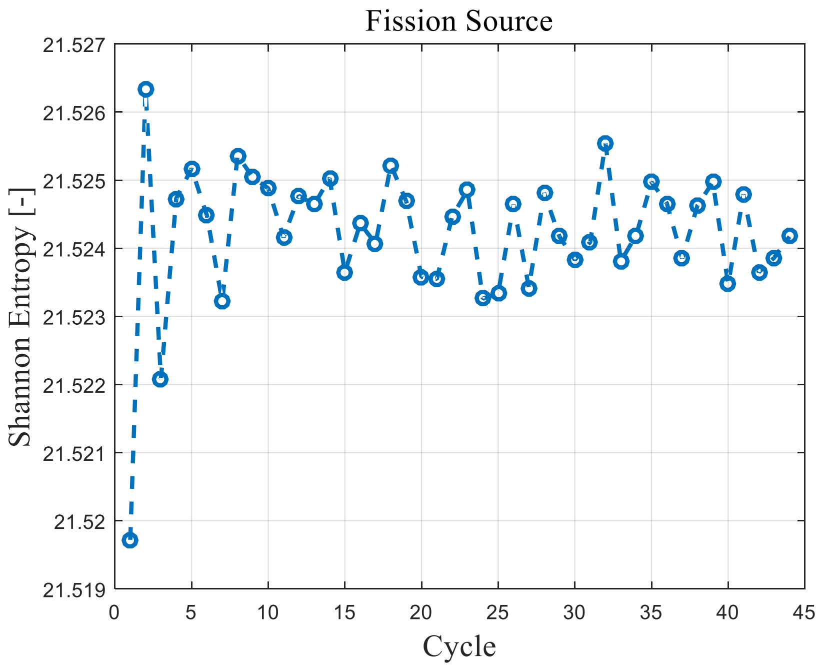
Core Power	3,411 MW
Inlet Coolant Temperature	560 °F
Pressure	2,250 psia
Core Flow Rate	61.5×10^{6} kg/hr
Control Rod Position	ARO

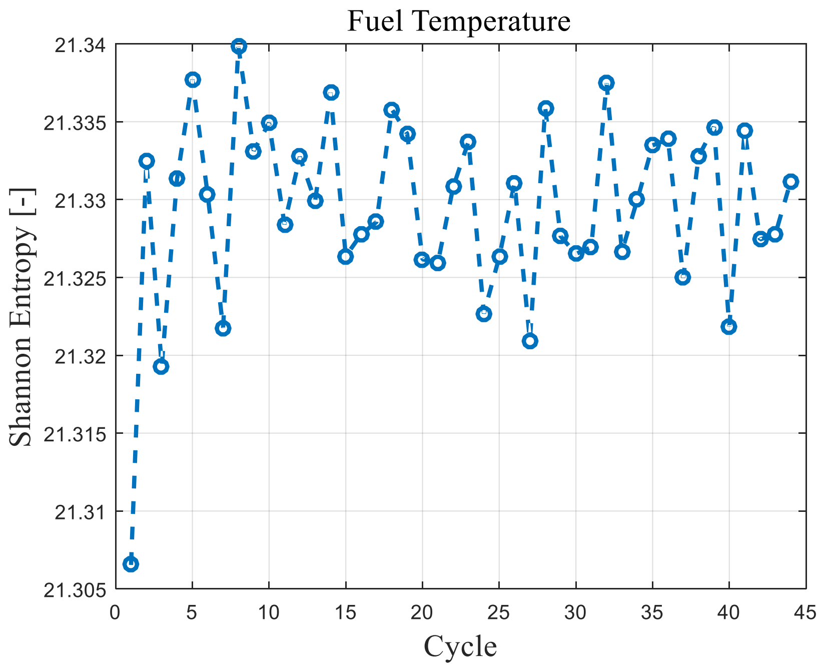
k_{eff}	1.00001 ± 0.00004
CBC	660 ± 0.281 ppm
Memory per Process	$\sim$ 17 GB
Simulation Time	29.8 hours
# of processes	48

▪ Critical Boron Centration



- **Shannon entropy of fission source and fuel temperature**
  - **# of inactive cycle = 4**





CONVERGENCE CHECK

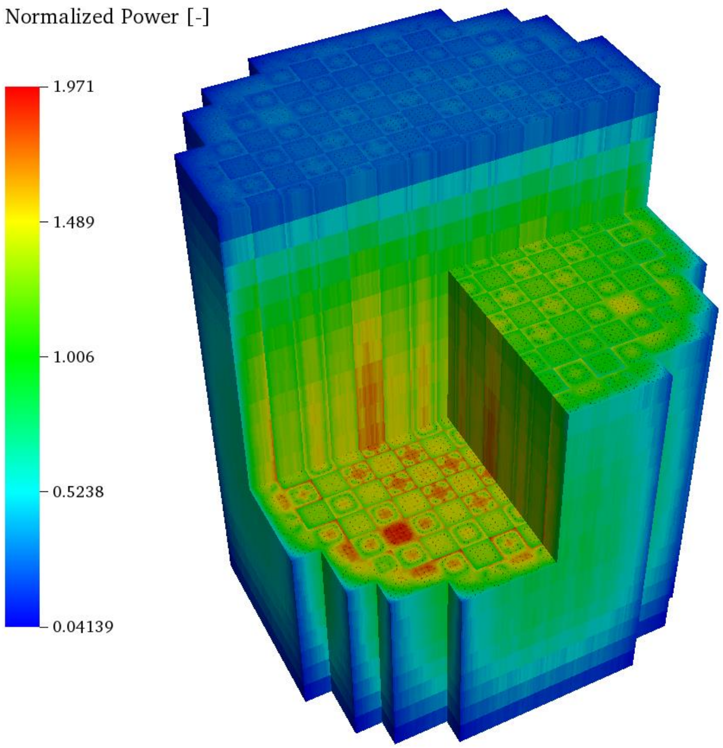
- **Simulation time for TH1D solver is about 20 seconds**

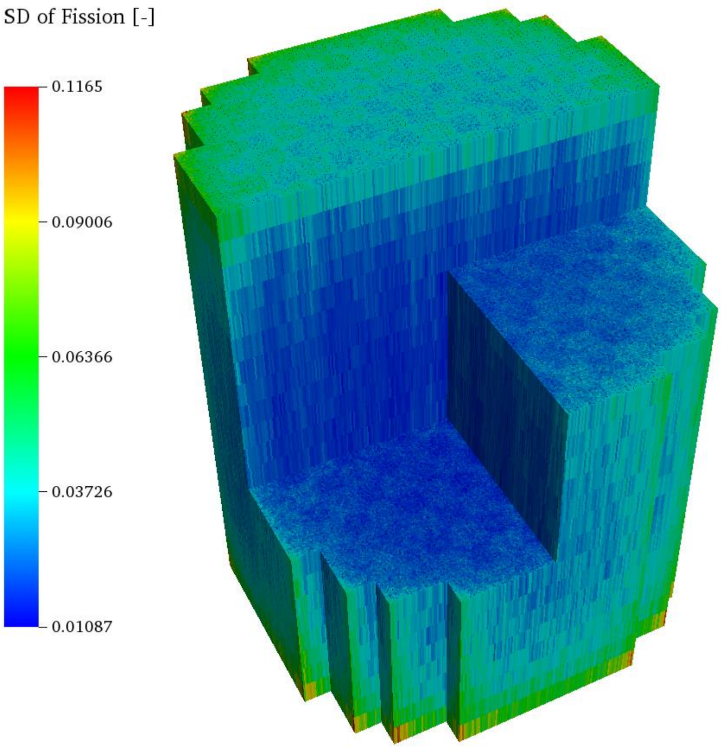
```
Solving TH1D solver...

          TH1D summary:
              # of pins: 50952
    # of pins converged: 50952
     # of pinx diverged: 0
   # of zero power pins: 0

...done // it took 20.28 sec
```

- **Diverged pin**
  - **If TH1D solver is diverged**
  - **If The solution is wrong**
    - **Fuel temperature is too high (> 3,000 K)**
    - **Water density is negative**

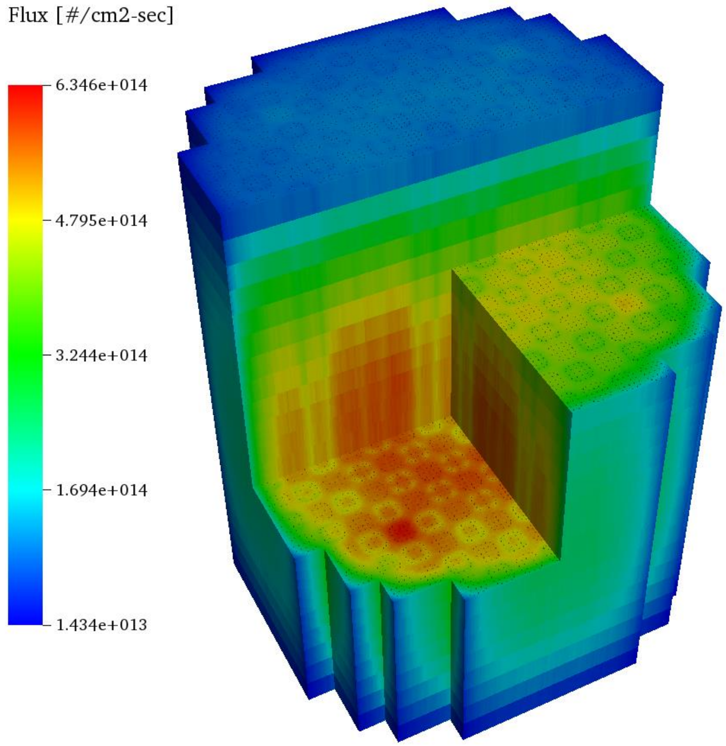
3D FIGURES

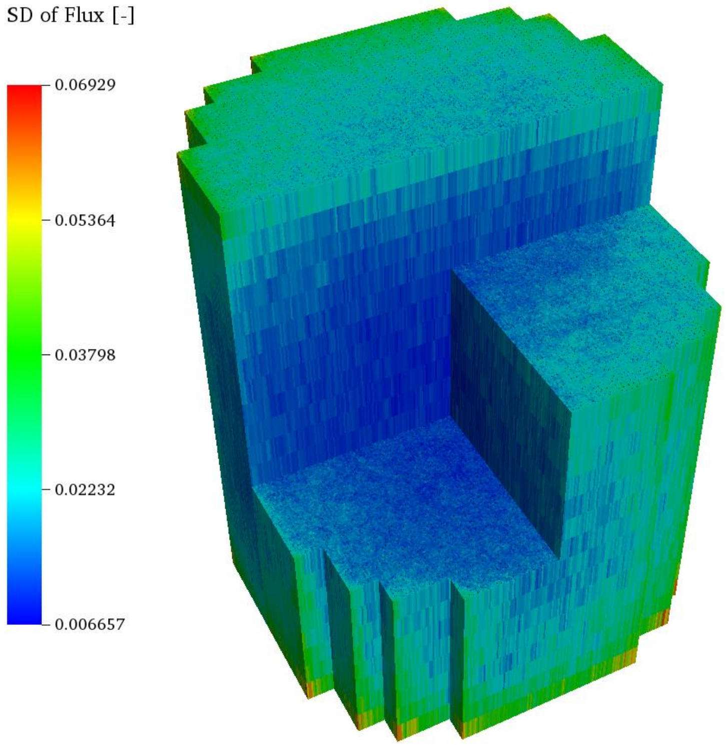
- **Normalized power and flux**



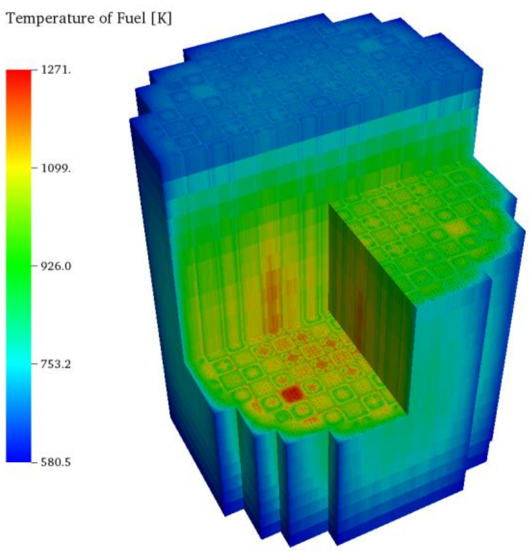


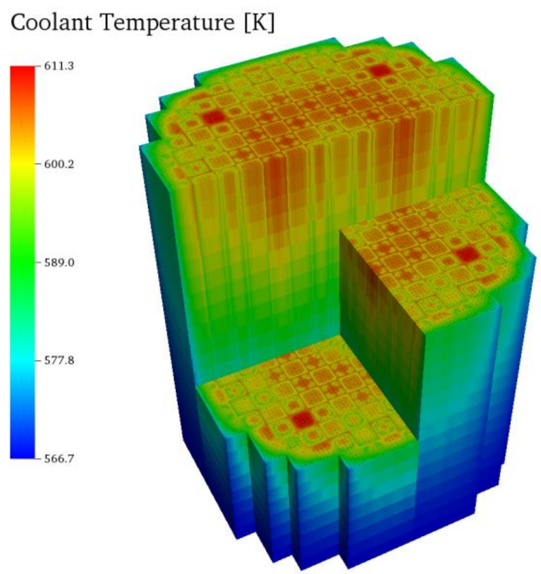
- **Normalized power and flux**

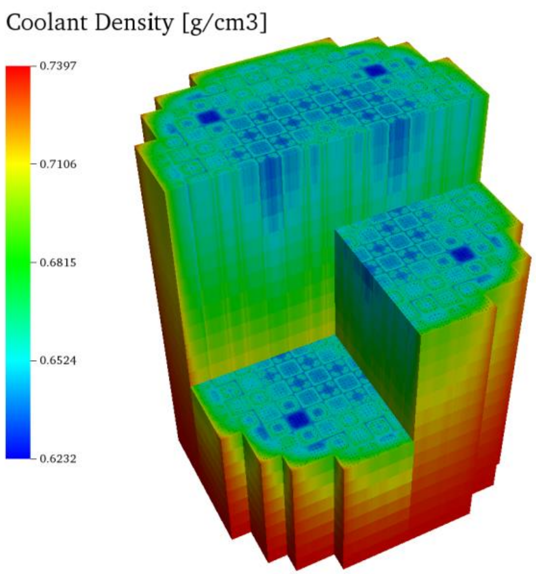




- **Fuel temperature, coolant temperature, and coolant density**

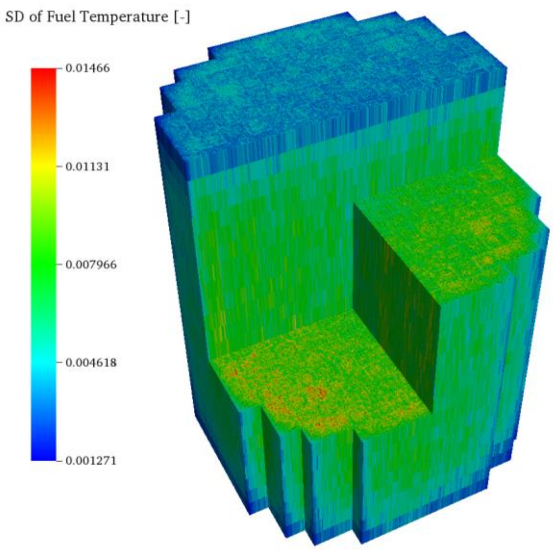


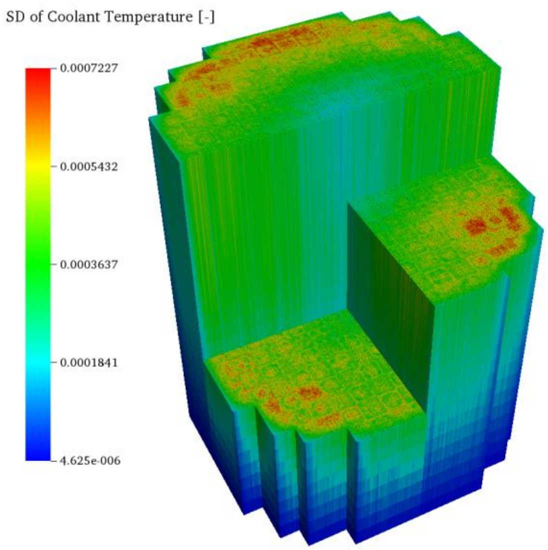


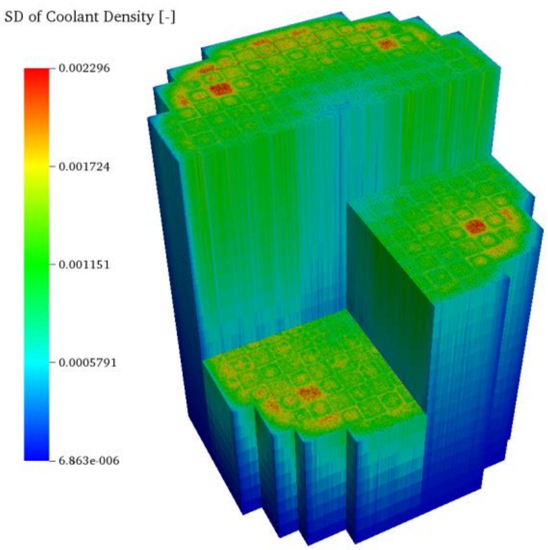


▪ Relative Statistical Error

- Fuel temperature : ~ 1.4 %
- Coolant temperature : ~ 0.07 %
- Coolant density : ~ 0.2 %

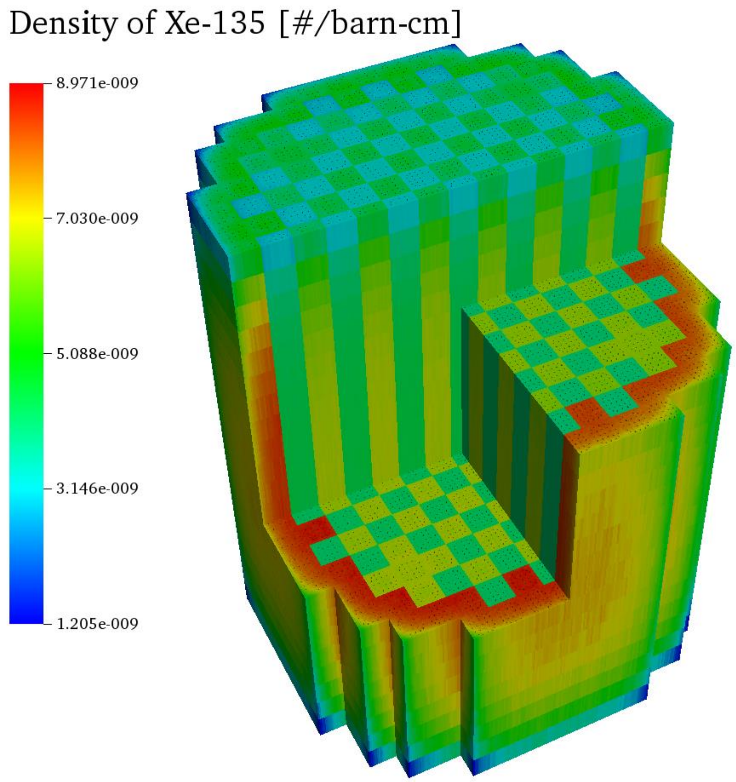


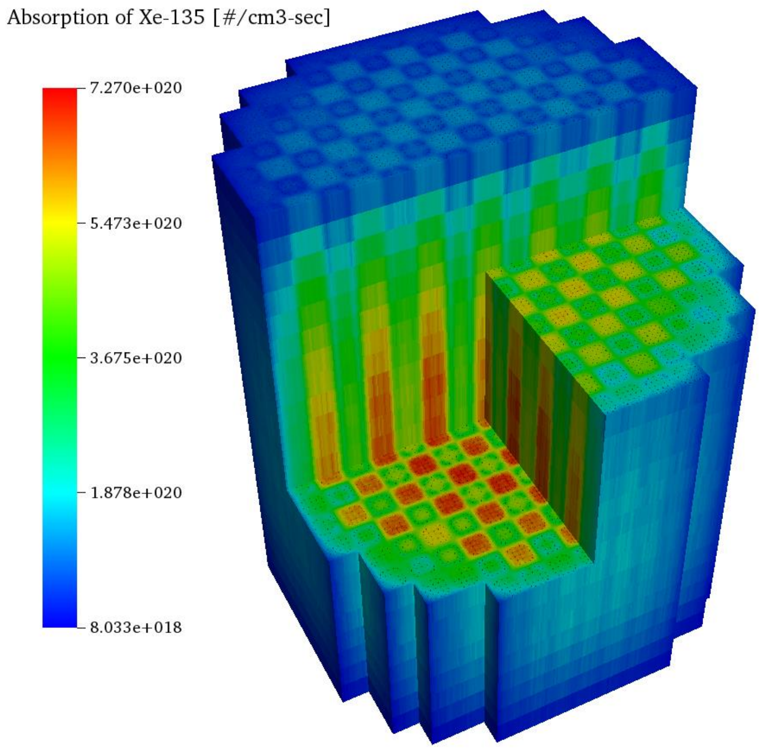




XENON NUMBER DENSITY

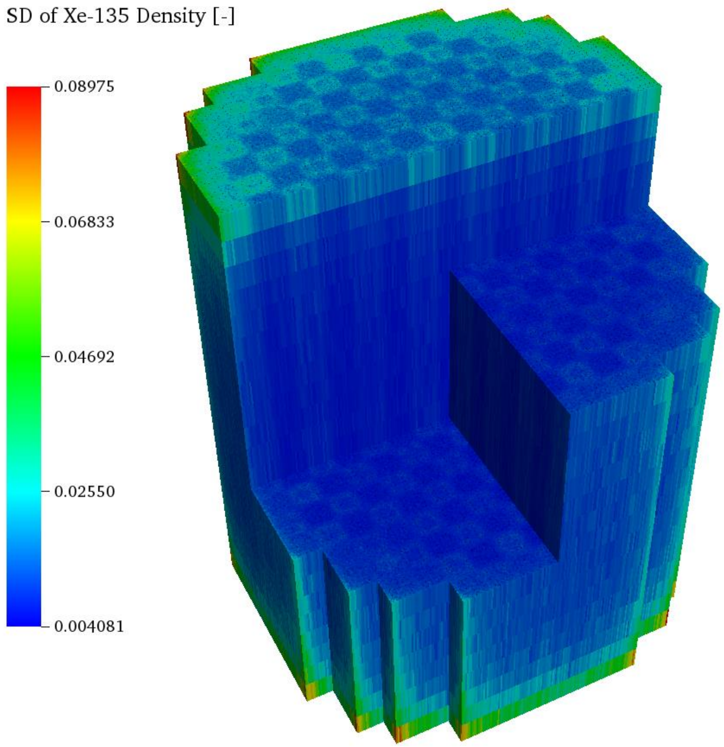
▪ Xe-135 Density and Absorption Reaction Rate

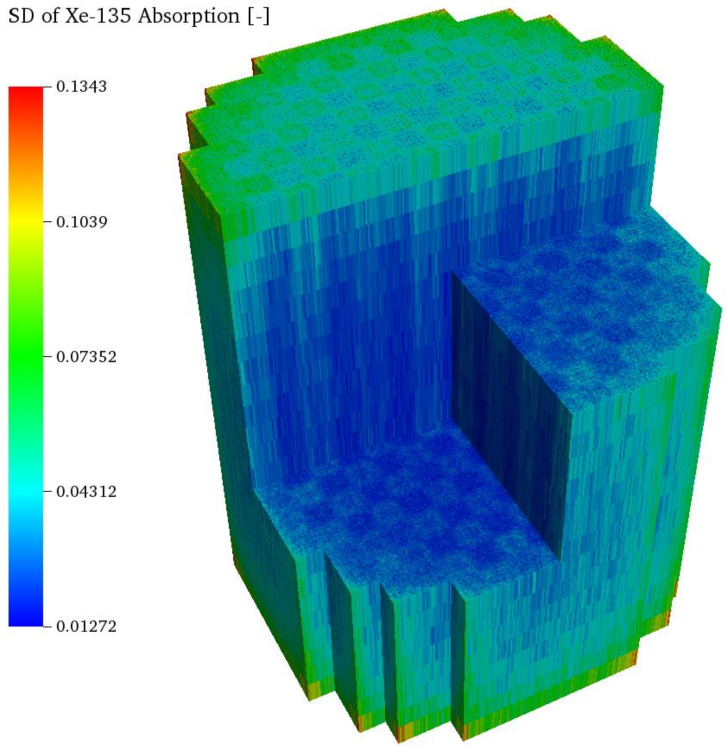




XENON NUMBER DENSITY

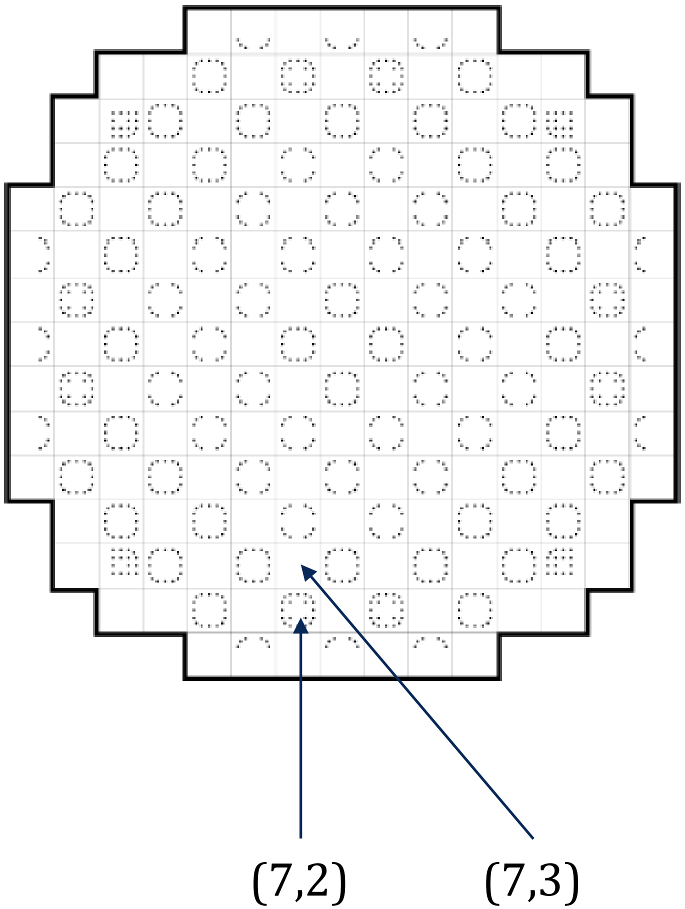
- **Statistical error of Xe-135 Density and Absorption Reaction Rate**
  - **Statistical error is similar with that of power**

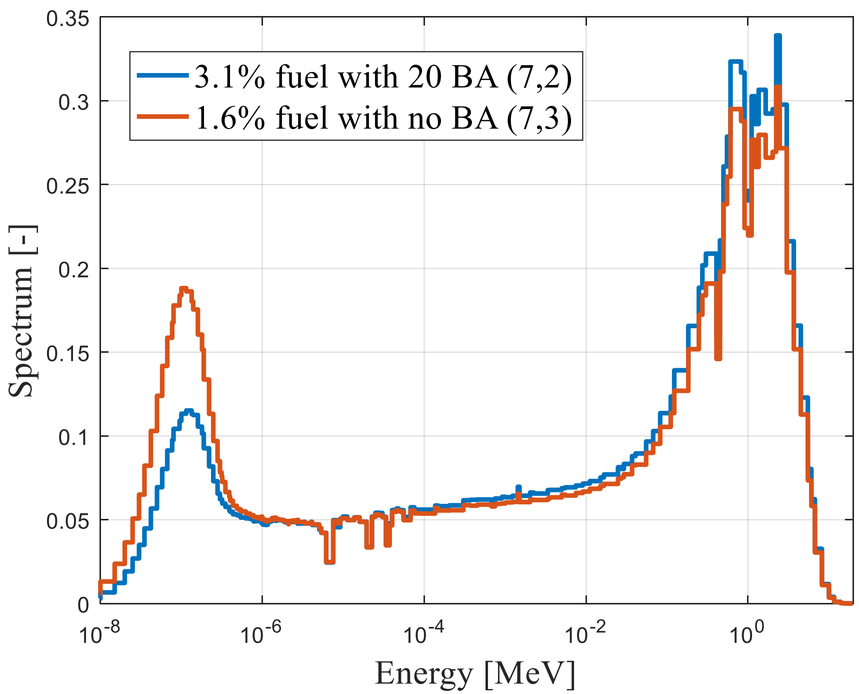




BA DISTRIBUTION & FLUX SPECTRUM

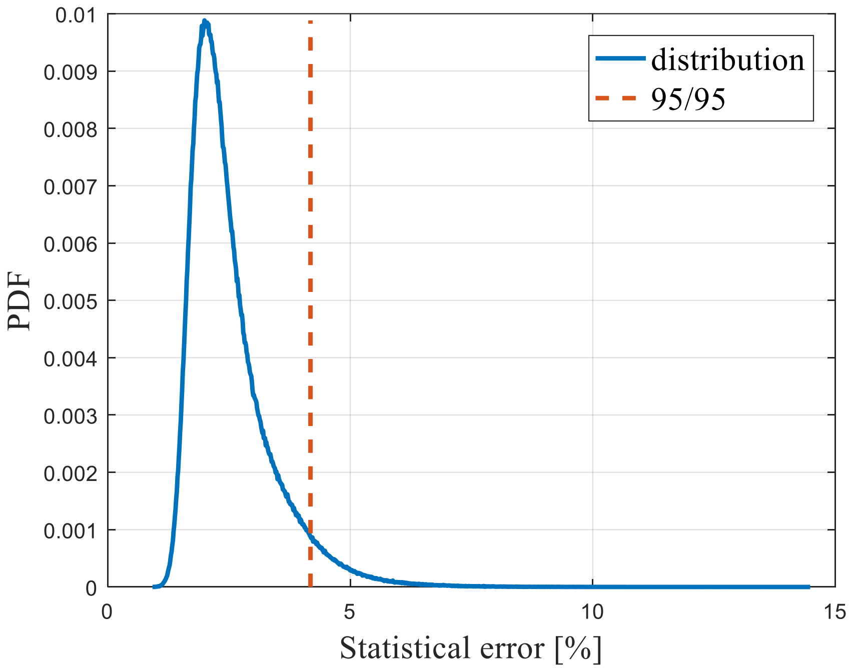
- **Integrated spectrum in assembly**

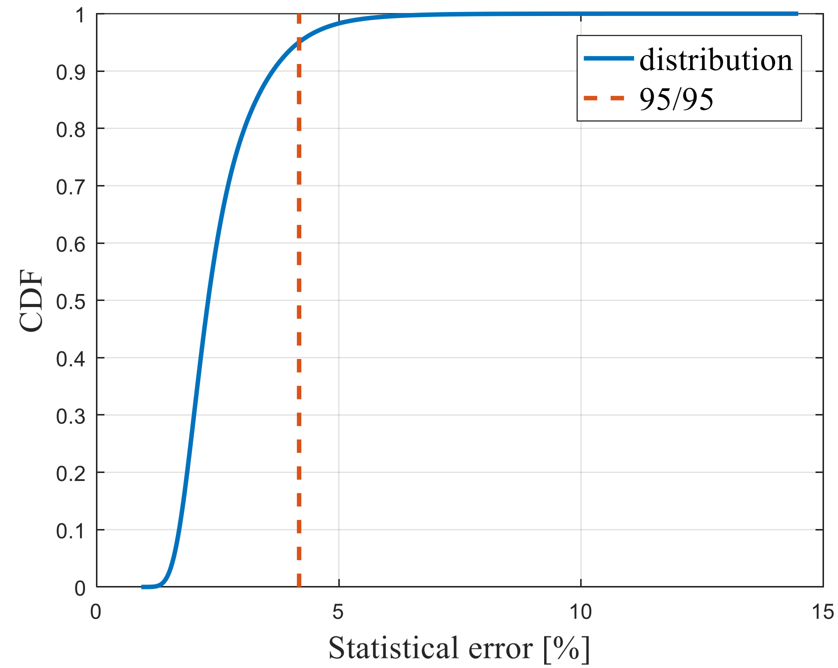




▪ Statistical error of power

- Statistical error at 95/95 cell : 4.18 %
- It will takes 22 days to get 1 % statistical error





BEAVRS TH-DEP CALCULATION

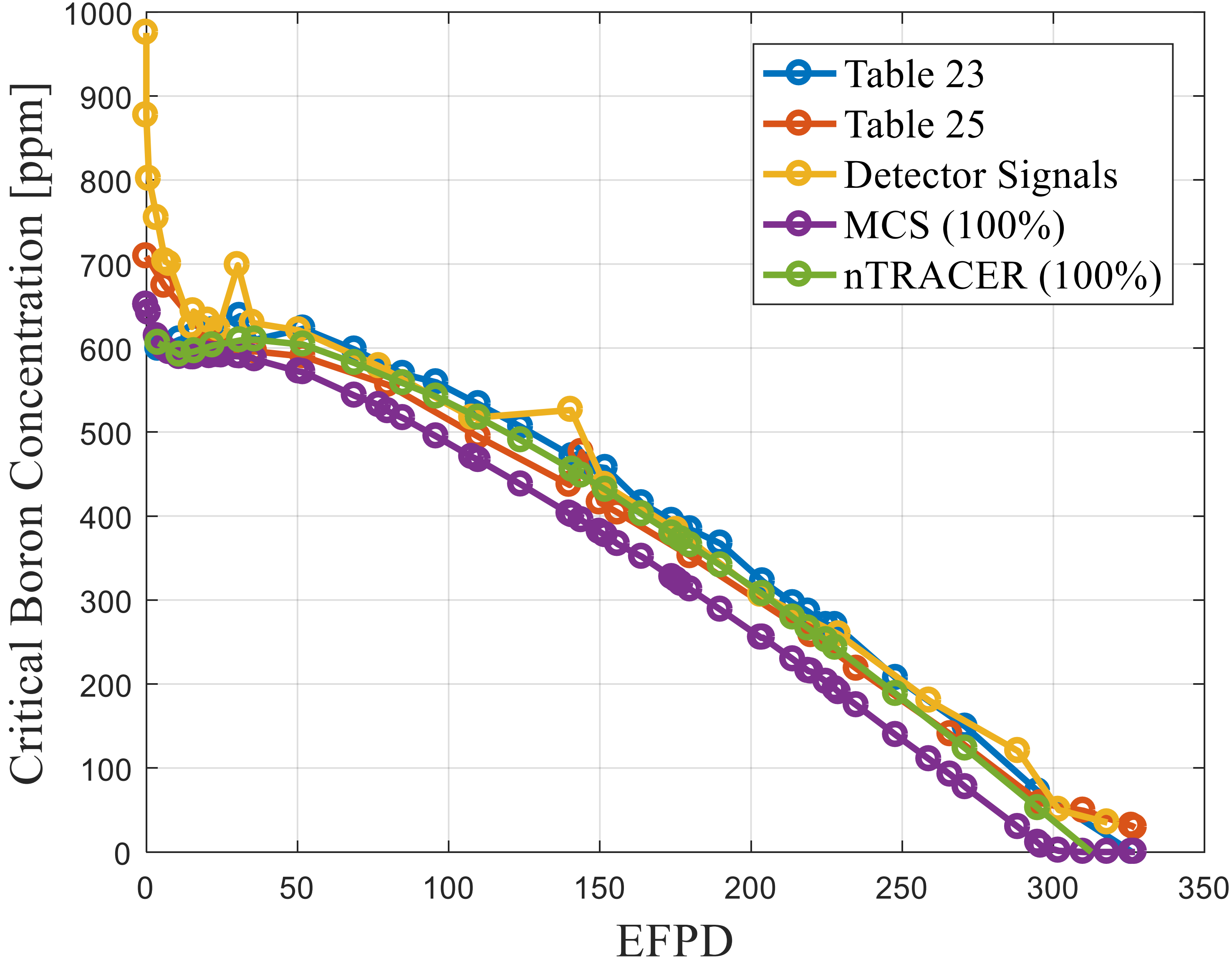
- **BEAVRS QUARTER CORE**
  - # of fuel cells : 14784 (whole core = 50952)
  - # of axial meshes : 10
  - # of radial meshes : 1

  - Library : ENDF-B/VII.1
  - OpenW : On
  - Equilibrium Xenon : On
  - TH feedback : On
  - Critical Boron Search : On
  - Tempdiff : inf. K

  - Power : 100% (constant)

  - Active : 40
  - Inactive : 4
  - Multicycle : 300
  - Histories : 10,000

BEAVRS CYCLE 1



RESTART

- **Restart with given condition**

Detector Signals										
Calander days	power	EFPD	Power [%]	Inlet	burnup [MWD/MT]	Average boron [ppm]	Position of Control Bank			
							A	B	C	D
0	24.07	0.00	0.71%	558.88	0.01	975.25	228	228	228	207
7	119.61	0.00	3.51%	558.13	0.0	876.79	229	176	69	215
18	692.69	0.90	20.31%	554.28	38.7	801.36	229	228	228	165
54	1105.96	3.49	32.42%	557.98	149.4	754.69	228	228	229	162
62	1660.93	6.27	48.69%	557.35	268.2	703.12	228	228	229	228
66	1668.06	7.63	48.90%	557.43	326.5	700.00	228	228	228	204
81	2525.37	15.07	74.04%	560.13	644.8	625.15	228	228	228	192
82	2495.80	15.64	73.17%	558.78	669.3	643.54	228	228	228	158
88	3051.70	20.53	89.47%	560.00	878.7	632.38	228	228	228	217
92	3365.70	23.91	98.67%	557.10	1023.3	622.62	228	228	228	207
161	2141.38	30.27	62.78%	556.40	1295.5	698.50	228	228	228	187
169	3403.53	35.21	99.78%	561.30	1506.8	629.86	228	228	228	198
187	3410.19	50.54	99.98%	561.38	2162.5	621.00	228	228	228	192
218	3198.76	77.05	93.78%	561.50	3297.1	578.23	228	228	228	195
251	3397.52	107.81	99.60%	560.93	4613.5	516.92	228	228	228	194
323	2171.18	140.50	63.65%	556.55	6012.2	526.18	228	228	228	179
339	3400.67	151.67	99.70%	560.98	6490.4	436.92	228	228	228	199
368	3378.21	175.45	99.04%	560.48	7508.0	383.21	228	228	228	215
403	3406.24	203.33	99.86%	560.60	8701.0	306.09	228	228	228	222
434	3394.23	229.08	99.51%	561.13	9802.9	259.00	228	228	228	207
468	3407.78	259.02	99.91%	560.83	11083.9	180.00	228	228	228	218
504	3403.71	288.40	99.79%	560.58	12341.2	120.00	228	228	228	215
551	2881.59	301.81	84.48%	558.95	12915.2	50.00	228	228	228	216
573	2382.84	317.90	69.86%	557.18	13603.4	35.00	228	228	228	208

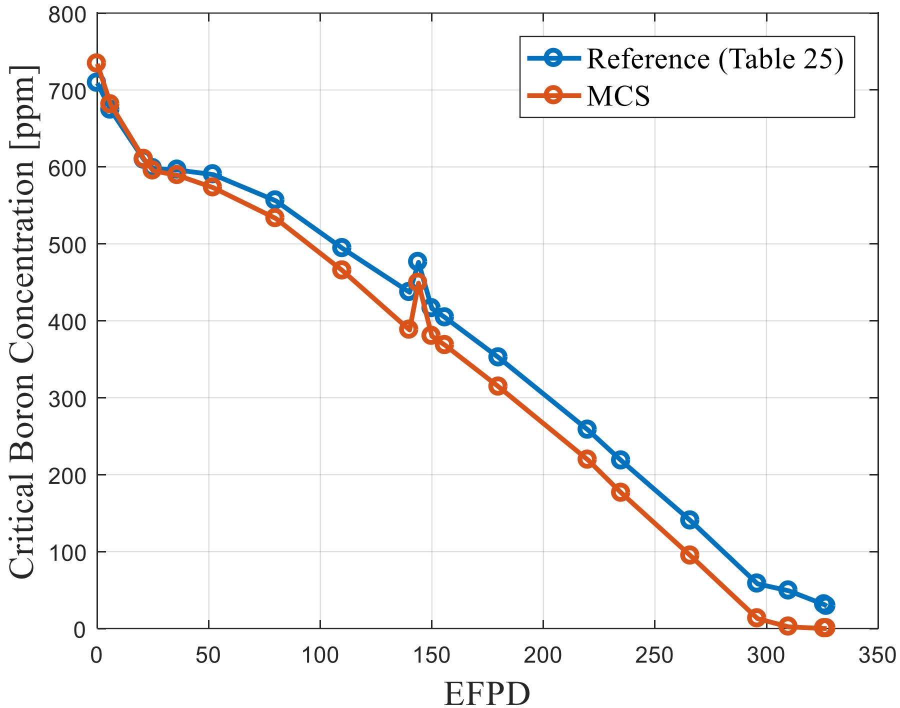
Table 23

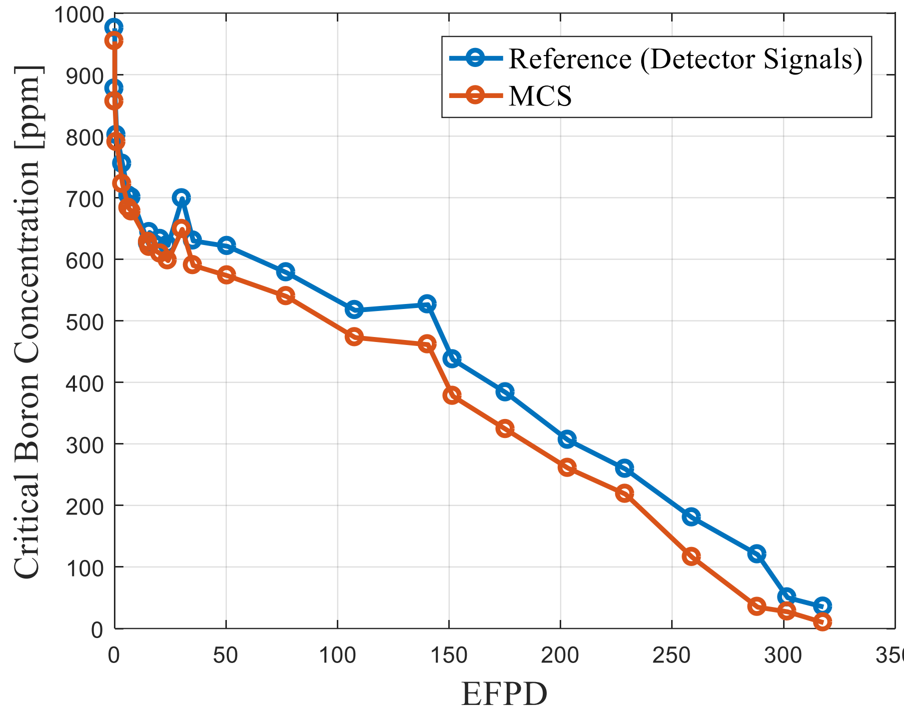
EFPD	Boron [pp	EFPD	Boron [ppm]
4	599	13	918
11	610	23	882
16	614	43	832
22	621	63	764
31	638	84	687
36	610	103	623
52	623	129	538
69	598	150	466
85	569	176	376
96	559	202	292
110	533	234	184
124	506	257	104
141	471		
144	461		
152	457		
164	415		
174	394		
177	384		
180	384		
190	367		
204	322		
214	296		
219	286		
225	270		
228	270		
248	207		
271	149		
295	72		
326	0		

Table 25

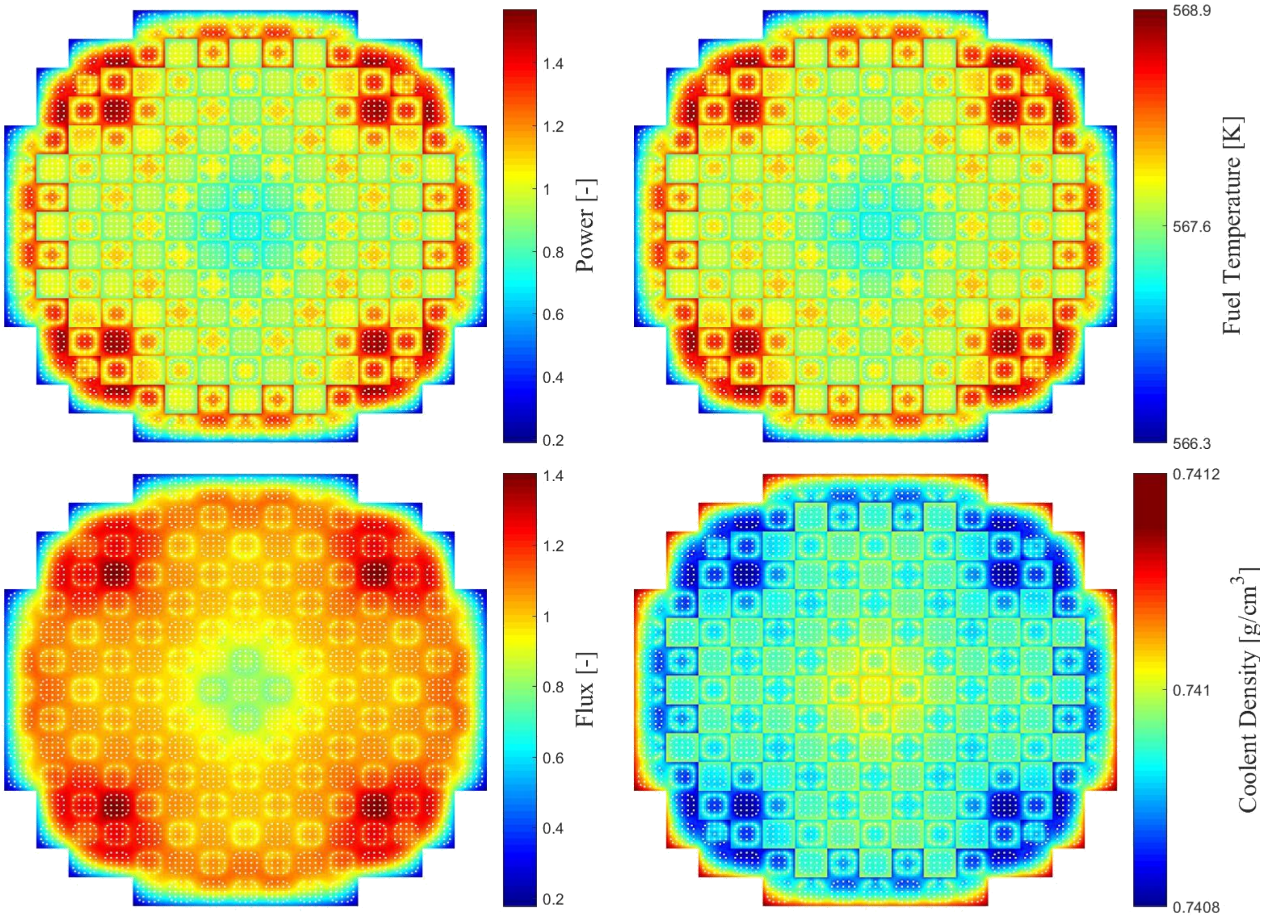
Exporsure	Boron [pp	Inlet [tem	Bank D	% Power
0	709	559.2	212	48.6
6	674	559.2	212	48.6
21	609	561.1	217	89.5
25	598	561.5	207	98.5
36	596	561.6	198	99.8
52	590	561.6	228	100
80	556	561.3	195	94
110	494	561.6	193	100
140	437	561.6	208	100
144	476	559.9	178	64
150	416	561.6	199	100
156	404	561.6	199	100
180	352	561.6	215	100
220	258	561.6	223	100
235	218	561.6	208	100
266	140	561.6	217	100
296	58	561.6	215	100
310	49	560.9	216	84.5
326	31	560.2	208	70
327	29	560.2	208	70

CBC


Reference (Table 25)
MCS
Critical Boron Concentration [ppm]
EFPD
0
100
200
300
400
500
600
700
800
50
150
250
350


Reference (Detector Signals)
MCS
Critical Boron Concentration [ppm]
EFPD
0
100
200
300
400
500
600
700
800
900
1000
50
150
250
350

▪ At BOC (step 1)



1.4
1.2
1
0.8
0.6
0.4
0.2
Power [-]
568.9
567.6
566.3
Fuel Temperature [K]
1.4
1.2
1
0.8
0.6
0.4
0.2
Flux [-]
0.7412
0.741
0.7408
Coolent Density [g/cm^3]

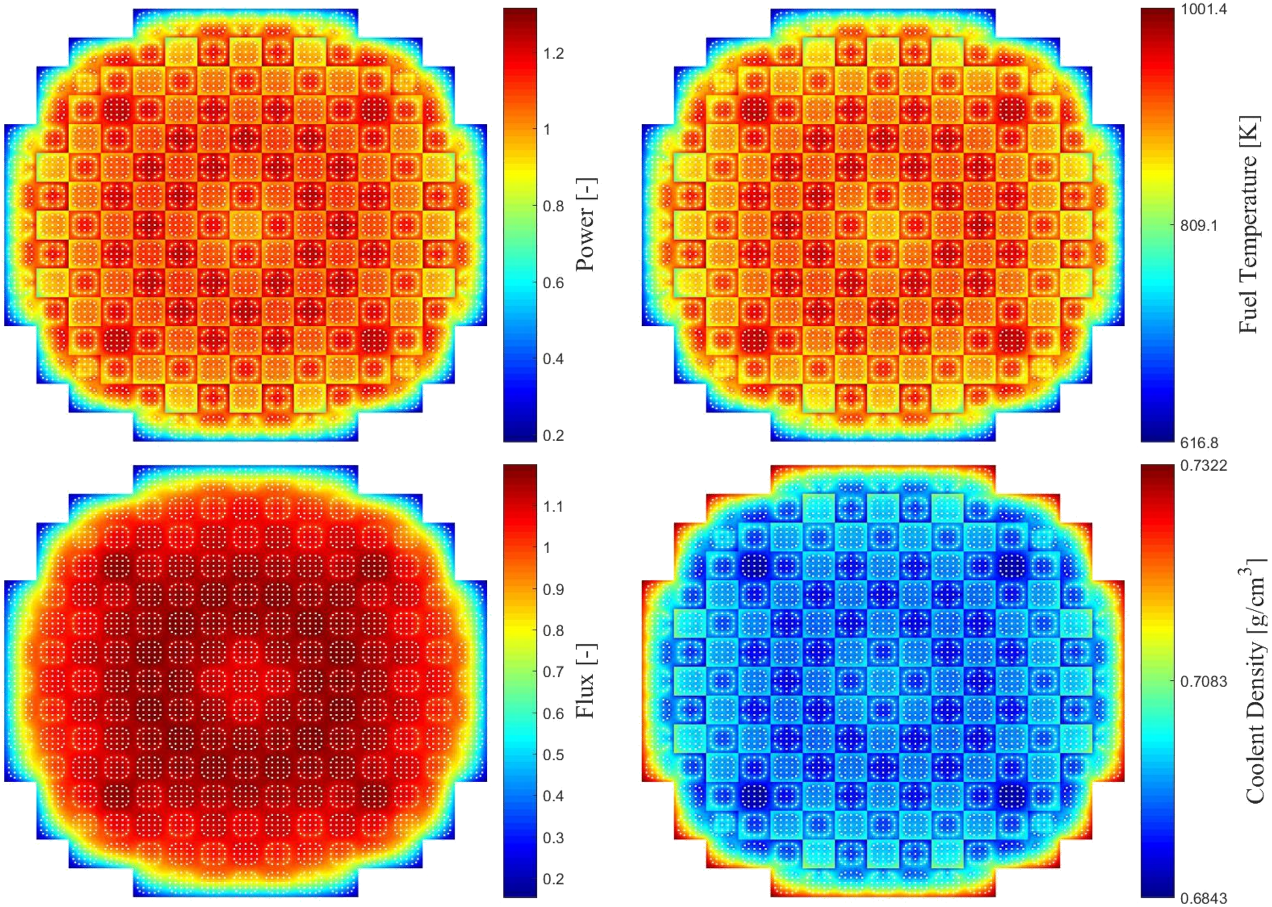
▪ Detector signal comparison

- - -	0.78 0.79 1.73	1.07 1.09 1.73	0.94 0.92 -2.71	1.15 1.16 0.66	0.94 0.92 -1.71	1.27 1.25 -1.04	0.78 0.76 -2.71
0.78 0.80 1.90	1.01 1.03 2.01	0.90 0.91 1.31	1.15 1.17 2.42	0.98 0.97 -0.35	1.17 1.20 2.79	0.84 0.85 1.41	0.82 0.78 -4.22
1.07 1.10 2.83	0.90 0.92 1.95	1.14 1.18 3.07	0.97 0.98 1.22	1.21 1.22 0.53	0.99 0.97 -2.16	1.25 1.24 -0.02	0.73 0.70 -4.31
0.94 0.93 -1.78	1.15 1.19 3.89	0.97 0.97 0.08	1.25 1.27 1.24	- - -	1.31 1.35 3.39	- - -	0.59 0.58 -1.44
1.15 1.19 3.77	0.98 0.98 0.74	1.21 1.22 0.36	- - -	1.35 1.29 -3.97	1.20 1.17 -2.46	0.96 0.93 -3.27	
0.94 0.94 0.08	1.17 1.21 3.26	0.99 0.98 -0.87	1.31 1.35 3.19	1.20 1.17 -2.83	0.85 0.83 -2.49	0.70 0.68 -2.79	
1.27 1.28 1.13	0.88 0.87 -0.33	1.25 1.25 0.79	- - -	0.96 0.93 -3.57	0.70 0.69 -2.42		
0.78 0.77 -1.41	0.82 0.80 -2.36	0.73 0.70 -4.47	0.59 0.57 -3.07				

Rel. Diff [%]	
Max	-4.47
Min	-0.02
RMS	2.41

BEAVRS
MCS
Rel. Diff. [%]

- **At MOC (step 15)**



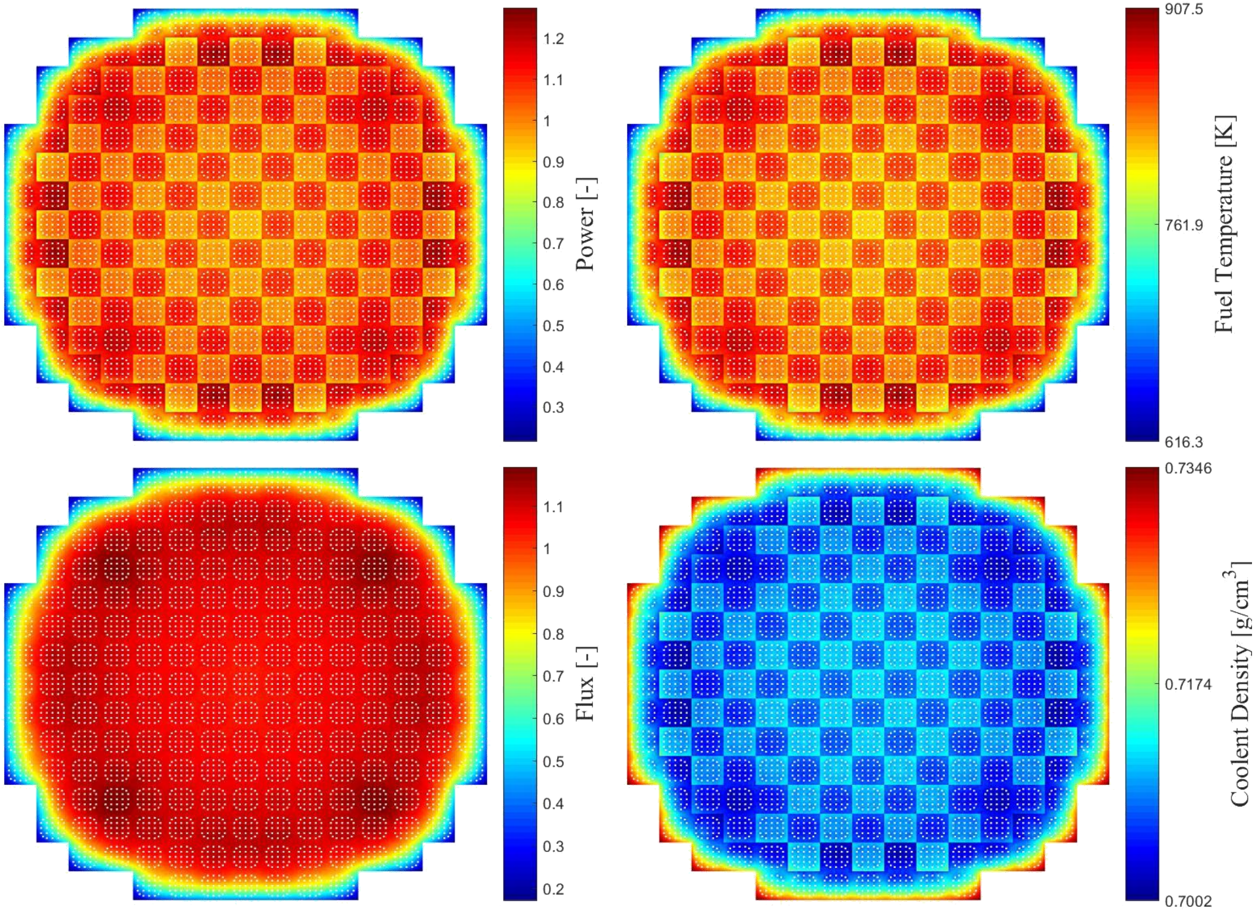
▪ Detector signal comparison

- - -	1.06 1.04 -1.28	1.30 1.31 0.27	1.11 1.10 -0.93	1.28 1.28 0.28	1.02 1.02 0.12	1.16 1.19 2.56	0.66 0.66 -0.14
1.06 1.03 -2.55	1.29 1.28 -0.85	1.11 1.10 -1.18	1.30 1.32 1.07	1.09 1.08 -0.71	- - -	0.83 0.83 -0.44	0.67 0.66 -1.00
1.30 1.31 0.31	1.11 1.09 -1.95	1.32 1.33 0.62	1.11 1.09 -1.91	1.26 1.28 1.62	1.01 1.01 -0.11	1.12 1.16 2.94	0.61 0.62 1.79
1.11 1.10 -0.60	1.30 1.34 2.58	1.11 1.09 -1.50	1.30 1.29 -0.60	- - -	1.21 1.22 0.69	- - -	0.50 0.49 -2.18
1.28 1.28 0.45	1.09 1.06 -2.12	1.26 1.27 1.03	- - -	1.09 1.10 0.64	1.00 0.99 -0.15	0.72 0.71 -1.39	
1.02 1.02 -0.29	- - -	1.01 0.99 -1.76	1.21 1.22 1.37	1.00 1.00 0.45	0.70 0.69 -0.97	0.53 0.52 -0.73	
1.16 1.18 1.84	0.83 0.83 -0.74	1.12 1.14 1.39	- - -	0.72 0.71 -0.68	0.53 0.53 0.81		
0.66 0.66 0.37	0.67 0.67 -0.02	0.61 0.61 0.32	0.50 0.49 -1.25				

Rel. Diff [%]	
Max	2.94
Min	-0.02
RMS	1.29

BEAVRS
MCS
Rel. Diff. [%]

▪ At EOC (step 23)



▪ Detector signal comparison

- - -	- - -	1.17 1.18 0.52	1.05 1.03 -1.56	1.20 1.25 3.97	1.06 1.08 1.25	1.20 1.23 2.48	0.68 0.70 2.28
- - -	1.18 1.20 1.09	1.03 1.03 -0.46	1.17 1.21 2.72	1.07 1.05 -1.07	- - -	0.93 0.92 -1.70	0.70 0.70 -0.45
1.17 1.18 1.20	1.03 1.03 -0.05	1.20 1.20 0.20	1.06 1.06 -0.25	1.23 1.23 0.77	1.08 1.07 -0.82	1.16 1.20 4.12	0.66 0.65 -1.93
1.05 1.03 -2.13	1.17 1.20 2.26	1.06 1.05 -0.72	1.24 1.24 -0.14	- - -	1.25 1.26 1.11	- - -	0.55 0.52 -4.91
1.20 1.23 2.69	1.07 1.06 -0.35	1.23 1.23 -0.02	- - -	1.13 1.13 0.35	1.11 1.08 -2.12	0.76 0.76 0.08	
1.06 1.08 1.17	- - -	1.08 1.06 -1.76	1.25 1.26 1.37	1.11 1.08 -2.51	0.82 0.78 -5.16	0.57 0.55 -3.10	
1.26 1.22 -3.17	0.93 0.92 -1.52	1.16 1.20 4.19	- - -	0.76 0.75 -1.68	0.57 0.54 -4.95		
0.68 0.69 1.65	0.70 0.72 1.49	0.66 0.65 -1.46	0.55 0.52 -6.16				

Rel. Diff [%]	
Max	-6.16
Min	-0.02
RMS	2.38

BEAVRS
MCS
Rel. Diff. [%]

ONGOING & PLAN

ONGOING & PLAN

- **Whole core simulation**
  - BEAVRS cycle 1 & 2
  - VERA
  - Youngkwang unit 3 cycle 1-2
  - Kori unit 4 cycle 1
  - Shin-Kori unit 1 cycle 1-4
  - Shin-Kori unit 3 cycle 1
- **Multipole (OTF-DB)**
  - Conversion of parameter (poles and residues)
- **Decomposition**
  - Domain decomposition
  - Data decomposition
- **Depletion**
  - Hybrid depletion (MC and MOC)
  - Depletion chain optimization

ONGOING & PLAN

- **Gamma transport capability**

- **Multi-physics**
  - Coupling with COBRA-TF (CTF)
  - Depletion calculation with TH-feedback

- **Generalized Perturbation Theory (GPT)**

- **Source term calculation**

- **Spent fuel pool & transportation vessel analysis**
  - USL evaluation

- **Acceleration technique**
  - Coarse Mesh Finite Difference Method (CMFD)
  - Modified Power Method (MPM)
  - Effect on active cycle (inter-cycle correlation)

UNIST CORE