Preliminary Analysis of Boron-free Operation Small Modular Reactor using McCARD and DeCART2D

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01 Introduction

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- **Background**
  - ***Boron-free Operation Small Modular Reactors***, such as the innovative SMR (**i-SMR**), aims for extended operational cycle, and flexible thermal power range and Soluble Boron-free (SBF) conditions.
  - SBF conditions enhances system integrity by reducing liquid waste, simplifying chemical control, and lowering the risk of boron dilution accidents.
  - To achieve SBF conditions, different operating conditions (e.g. enriched gadolinium) than commercial PWRs are required. This means that a core analysis code system suitable for SBF conditions is required.
  - To establish a new high-fidelity nuclear core analysis code system for SBF conditions, the ***errors*** in an ***existing core design analysis code system*** must be quantitatively evaluated.

- **Introduction**
  - ***Target SBF system***

    Our goal is to perform and quantify the errors for newly-developing i-SMR, but the specifications of i-SMR have not been finalized. Accordingly, old data from the paper of J.S. Kim[1][2] was used in this study.

  - ***Target core design code***

    Deterministic 2-Step procedure core analysis code system is being performed utilizing two libraries for the target SBF system by ***DeCART2D***/***MASTER***, which are developed by KAERI.

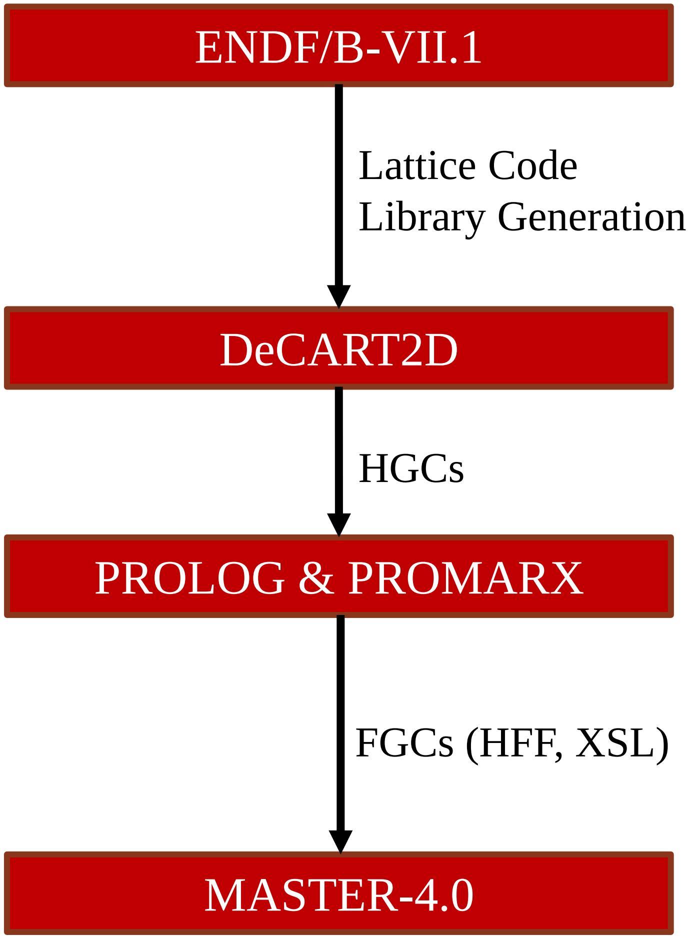
  - ***Reference***

    ✓ ***McCARD*** Monte-Carlo (MC) calculations were performed to provide the reference solutions for V&V calculations.

    ✓ Based on the results for the target SBF system, the error was evaluated through comparison and verification in the McCARD and MASTER codes.

- **Computational Code**
  - McCARD[3]
    - ✓ Developed by Seoul National University
    - ✓ Neutron/Photon Monte-Carlo transport analysis
    - ✓ Can handle Continuous cross-section library
    - ✓ Used ENDF/B-VII.1
    - ✓ Used as design code for ***JRTR*** and ***KJRR***
  - DeCART2D[4]/MASTER[5]
    - ✓ Developed by KAERI
    - ✓ 2-Step procedure core analysis code system
      - DeCART2D: MOC Calc. (Lattice code)
      - MASTER-4.0: Nodal Calc. (Whole Core analysis code)
    - ✓ ENDF/B-VII.1 based on Library (47-Groups)
    - ✓ Used as design analysis for ***SMART***, ***ARA Rx***

DeCART2D/MASTER 2-Step procedure code system



02 Design & Specifications

- **Core Specifications of Boron-free Operation SMR**
  - Extended operational cycle (**24 months**) + ***SBF Condition***
    - ✓ Need a lot of burnable absorber for excess reactivity control.
    - ✓ The stainless steel was used as a reflector.

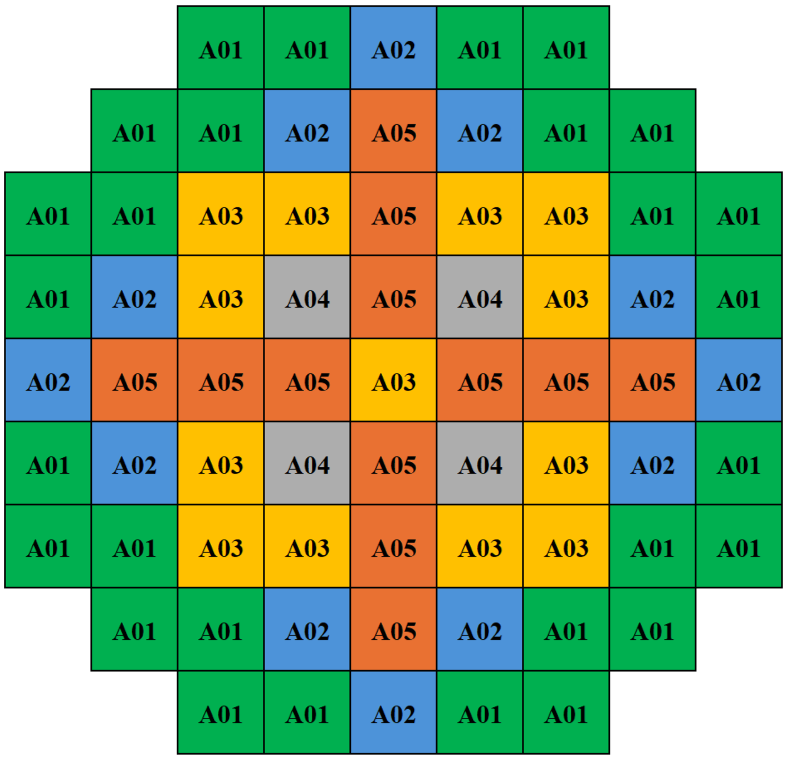


Fig. 1. Configuration of the core models

Table. I. Core Specifications

Parameters	Value
Power	540 MW_{th}
Number of FA	69
Refueling cycle	24 months
Batch	2 batches
Inlet coolant	548.15 K
Outlet coolant	598.15 K
Boron concentration	0 ppm
Active core height	240 cm

- **Enriched gadolinium in Burnable Absorber**
  - Excess reactivity control
    - ✓ Commercial PWR → Soluble Boron + Burnable Absorber Rods + Control Rods
    - ✓ Boron-free SMR → Burnable Absorber Rods + Control Rods
  - Enriched gadolinium are required due to the thermal conductivity and content of UO_2
  - The combined abundance of ^{155}Gd and ^{157}Gd, which have high absorption cross-sections, was enriched to 50% and 70%, respectively.

Table. II. Abundance of natural and enriched Gadolinium isotopes

Isotope	Abundance (%)		
^{152}Gd	0.20	0.14	0.09
^{154}Gd	2.18	1.57	0.94
^{155}Gd	14.80	24.30	34.02
^{156}Gd	20.47	14.72	8.83
^{157}Gd	15.65	25.70	35.98
^{158}Gd	24.84	17.86	10.71
^{160}Gd	21.86	15.72	9.43
Sum (=^{155}Gd + ^{157}Gd)	30.45 (Nat.)	**50.00**	**70.00**

- **FA Specifications of Boron-free Operation SMR**
  - FA Type (Westing House) → Control Rod worth
  - Additionally, high-concentration, low-content, gadolinia was also loaded.

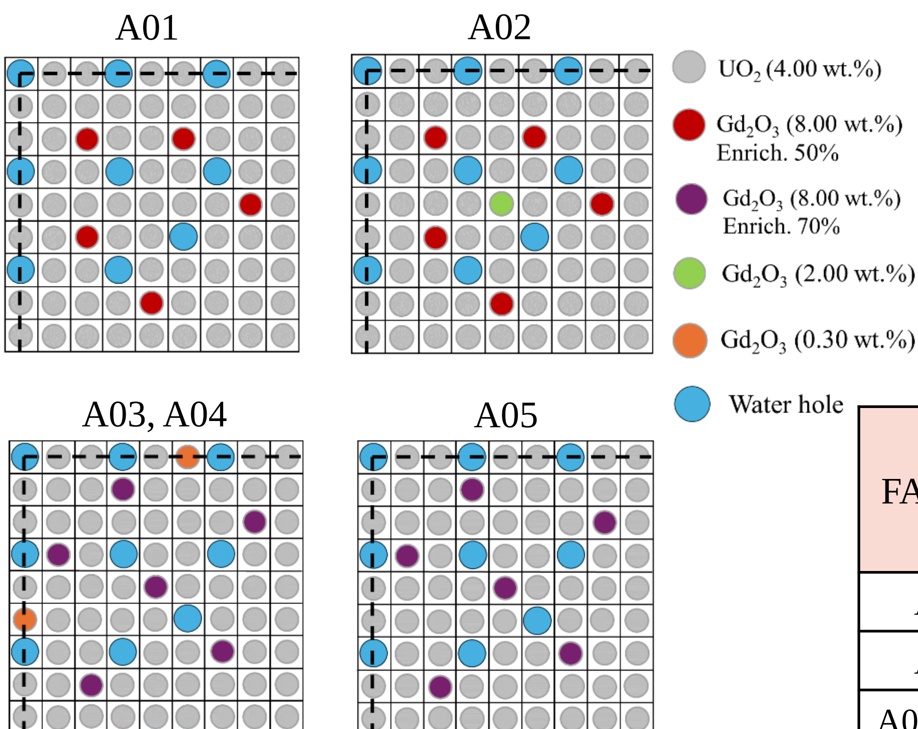


Fig. 2. Configuration of the FA models

Table. III. FA Specifications

Parameters	Value
Array	17 x 17
Rod pitch	1.26 cm
Assembly pitch	21.5 cm
Pellet radius	0.4096 cm
Guide tube Inner / Outer radius	0.5613 / 0.6124 cm

Table. IV. Composition of Burnable Absorber by FA Type

FA Type	Gd atomic ratio (a/o)	Gd_2O_3 (wt.%)		U_{235} Enrichment (wt.%)	
		High	Low	High	Low
A01	50	8.00	-	2.30	-
A02	50	8.00	2.00	2.30	2.90
A03, A04	70	8.00	0.30	2.30	3.90
A05	70	8.00	-	2.30	-

02 Design & Specifications

- **Improvement of Library Generation Code System for DeCART2D**
  - DeCART2D cross-section library for lattice code contains nuclide-wise nuclear reaction cross section and burnup dependent data.
  - Recently, Kim and Park applied the new cross section library correction procedure into the KAERI library generation code system.
    - ✓ ***CORRXS*** : Multi-group Cross Section Correction
    - ✓ ***CORRIT*** : Resonance Integral Table Correction

- **Correction Cross-section**
  - Correction factors based on MC
    - ✓ Absorption, nu-fission cross section
    - ✓ Scattering Matrix

$$f_{x,g}^{n+1} = \frac{\sigma_{x,g}^{MC}\phi_{x,g}^{MC}}{\sigma_{x,g}^{DE,n}\phi_{x,g}^{DE,n}}$$

$$\sigma_{x,g}^{DE,n+1} = f_{x,g}^{n+1}\sigma_{x,g}^{DE,n}$$

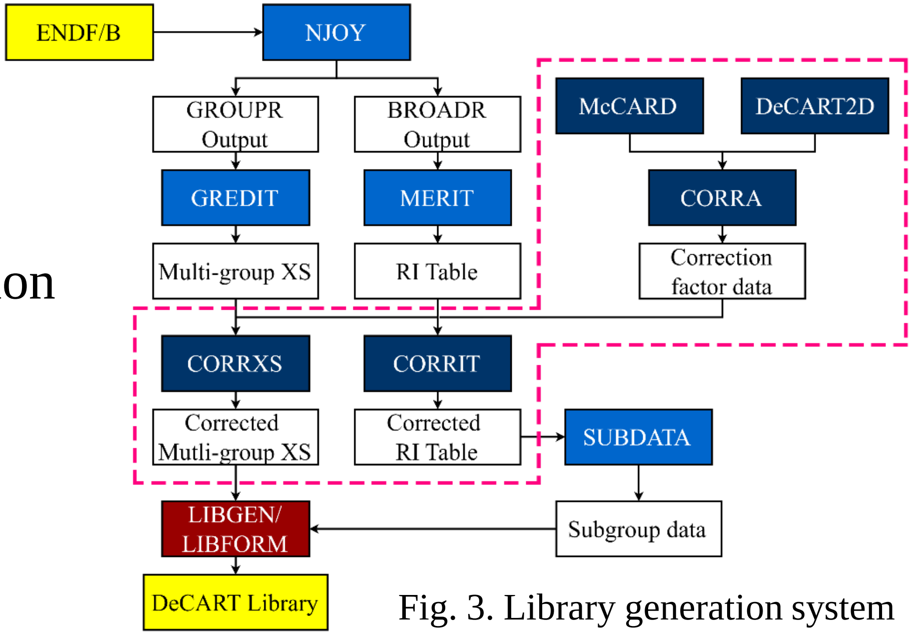


Fig. 3. Library generation system

※ $\sigma_{x,g}^{MC}$ and $\sigma_{x,g}^{DE,n}$: g^{th} energy group cross section for reaction type x by McCARD and DeCART2D.
※ $\phi_{x,g}^{MC}$ and $\phi_{x,g}^{DE,n}$: g^{th} energy group flux produced by McCARD and DeCART2D.

02 Design & Specifications

- **Calculation Conditions**
  - Based on ENDF/B-VII.1 nuclear data library
  - Temperature condition: HFP
    - ✓ Fuel: 900 K, Clad: 600 K, Moderator: 600 K
  - Boron concentration: 0 ppm (SBF)
- **McCARD calculation conditions**

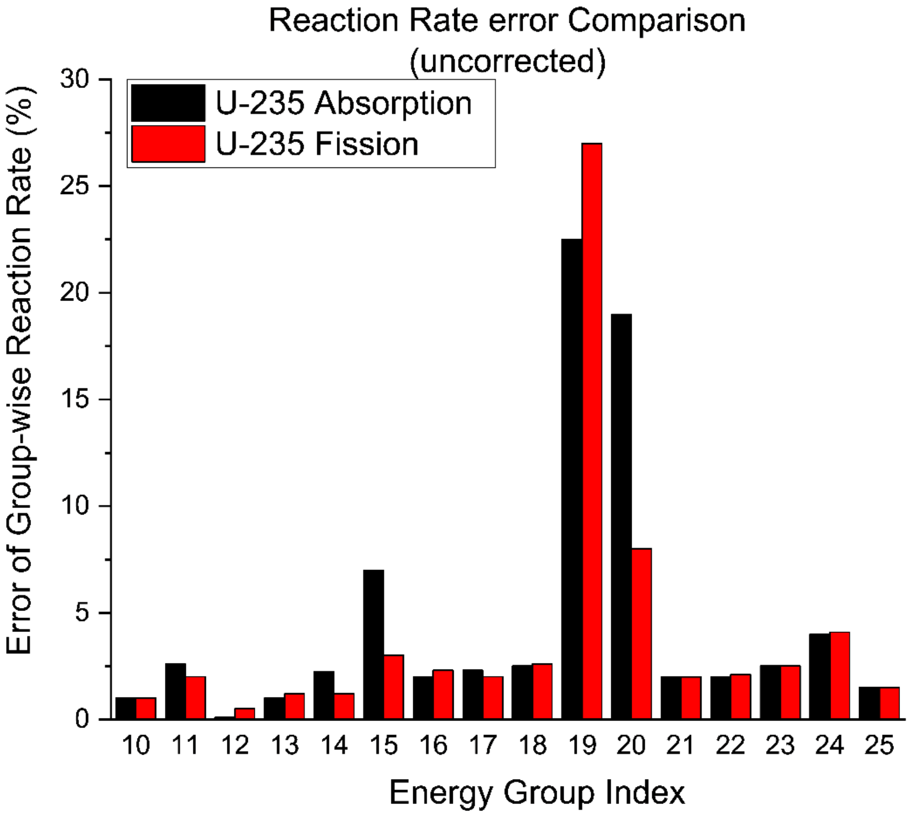
Case	Histories / Active cycles / Inactive cycles	Stochastic uncertainties (=1σ)
FA	50000 / 500 / 200	< 14 pcm
2D core	50000 / 1500 / 1000	< 13 pcm
Depletion	20000 / 150 / 100	< 40 pcm

- **Cross-Section Library for DeCART2D**

Library name	Library code	Note
Old Library	PV01-CR08	Existing library for analysis commercial PWR - U^{235}, U^{238} corrected
New Library	PV05-iSMR-CR04	Preliminary library for analysis Boron-free SMR - U^{235}, U^{238}, **Gd^{154}, Gd^{155}, Gd^{156}, Gd^{157}, Gd^{158}, Gd^{160}, H^{1}** corrected

03 Numerical Results

- **Boron-free Operation SMR Optimized Library Generation**
  - Large errors in group-wise reaction rates from uncorrected DeCART2D library
  - New DeCART2D library generation by multi-round corrections (improved system)
  - Corrected **U^{235}, U^{238}**, **Gd^{154}, Gd^{155}, Gd^{156}, Gd^{157}, Gd^{158}, Gd^{160}, H^1** isotopes



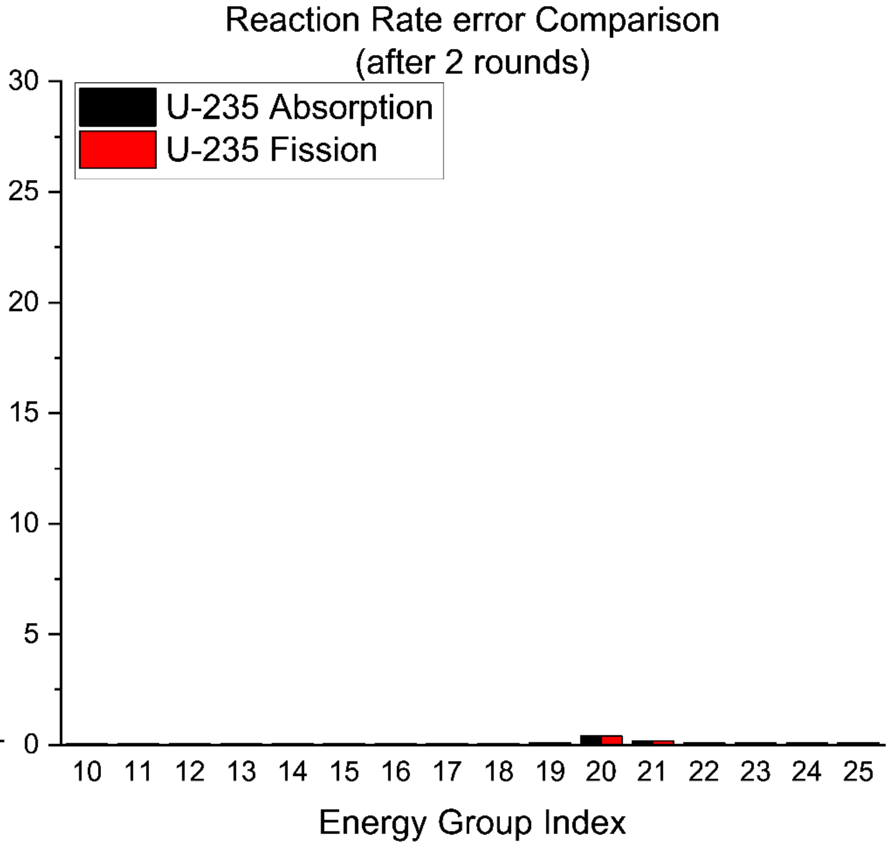


Fig. 4. Example of multi-round group-wise reaction rate corrections

- **FA Benchmark**
  - 5 FA benchmark problems - DeCART2D and McCARD (***reference***).
    - ✓ Old Library : Uncertainties in k_{eff} are less than 150 pcm.
    - ✓ New Library : Uncertainties in k_{eff} are less than 50 pcm. ➔ improvement of accuracy

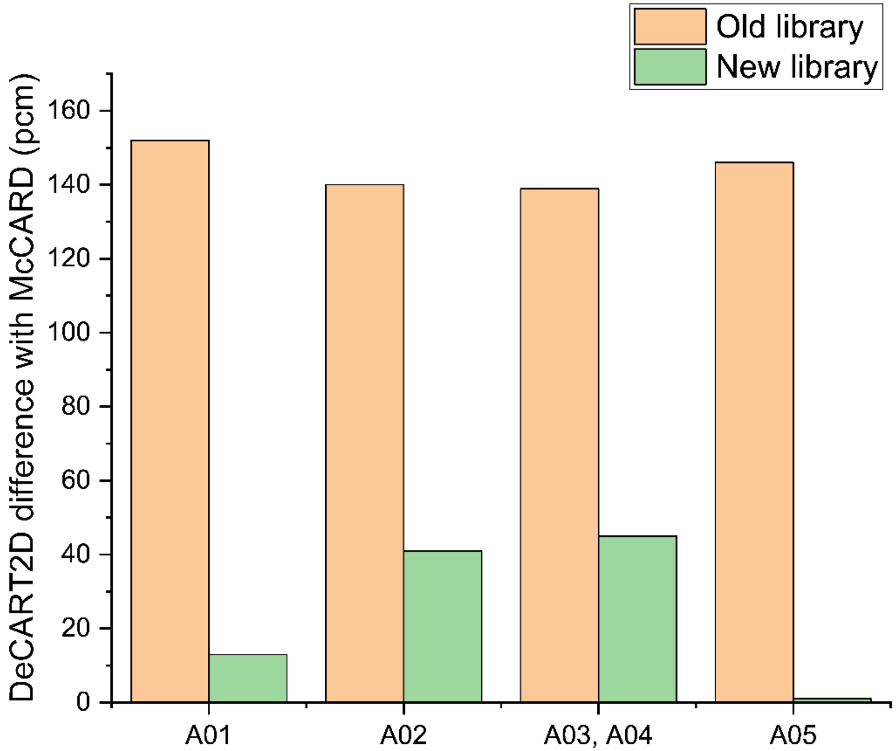


Fig. 5. Results of the FA models

Table. V. Multiplication factors of FA

Case	McCARD[1)]	DeCART2D difference with McCARD (pcm)	
	k_{eff}	Old[2)]	New[3)]
A01	1.09874	152	**13**
A02	1.06743	140	**41**
A03, A04	1.01797	139	**45**
A05	1.03422	146	**1**

1) Stochastic uncertainty (=1σ) is less than 0.00014
2) PV01-CR08 library
3) PV05-iSMR-CR04 library
4) $k_{DeCART2D} > k_{McCARD}$

- **2D Core Benchmark**
  - 2D core benchmark problem for the SBF system were performed by DeCART2D and McCARD.
    - ✓ Old Library : Uncertainties in k_{eff} are about 400 pcm.
    - ✓ New Library : Uncertainties in k_{eff} are about 20 pcm. ➔ improvement of accuracy

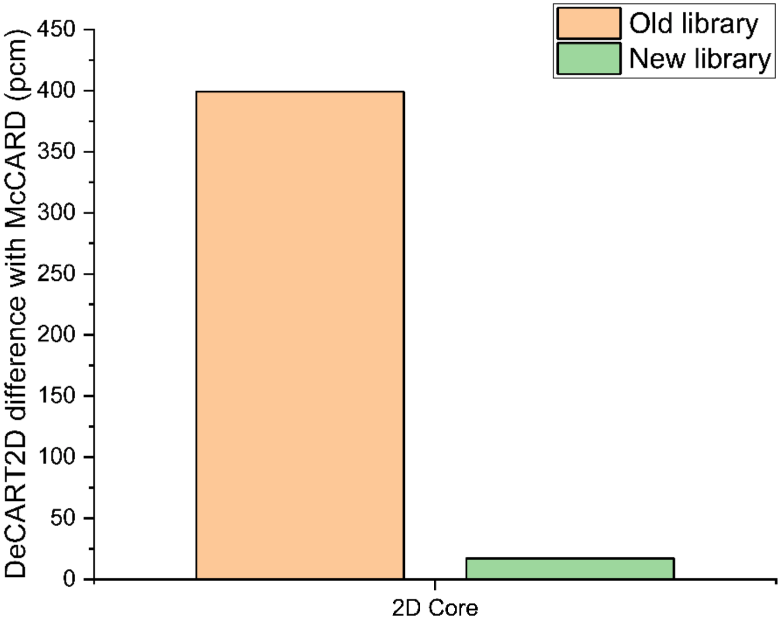


Fig. 6. Result of the 2D Core

Table. VI. Multiplication factors of 2D Core

Case	McCARD[1]	DeCART2D difference with McCARD (pcm)	
	k_{eff}	Old[2]	New[3]
2D Core	1.04240	399	**17**

1) Stochastic uncertainty (=1σ) is less than 0.00013
2) PV01-CR08 library
3) PV05-iSMR-CR04 library
4) $k_{DeCART2D} > k_{McCARD}$

- **2D Core Benchmark**
  - RMSE (maximum error) in FA-wise power distribution
    - ✓ Old Library : 1.08% (1.89%)
    - ✓ New Library : 0.47% (0.90%)

	E	F	G	H	J
	A03	**A05**	**A05**	**A05**	**A02**
5	-0.52%	-0.76%	-0.97%	-0.59%	1.19%
	-0.27%	-0.55%	-0.61%	-0.28%	0.42%
	A05	**A04**	**A03**	**A02**	**A01**
6	-0.76%	-0.74%	-0.94%	-0.37%	1.30%
	-0.55%	-0.41%	-0.44%	0.00%	0.44%
	A05	**A03**	**A03**	**A01**	**A01**
7	-0.97%	-0.94%	-0.36%	0.41%	1.89%
	-0.61%	-0.44%	0.17%	0.42%	0.57%
	A05	**A02**	**A01**	**A01**	
8	-0.59%	-0.37%	0.41%	1.74%	
	-0.28%	0.00%	0.42%	0.90%	
	A02	**A01**	**A01**		
9	1.19%	1.30%	1.89%		
	0.42%	0.44%	0.57%		

Fig. 6. FA-wise power distribution by McCARD and DeCART2D

Assembly
Old[1)]
New[2)]

RMSE
1.08%
0.47%

Max.
1.89%
0.90%

1) PV01-CR08 library
2) PV05-iSMR-CR04 library

- **Reference Solution Generation for FA Depletion Problem**
  - A03-type FA problem.
  - McCARD reference solutions : 98 DTS with QE/QI option.

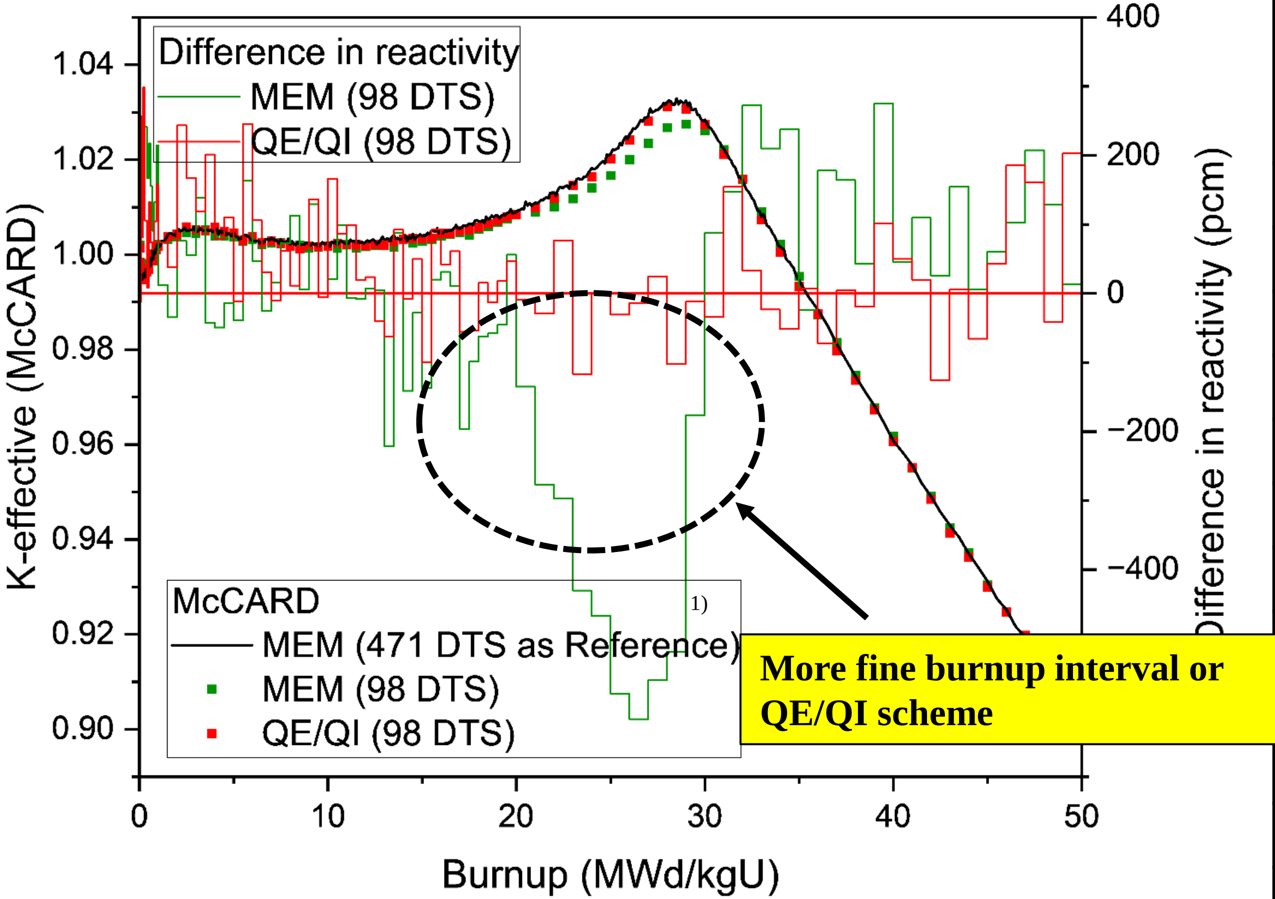


Fig. 7. Differences in reactivity among McCARD burnup analyses with various options

Burnup (MWd/kgU)	Difference (pcm)	
	MEM (98 DTS)	QE/QI (98 DTS)
0	61	-55
1	65	24
2	-115	-63
5	-110	-10
10	-95	-95
15	-111	-55
20	-50	-57
25	-430	-91
30	-219	-99
40	109	-17
50	-81	56
RMSE	**160**	**83**

- **FA Depletion Problem**
  - RMSE(New Library) = 98 pcm < RMSE(Old Library) = 130 pcm
  - Errors in reactivity after MOC may induce from the uncorrected actinide isotopes

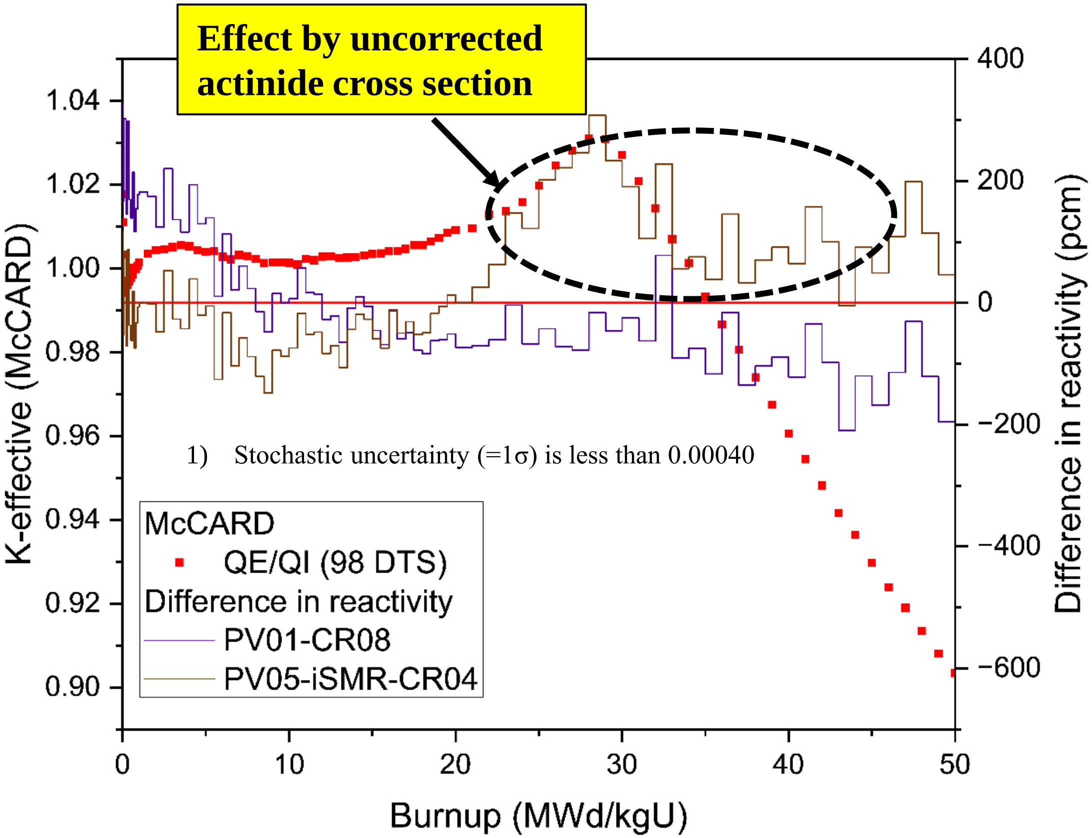


Fig. 8. Differences in reactivity among McCARD and DeCART2D

Burnup (MWd/kgU)	Difference (pcm)	
	Old	New
0	180	-5
1	182	0
2	124	47
5	139	5
10	7	-73
15	-45	-59
20	-72	0
25	-42	201
30	-24	191
40	-121	64
50	-63	185
RMSE	**130**	**98**

- **3D Core calculation**
  - Compared KARMA/ASTRA results of the paper of J.S. Kim[1][2]
  - Similar ***ASI*** and ***Fq***, but Large difference in ***reactivity*** between ASTRA and MASTER
    - ✓ Uncertain and unclear specification : cutback region, reflector, enrichments

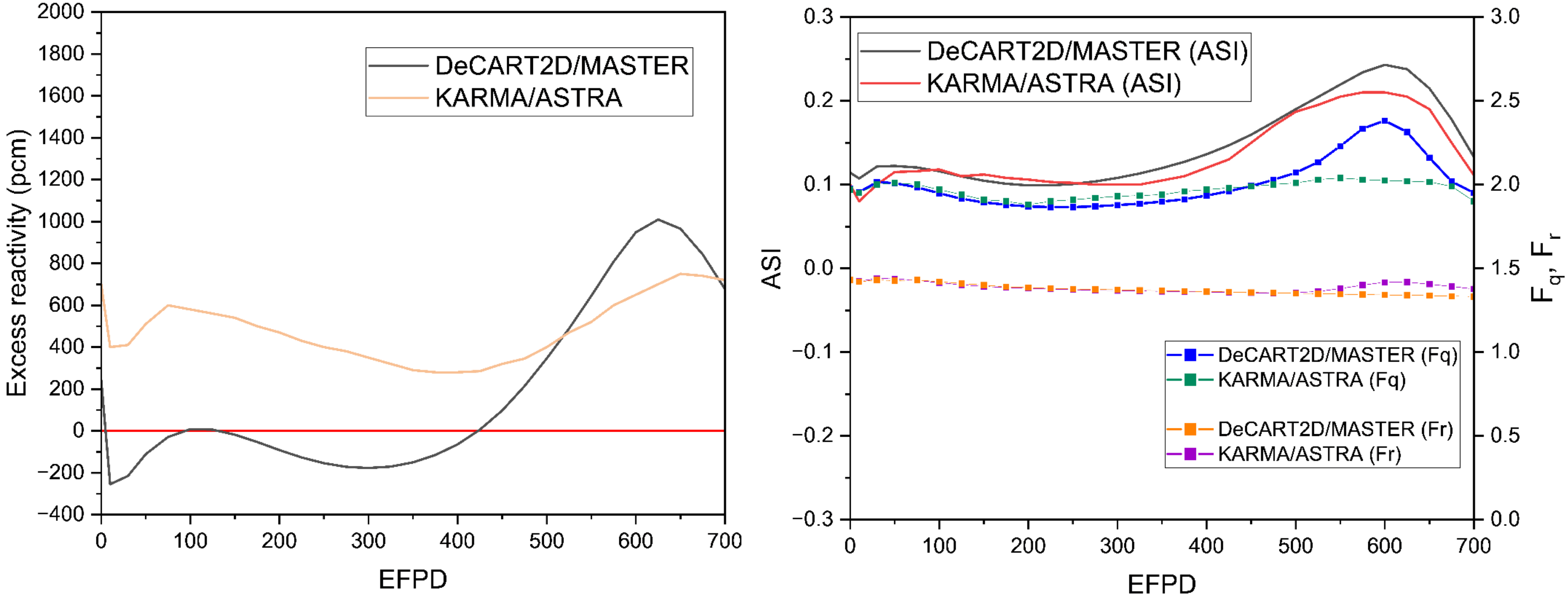


Fig. 9. Differences DeCART2D/MASTER and KARMA/ASTRA

04 Conclusions & Future works

04 Conclusions & Future works

- **Conclusions**
  - Preliminary analysis for Boron-free SMR has been successfully conducted using ***DeCART2D/MASTER*** 2-Step procedure code system.
  - Reference solutions were generated by ***McCARD*** MC code.
  - Generated new Boron-free SMR optimized DeCART2D library (***New library***) using the improved KAERI library generation code system.

  - Summary of Results

Case	ρ difference	
	Old	New
A01	152	13
A02	140	41
A03, A04	139	45
A05	146	1
2D Core	399	17

Power distribution	Difference (%)	
	Old	New
RMSE	1.08	0.47

Burnup	Difference (pcm)	
	Old	New
RMSE	130	98

  - The new Boron-free SMR optimized library shows better performance in estimating reactivity, power distributions.

04 Conclusions & Future works

- **Future works**
  - In the near future, 3D Core multi-cycle analysis for up-to-date or finalized i-SMR core design by MASTER code will be conducted.
    - ✓ Core follow analysis
    - ✓ Comparison of nuclear design parameters
  - The i-SMR optimized library will be generated, especially the cross sections for Pu and minor actinide isotopes will be corrected for the depletion analysis.

05 References

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Thank you!

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