Preliminary Benchmarking of DeCART2D/MASTER Two-Step Core Design System for APR-1400 Benchmark using Improved Cross Section Library

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1. Introduction

A common two-step analysis system has been widely used for one of the nuclear core analysis systems due to its computational efficiency. The two-step analysis system consists of a lattice analysis for few-group constant (FGC) generations and a nodal analysis for a whole core analysis. In the two-step procedure, a nuclear reaction cross section library used in the lattice analysis code is very important because it directly determines the accuracy of the burnup-dependent FGCs. Therefore, in various reactor core design code systems, producing a system-optimized library for a target system is crucially considered. In general, nuclear reaction cross sections are generated by solving slowing-down equations using an approximate spectrum similar to the target system. Accordingly, an error of a design parameter may occur due to the spectrum approximations. Hence, the initially produced library may be corrected to suit the system in the subsequent stage. The nuclear reaction cross section library correction can be carried out by applying the ratio of group-wise reaction rates of a design code to a reference code as a correction factor [1,2].

In this study, the DeCART2D [3]/MASTER [4] two-step code system developed by Korea Atomic Energy Research Institute (KAERI) is used as the two-step analysis code system, and McCARD [5], the Monte Carlo (MC) neutron/gamma transport code is used as the reference code for the library correction. Until now, in the DeCART2D lattice library generation code system, the library correction process has been manually conducted rather than automatically. In this study, the library correction process has been improved by automating the process of correction factor generations for each isotope and energy group. In this study, the target problem for the library correction is the APR-1400 benchmark problem [6], which is a product of the US/ROK I-NERI program and it provides detailed problem conditions and results from single pin cells to fuel assemblies (FAs), 2D cores, and 3D cores. In addition, the results of this DeCART2D/MASTER code system are also compared with the DeCART solution [7] contained in the APR-1400 benchmark.

2. Brief Description of APR-1400 Benchmark

The APR-1400 benchmark documentation [6] provides detailed specifications for geometric information and material composition. The APR1400 reactor core is composed of 17x17 core lattice with 241 fuel assemblies (FAs). Each assembly has 236 fuel or burnable absorber rods, and 5 tube cells occupy 2x2 pin cell size. The pitch of a fuel pin is about 1.285 cm, and the pitch of a FA is 20.77cm. There are 9 FAs from A0 to C3 in the benchmark problem, and these assemblies are distinguished by fuel enrichment or Gd burnable absorber rod arrangement. There are 9 spacer grids smeared to the corresponding axial location of assembly [6]. Table I shows the description of the sub-problems provided in the APR-1400 benchmark.

Table I. APR-1400 benchmark problem

No.	Name	Conditions	Number of Problem
1	Single pin cell	5 enrichments 3 temperatures 3 boron concentrations	45
2	2D assembly	9 assemblies 3 temperatures 3 boron concentrations	81
3	2D core	3 temperatures 3 boron concentrations	9
4	3D core	3 temperatures 3 boron concentrations	9

Table II. Conditions of temperature and boron concentration for APR-1400 Benchmark

No.	Problem ID*	Temperature [K]			Boron [ppm]
		Fuel	Clad	Moderator	
1	CZP0	300	300	300	0
2	HZP0	600	600	600	0
3	HFP0	900	600	600	0
4	CZP1	300	300	300	1000
5	HZP1	600	600	600	1000
6	HFP1	900	600	600	1000
7	CZP2	300	300	300	2000
8	HZP2	600	600	600	2000
9	HFP2	900	600	600	2000

* CZP, HZP, and HFP indicate cold zero power, hot zero power, and hot full power condition. And 0, 1, 2 indicate 0, 1000, 2000 boron concentration(ppm).

In the APR-1400 benchmark, various enrichment of nuclear fuel rods is utilized - 1.71w/o, 2.00w/o, 2.64w/o, 3.14w/o, and 3.64w/o. According to the enrichment and Gd burnable absorber arrangements, FAs consist of A0 to C3 assemblies. The condition of temperature and boron concentrations in the benchmark are also described in Table II.

3. Improvement of DeCART2D Library Correction Code System

3.1 Library Correction Procedure

A lattice code library contains nuclear reaction neutron cross section data and depletion data for each nuclide. To enhance the accuracy and precision of the library, it is necessary to improve the accuracy of group-wise nuclear reaction cross-sections or group-wise nuclear reaction rates. Because a MC code provides high fidelity solutions for neutron transport analysis, in this study, the factors for the nuclear reaction cross section correction of the DeCART2D lattice code will be generated by Monte Carlo core analysis code, McCARD. Through this library correction process, the group-wise reaction rates or cross sections will matches the reference from the McCARD results as closely as possible.To match the reaction rate of DeCART2D with McCARD, correction factors are generated for each energy group. This can preserve the group-wise reaction rates of the reference and it is a simple yet powerful cross section adjustment method. The correction factor can be calculated by

$$f_{x,g}^{n+1} = \frac{\sigma_{x,g}^{MC}\phi_g^{MC}}{\sigma_{x,g}^{DE,n}\phi_g^{DE,n}}, \quad \ldots (1)$$

$$\sigma_{x.g} = \frac{\int_{\Delta E_g}\sigma_x(E)\phi(E)dE}{\int_{\Delta E_g}\phi(E)dE}, \quad \ldots (2)$$

where $\sigma_{x,g}^{MC}$ and $\sigma_{x,g}^{DE,n}$ indicate g-th energy group cross section for x-type reaction by McCARD and DeCART, respectively. And ϕ_g^{MC} and $\phi_g^{DE,n}$ denote g-th energy group flux produced by McCARD and DeCART2D. The correction factor, $f_{x,g}^{n}$, is the ratio of the reaction rates from McCARD to DeCART2D at an iteration index n for x-type reaction and g-th energy group. The cross section at the next iteration stage will be produced by multiplying the cross section at the current stage by the correction factor as below:

$$\sigma_{x,g}^{DE,n+1} = f_{x,g}^{n+1}\sigma_{x,g}^{DE,n}. \quad \ldots (3)$$

Figure 1 shows correction results of group-wise reaction rates by the correction factors. After the iteration step 2, it is observed that the relative error of the isotope-wise reaction rates has significantly decreased.

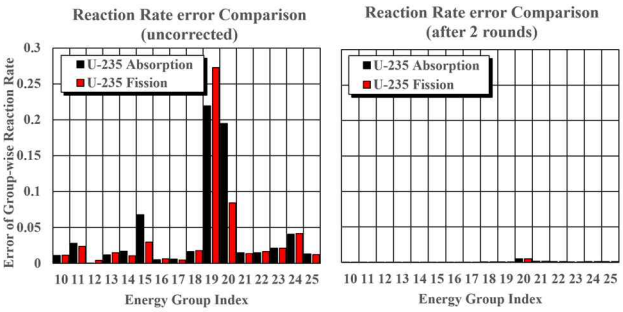

Figure 1. Change of the errors by reaction rate adjustments using correction factors (Left: uncorrected, Right: 2nd iterations)

3.2 Automation of the DeCART2D Library Correction System

For DeCART2D lattice code library generation, the code system was established by KAERI [2]. Then, the CORRXS and CORRIT codes for library correction was developed by Park et al. [1] In the library correction code system, CORRXS and CORRIT correct multi-group cross sections and reactivity integral tables (RITs). For the target nuclides and given temperature conditions, the two codes calculate the correction factors between McCARD and DeCART2D and correct the cross sections. However, some process to produce correction factors have been manually performed. To fully automate this process, the CORRA program, an automated correction factor generator, was developed. Figure 2 shows the flow chart of the improved library correction system.

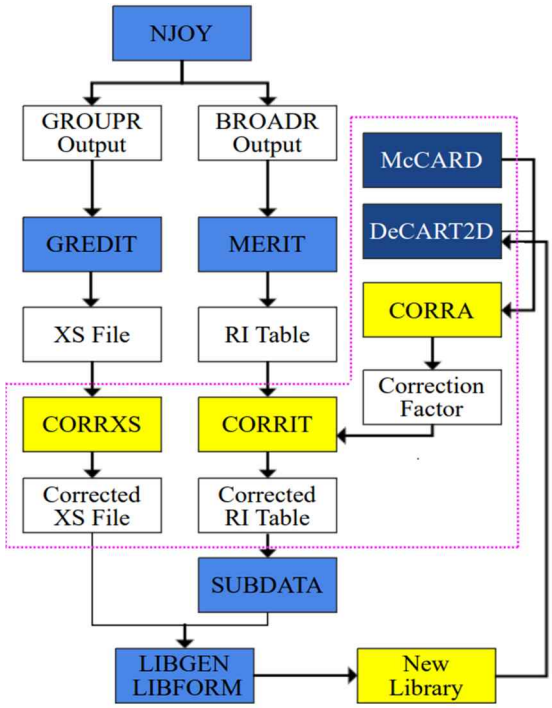

Figure 2. Flow chart of cross section correction procedure in KAERI library generation system

4. DeCART2D/MASTER Results for APR-1400 Benchmark with the improved library

A new library (*CR05-R15*) was generated with 15 iterations of correction for 9 major nuclides (i.e., ^{235}U, ^{238}U, ^{154}Gd, ^{155}Gd, ^{156}Gd, ^{158}Gd, ^{160}Gd, ^{10}B, ^{11}B) using the automated library correction system. In this study, all APR-1400 benchmark calculations were calculated using the DeCART2D with the newly generated *CR05-R15* library. Library correction has been conducted based on ENDF/B-VII.1 nuclear data library.

4.1 Single Pin Cell Problem

In the single pin cell problem, the average reactivity difference between the McCARD reference solutions and the DeCART2D results by the *CR03-R12* library is about 36 pcm and RMS error is 55 pcm. The DeCART solution, which were taken from Ref [7], has an average reactivity difference of 57 pcm and a RMS error of 107 pcm. Figure 3 shows the results of the single pin problem. However, relatively large errors still occurred under the CZP condition.

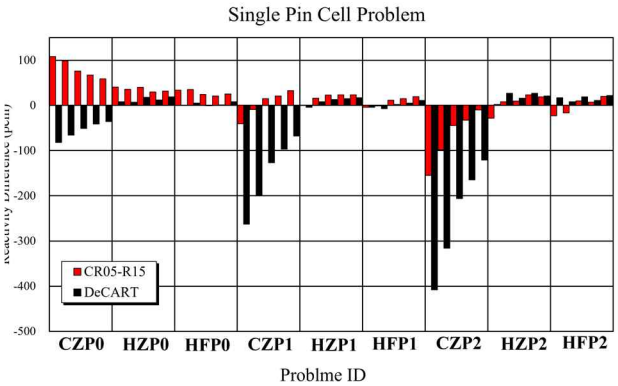

Figure 3. Reactivity difference for single pin cell problem compared with DeCART solution

4.2 2D FA Problem

In the 2D FA problem, there are no significant difference between the DeCART solutions and the McCARD results. The average error in reactivity is 41 pcm and the RMS error is 53 pcm. The DeCART solution had an average reactivity difference of 45 pcm and a RMS error of 60 pcm. It is noted that the maximum and RMS errors in the pin power are less than the DeCART solution. Figure 4 shows the reactivity difference for the 2D FA problem, and Figure 5 shows the RMS error (%) of the pin-power distribution for FAs C1, C2, and C3.

4.3 Depletion Problem for Pin and FA

To confirm the accuracy of the new library over burnup, APR-1400 depletion benchmark problems are introduced. All depletion analyses were performed over 18 MWD/kgU. The reference solution for the depletion benchmark problems were calculated by the McCARD code. In the reference solution, the stochastic uncertainties in k_{eff} ranged from 70 pcm to 80 pcm at each depletion time step. Figure 6 compared the k_{eff} by the DeCART2D with the new library and the McCARD reference solutions for 3.14 w/o and 3.65 w/o pin problems with 1,000 ppm boron concentration under the HFP condition. The RMS error in reactivity for 3.14 w/o and 3.65 w/o problems are 73 pcm and 79 pcm over burnup, respectively. Figure 7 presents the McCARD and DeCART2D results for 2 FA depletion problems. For FA depletion benchmark, B0 and B3 FA problem were selected. The RMS error in reactivity for B0 and B3 FA depletion problems are 73 pcm and 170 pcm over burnup, respectively.

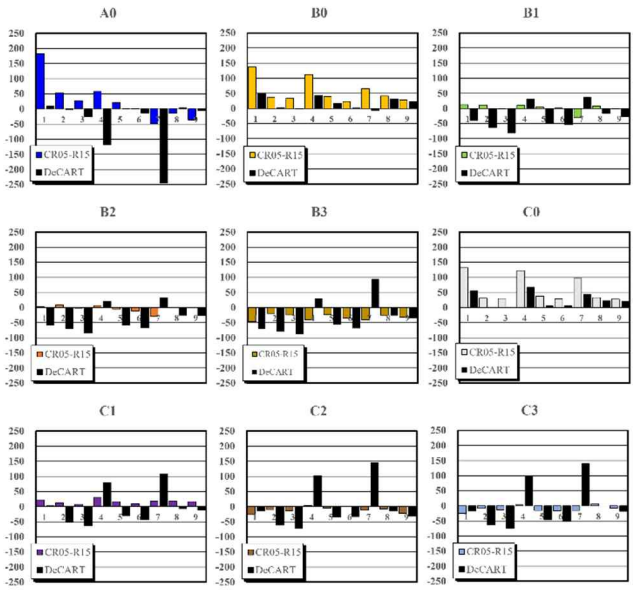

Figure 4. Reactivity difference for 2D assembly problem

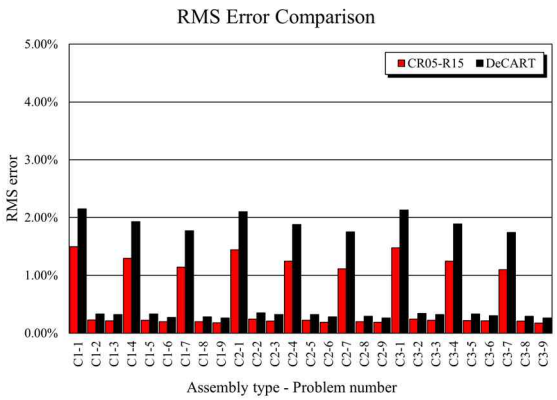

Figure 5. RMS error for 2D assembly problem's pin-wise fission power distribution

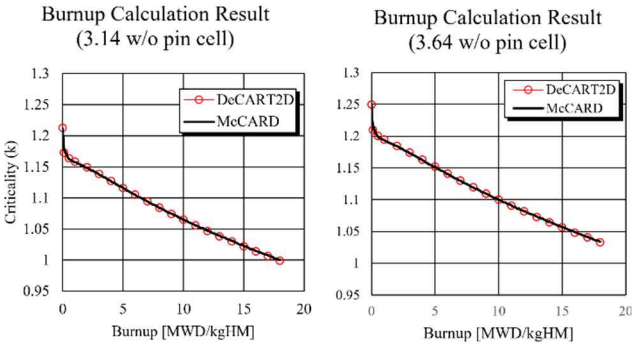

Figure 6. Criticality trend in single pin cell burnup calculation over burnup

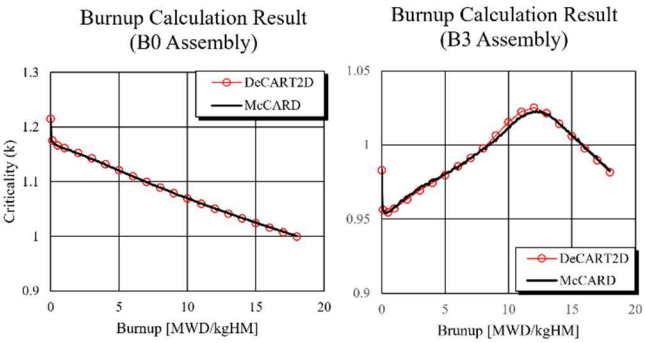

Figure 7. Criticality trend in 2D assembly burnup calculation according to burnup

4.4 2D Core Problem

In the 2D core problem, DeCART2D obtained results of an average reactivity difference of 92 pcm and an RMS error of 102 pcm, as shown in Figure 8. In the DeCART solution, these are 25 pcm and 29 pcm respectively.

4.5 3D Core Problem

In this study, the 3D core benchmark problems for APR-1400 were solved by the DeCART2D/MASTER two-step core analysis system. As shown in Figure 8, the 3D core problem has an average reactivity difference of 126 pcm and a RMS error of 139 pcm. Meanwhile, the DeCART solution has an average reactivity difference of 32 pcm and RMS error of 41 pcm. Figure 9 is the assembly-wise power distribution of the 3D core problem. The power distribution shows a tilted-tendency for the radius. This is suspected to be an effect of uncorrected cross section in the reflector region, and it is an essential issue to be solved in 2D and 3D core problems.

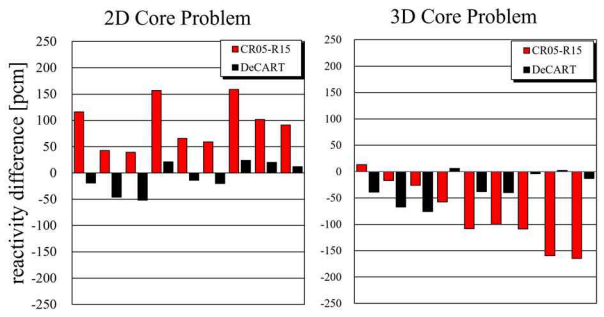

Figure 8. Reactivity difference for 2D and 3D core problem

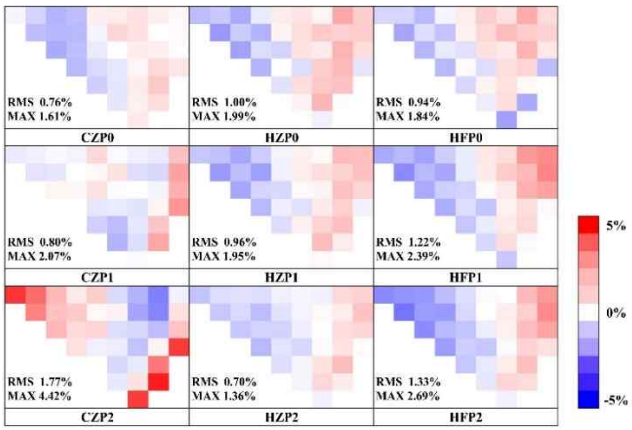

Figure 9. Assembly-wise power distribution for 3D core problems

Figure 10 compared the CBC letdown curves by the DeCART2D/MASTER, DeCART, nTRACER, and MPACT code. The DeCART results are taken from Ref. [7] and the nTRACER and MPACT from Ref. [8]. The number of depletion time steps is 20 over 18 MWd/kgU. It is observed that the CBC results by DeCART2D/MASTER are very similar to DeCART and nTRACER at BOC, and MPACT at EOC.

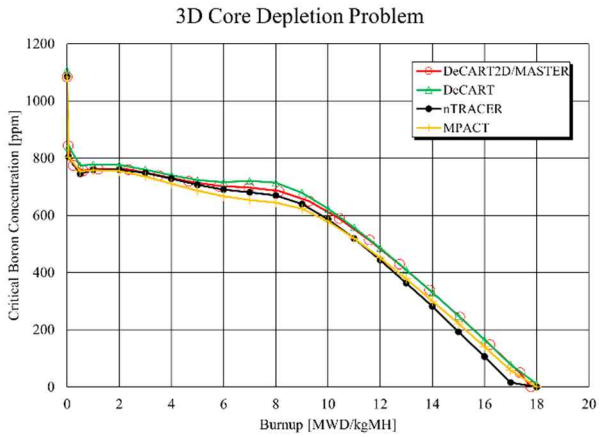

Figure 10. Critical boron concentration letdown curve for APR-1400 3D core depletion problem

5. Conclusion

In this study, the DeCART2D library generation system was improved by the automation of the correction factor generation process. It can treat numerous correction processes easily and efficiently. The new DeCART2D library was generated by the corrections for 9 major nuclides (i.e., ^{235}U, ^{238}U, ^{154}Gd, ^{155}Gd, ^{156}Gd, ^{158}Gd, ^{160}Gd, ^{10}B, ^{11}B).

A preliminary solution to the APR-1400 benchmark problem with the newly generated DeCART2D library was applied to the DeCART2D/MASTER code system. The improved library showed improved results over the reference DeCART solution for pin and FA problems. More even results were obtained than before in pin-wise power distribution, and stable reactivity differences were also seen in the additionally solved burnup problem.

However, in the 2D and 3D core problem, there are significant differences in FA-wise power distributions between the reference and DeCART2D/MASTER. This tilt behavior may be caused by the error from the uncorrected reflector cross section. In the near future, the automate library correction process will be extended to the reflector cross section correction.

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