DeCART Solutions of APR1400 Reactor Core Benchmark Problems

Seungsu Yuk* and Jin Young Cho
Korea Atomic Energy Research Institute, 111, Daedeok-daero 989beon-gil, Daejeon, 34057, Korea
**Corresponding author: syuk@kaeri.re.kr*

1. Introduction

In the development of advanced nuclear reactors, the importance of high-fidelity reactor analysis is gradually emerging. DeCART [1], a whole-core transport analysis code developed by KAERI, provides fine-mesh level solution that yields the power distribution inside the fuel pins over the whole core region. Therefore, DeCART can provide high-fidelity analysis at the level desired for advanced reactor development.

Before the application to advanced reactor core development, the verification and validation should be required for DeCART code. APR1400 reactor core benchmark problem [2] is one of the benchmark problems, which is developed for the above purpose. KAERI constructed a benchmark suite based on published specifications from the APR1400 reactor [3] and performed calculations via McCARD [4], a continuous energy Monte Carlo code, to prepare a reference solution.

This paper presents DeCART analysis results for the APR1400 reactor core benchmark problems. DeCART calculations were performed for various problems, from fuel pin problems to three-dimensional core problems. In addition, multi-physics simulation using self-hydraulic analysis function was performed to carry out single-cycle depletion calculation of the hot full power state.

2. APR1400 Reactor Core Benchmark Problems

APR1400 reactor core benchmark problems describes in detail the core structure of a PWR based on the published data of Shin-Kori Unit 3 reactor core. Benchmark problems are classified into six categories according to the structure and the specification of the problem as follows.

1) Single fuel pin problems (2-D)
2) Single fuel assembly problems (2-D)
3) 2-D core problems
4) 3-D core problems
5) Control rod worth problems
6) A single cycle depletion problem

The first four categories classify the problems according to the temperature of the fuel/clad/coolant and the concentration of soluble boron. Table I summarizes the temperature conditions and boron concentration conditions used in the benchmark problems.

Table I: Temperature and Boron Concentration Conditions for APR1400 Benchmark Problems

Conditions		Temperature [K]			Boron concentration [ppm]
		Fuel	Clad	Coolant	
1	CZP*, 0 ppm	300	300	300	0
2	HZP*, 0 ppm	600	600	600	
3	HFP*, 0 ppm	900	600	600	
4	CZP, 1000 ppm	300	300	300	1000
5	HZP, 1000 ppm	600	600	600	
6	HFP, 1000 ppm	900	600	600	
7	CZP, 2000 ppm	300	300	300	2000
8	HZP, 2000 ppm	600	600	600	
9	HFP, 2000 ppm	900	600	600	

*CZP: cold zero power, HZP: hot zero power, HFP: hot full power

In the fifth category, problems are classified according to the state of insertion of the control rod groups under the condition of hot zero power and 0 ppm boron concentration. The final problem is the core depletion calculation to search for the critical boron concentration at each burnup step.

The total number of problems is 152:
1) 45 single fuel pin problems
(Problem IDs: APR01V01 ~ APR01V45)
2) 81 single nuclear fuel assembly problems
(Problem IDs: APR02A0V01 ~ APR02C3V09)
3) Nine 2-D core problems
(Problem IDs: APR03V01 ~ APR03V09)
4) Nine 3-D core problems
(Problem IDs: APR04V01 ~ APR04V09)
5) Seven control rod worth problems
(Problem IDs: APR05V01 ~ APR05V07)
6) One core depletion problem
(Problem ID: APR06V01)

Reference solutions to benchmark problems were produced using the continuous-energy Monte Carlo code McCARD with ENDF/B-VII.1 neutron cross section library. The standard deviation of multiplication factors for McCARD results were within 4~7 pcm. The detailed specifications and references of each problem were published as a benchmark problem book [2].

3. Calculations and Results

The APR1400 benchmark problems were solved using DeCART, and the results were compared with reference solution in [2]. The DeCART calculations were conducted with the ENDF/B-VII.1 based 47-group cross section library [5]. The anisotropic scattering source is treated by the order of P2 developed in [6].

For the ray tracing option, the ray-spacing of 0.02 cm, 4 polar angles of 90, and 8 azimuthal angles of 90 were used.

The calculation results are summarized for each category of benchmark problem as follows.

3.1 Single Fuel Pin Cell Problems

There were 45 single nuclear fuel rod problems with 5 kinds of nuclear fuel (U-235 enrichment: 1.71%, 2.00%, 2.64%, 3.14% and 3.64%) and 9 conditions shown in Table I. Fig. 1 shows the reactivity error of DeCART calculation. Here, the horizontal axis is the end index of the problem ID, ranging from 1 to 45. The reactivity error is within 30 pcm in the problem except for the cold zero power condition. The DeCART result is well matched with the reference solution. It shows a somewhat large error at CZP, and the maximum error value of 408 pcm can be shown in the conditions of concentration 1.71%, CZP, and 2000 boron ppm. These large errors come from the multi-group cross section library that focuses on reactor operating temperature.

3.2 2-D Fuel Assembly Problems

This category deals with nine different fuel assemblies (A0, B0-B3, C0-C3) used in the first cycle of APR1400 core. For each nuclear fuel assembly, nine conditions shown in Table I were considered (total: 81 problems). Fig. 2 shows the reactivity errors of DeCART. Here, the horizontal axis is the nuclear fuel assembly name and end index of problem ID. Except when the boron concentration is not 0 ppm at CZP (the end of the problem ID is 4, 7), the error is at the level of several tens of pcm and agrees well with reference solution. The maximum reactivity error occurs at APR02A0V07 (A0 assembly, CZP, 2000 boron ppm) and is about 244 pcm.

Table II shows the average of the DeCART pin power RMS errors under nine problem conditions for each assembly type. Here, the average of the pin power RMS error does not exceed 0.87%.

3.3 2-D Core Problems

For the two-dimensional core problem, we referred to the fuel loading pattern of the first cycle for Shin-Kori Unit 3. Nine conditions shown in Table I were considered. Fig. 3 shows the DeCART reactivity error and the maximum error in the assembly-wise power distribution. Here, the horizontal axis is the problem ID. In all problems, the reactivity error does not exceed 60 pcm, and the maximum error of the power distribution does not exceed 1.8%.

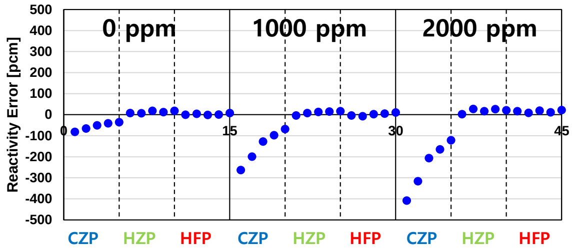


Fig. 1. Reactivity difference between DeCART and McCARD for single fuel pin cell problems

Table II: The Average of Pin Power RMS Error for APR1400 Single Fuel Assembly Problems

Assembly Type	Average of Pin Power RMS Error [%]	Assembly Type	Average of Pin Power RMS Error [%]
A0	0.21	C0	0.29
B0	0.25	C1	0.85
B1	0.87	C2	0.84
B2	0.87	C3	0.84
B3	0.87		

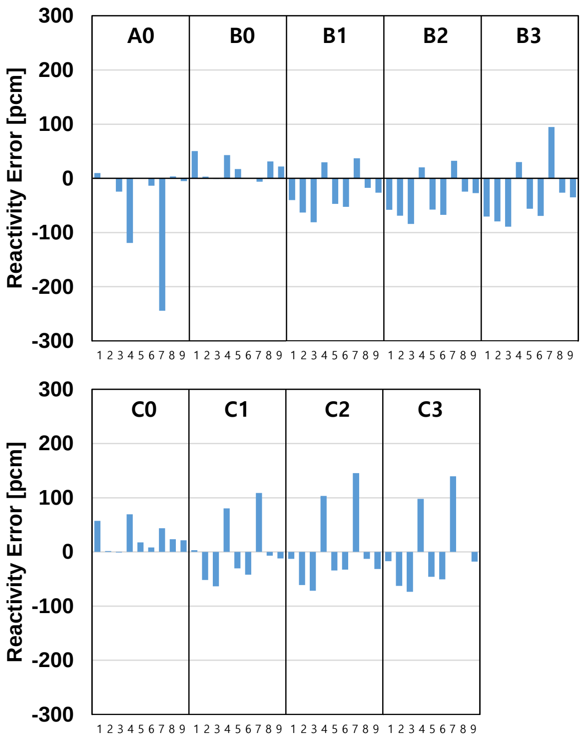


Fig. 2. Reactivity difference between DeCART and McCARD for single fuel assembly problems

3.4 3-D Core Problems

For the three-dimensional core problem, the nuclear fuel loading pattern of the first cycle of Shin-Kori Unit 3 was considered and the axial structure was described in detail. As with the two-dimensional core problem, nine conditions shown in Table I were considered. Fig.

4 shows the DeCART reactivity error and the maximum error in the assembly-wise power distribution. Here, the horizontal axis is the problem ID. In all problems, the reactivity error does not exceed 80 pcm, and the maximum error of the power distribution does not exceed 3.0%. Fig. 5 and Fig. 6 show the radial and axial power distribution of the APR04V06 problem (full power state, boron concentration 1000 ppm), respectively. Most of the DeCART calculation results agree well with the reference solution. However, the maximum errors of 1.48% and 1.01% occur at the outer region of core and the top of the core with low power, respectively.

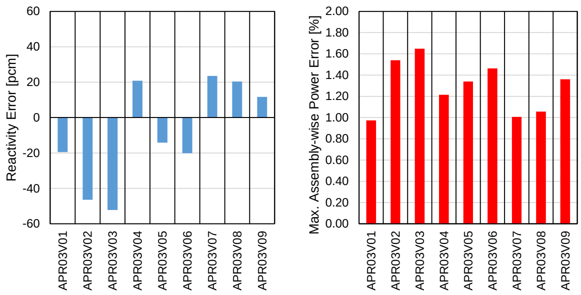


Fig. 3. The numerical results of DeCART for APR1400 2-D core problem

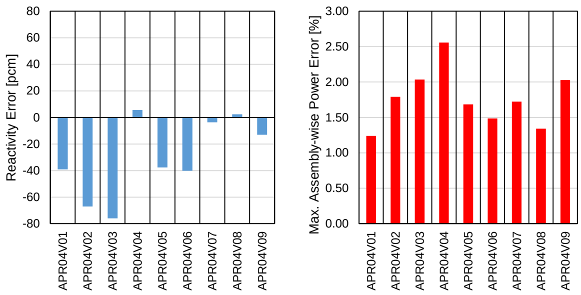
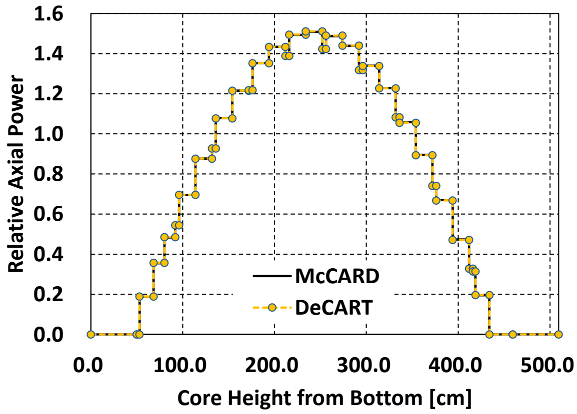


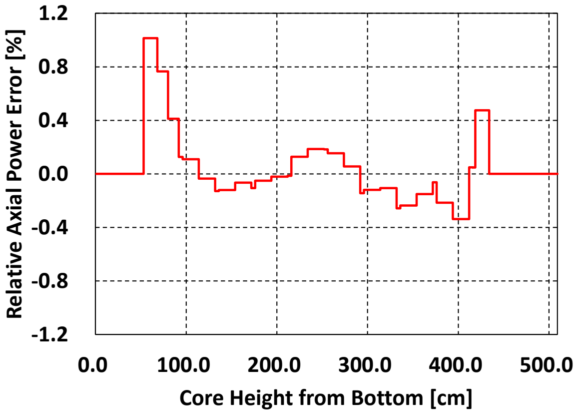
Fig. 4. The numerical results of DeCART for APR1400 3-D core problem

1.0174	0.9686	1.1744	0.9781	1.2177	0.9989	1.0589	1.0736	0.9638
1.0272	0.9776	1.1831	0.9880	1.2250	1.0029	1.0545	1.0644	0.9497
-0.95	-0.92	-0.73	-1.00	-0.59	-0.40	0.42	0.87	1.48
	1.0891	0.9629	1.1093	0.9976	1.2037	0.9479	0.9955	0.9994
	1.0972	0.9735	1.1156	1.0052	1.2044	0.9487	0.9889	0.9848
	-0.74	-1.08	-0.56	-0.76	-0.06	-0.08	0.67	1.48
		1.2071	0.9672	1.1875	0.9690	1.1254	1.0124	0.8716
		1.2126	0.9750	1.1902	0.9732	1.1224	1.0073	0.8606
		-0.45	-0.80	-0.22	-0.43	0.27	0.51	1.28
			1.0929	0.9510	1.0693	0.9209	0.9313	0.6897
			1.0963	0.9576	1.0719	0.9223	0.9282	0.6815
			-0.31	-0.69	-0.24	-0.15	0.33	1.20
	DeCART			1.1706	0.9227	1.0715	1.0150	
	McCARD			1.1722	0.9272	1.0697	1.0085	
	Diff. [%]			-0.14	-0.48	0.17	0.64	
					0.9810	0.9924	0.7186	
					0.9825	0.9889	0.7111	
					-0.15	0.36	1.06	
	RMS Diff.	0.72 %				0.7572		
	Avg. Diff.	0.61 %				0.7544		
	Max. Diff.	1.48 %				0.37		

Fig. 5. Radial and axial power distribution of APR04V06 3-D core problem



(a) Axial power distribution



(b) Axial power error

Fig. 6. Axial power distribution of APR04V06 3-D core problem

3.5 Control Rod Worth Problems

This benchmark problem deals with the control rod worth of each control rod group by inserting the control rod groups. The base problem is APR04V02 problem (all control rod withdrawal, HZP, 0 boron ppm). Control rod specification, location, and insertion order of the control rod groups were referred to the first cycle of Shin-Kori Unit 3. Table III shows the control rod worth error of DeCART. It shows that most of them are within 1% of the reference solution, but when the B control rod group is inserted, the error of the control rod worth is the largest.

Table III: DeCART numerical results for APR1400 control rod worth problems

Problems	Inserted Control Rod Groups	Group-wise CRW Error [%]	Accumulated CRW Error [%]
APR05V01	5	0.36	0.36
APR05V02	5-4	1.13	0.72
APR05V03	5-4-3	0.89	0.82
APR05V04	5-4-3-2	0.65	0.76
APR05V05	5-4-3-2-1	-0.06	0.41
APR05V06	5-4-3-2-1-B	1.89	1.10
APR05V07	5-4-3-2-1-B-A	0.34	0.76

3.6 3-D Core Depletion Problem

This benchmark problem is a problem of calculating the first-cycle depletion at HFP with critical state. The first cycle of Shin-Kori Unit 3 reactor core is referred and depletion calculation is started without xenon. The temperature distribution at HFP state should be obtained through thermal fluid analysis. The calculation was performed using DeCART's own thermal fluid analysis module, and the result is shown in Fig. 7. With this calculation, it shows that DeCART well coupled with neutron flux calculation, depletion calculation, critical boron concentration search, and core temperature calculation. When compared with the graph from the first cycle critical boron concentration graph of the APR1400 Design Control Document, it shows that the graph is similar except for the initial boron concentration due to the difference in initial problem conditions.

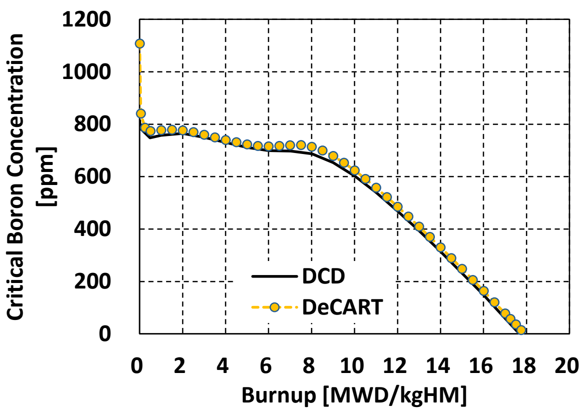


Fig. 7. Critical boron concentration in the first cycle of APR1400 depletion problem.

4. Conclusions

In this paper, DeCART was used to solve the APR1400 benchmark problem and the results were compared with reference solution. For the problem of single nuclear fuel rod or single nuclear fuel assembly, the reactivity error of several tens of pcm was shown, except at CZP, and accurate calculation results were given. However, in the case of the CZP state, the maximum reactivity error was 408 pcm. To improve this, it seems necessary to supplement the CZP state of the neutron multi-group nuclear cross-sectional library currently being used. On the other hand, for the core problem, a small reactivity error was shown regardless of the temperature condition or boron concentration. In most cases, the power distribution error is also at a small level. It is also worth mentioning that the DeCART calculation was at least tens of times faster than the Monte Carlo reference calculation. Therefore, it is concluded that DeCART can analyzes the advanced nuclear reactor such as APR1400 with appropriate accuracy.

ACKNOWLEDGEMENTS

This study was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT). (No. 2017M2A8A1092448).

REFERENCES

[1] J. Y. Cho and H. G. Joo, “Solution of the C5G7MOX benchmark three-dimensional extension problems by the DeCART direct whole core calculation code,” Prog. Nucl. Energy, vol. 48(5), pp. 456-466, July 2006.

[2] S. Yuk et al., “APR1400 Reactor Core Benchmark Problems,” KAERI/TR-7822/2019, 2019.

[3] ″APR1400 Design Control Document Tier 2, Chapter 4 Reactor,” APR1400-K-X-FS-14002-NP, Revision 3, Aug. 2018.

[4] H. J. Shim et al., “McCARD: Monte Carlo Code for Advanced Reactor Design and Analysis,” Nucl. Eng. Technol., vol. 44(2), pp. 161-176, Mar. 2012.

[5] H. J. Park et al., “An improved DeCART library generation procedure with explicit resonance interference using continuous energy Monte Carlo calculation,” Ann. Nucl. Energy, vol. 105, pp. 95-105, July 2017.

[6] J. Y. Cho et al., “Axial SPN and Radial MOC Coupled Whole Core Transport Calculation,” J. Nucl. Sci. Technol., vol. 44(9), pp. 1156-1171, 2007.