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Evaluation of HTTR Core Physics Benchmark using McCARD

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1. Introduction

The nuclear design code system of DeCART2D/CAPP [1], developed for the core design and analysis of very high temperature reactor (VHTR), has been established at KAERI. To verify this code system, its results were compared to solutions obtained from McCARD [2] for the two-dimensional single-cell, single-block, and core models of the high temperature engineering test reactor (HTTR). This comparison with a verified code is essential for ensuring the reliability of the code system.

Furthermore, for the code system to be applicable to VHTR design, validation through comparison with actual experimental data is also necessary. Specifically, the HTTR benchmark [3,4] provides measured values of important nuclear design factors essential for code validation, such as excess reactivity, shutdown margin, and isothermal temperature coefficient, obtained from the reactor start-up core physics test.

In this study, the McCARD was used to evaluate HTTR benchmark before performing the HTTR benchmark analysis using DeCART2D/CAPP. The results of McCARD calculation for the HTTR can be used to validate the DeCART2D/CAPP code system.

2. Description of HTTR benchmark

The HTTR core physics benchmark consists of measurements of critical approach, critical control rod position, excess reactivity, shutdown margin, and isothermal temperature coefficient.

During the critical approach using the fuel addition method, the effective multiplication factors were measured by the 1/M method until the first critical was achieved with 19 fuel columns loaded. The measurements were conducted with the control rods fully withdrawn. The excess reactivities were also measured using the inverse kinetics method from the first critical core to the fully loaded core of 30 fuel columns.

The critical control rod positions were measured for six different cases, as shown in Table 1. The fully inserted position of the control rods corresponds to the bottom of the fuel block. The fully withdrawn position of control rods C, R1, and R3 is approximately 405.0 cm, while that of control rod R2 is 332.5 cm.

The shutdown margin was measured using a two-step scram procedure, where the control rods were inserted first in the reflector region (R2 and R3) and then in the fuel region (C and R1). The scram reactivity was measured by the inverse kinetic method. The initial position of the control rods was identical to that of Case 6 in Table 1.

Six isothermal temperature coefficients are provided, ranging from 340 K to 740 K. Additionally, the derived critical control rods position for each temperature are provided to calculate the reactivity difference due to temperature changes.

Table 1. Measured critical control rod position

Case	Fuel column	Control rod position (cm)			
		C	R1	R2	R3
1	19	173.9	405.0	332.5	405.0
2	21	264.7	264.5	264.6	404.9
3	24	221.3	221.5	221.5	404.9
4	24	405.1	405.0	159.3	159.2
5	27	190.1	189.9	189.9	405.0
6	30	177.5	177.5	177.5	404.9

3. Result and discussion

The McCARD calculation was performed using the nuclear libraries of ENDF/B-VII.1 and ENDF/B-VIII.0. The effective multiplication factors at six critical conditions from Table 1 were calculated, and the results were compared to the corresponding measured values, as shown in Table 2. As dummy blocks are replaced by fuel blocks, the difference between the calculation and experiment decreases. Although the exact reason is unknown, the impurities of the dummy graphite blocks, provided as equivalent boron contents in the JAERI document[5], may have been underestimated. In the case of the fully-loaded core, the calculated values obtained using ENDF/B-VII.1 and ENDF/B-VIII.0 differ from the measured value by -67 pcm and 283 pcm, respectively.

Table 2. Comparison of measured and calculated effective multiplication factor at critical condition

Case	k_E	ENDF/B-VII.1		ENDF/B-VIII.0	
		k_C	k_C-k_E (pcm)	k_C	k_C-k_E (pcm)
1	1.00049	1.01053	1004	1.01208	1159
2	1.00037	1.00998	961	1.01240	1203
3	1.00037	1.00581	544	1.00836	799
4	1.00037	1.00700	663	1.00936	899
5	1.00037	1.00274	237	1.00606	569
6	1.00025	0.99958	-67	1.00308	283

The effective multiplication factors for the number of fuel columns from 9 to 30 are shown in Figure 1. The McCARD results are larger than the measured values, and the first critical is achieved with 18 fuel columns loaded core. The calculated values using ENDF/B-VIII.0 are higher than those obtained with ENDF/B-VII.1 by 125 ~ 221 pcm. Table 3 presents the measured and calculated excess reactivities. For the fully-loaded core, the calculated excess reactivities from both nuclear libraries agree well with the measured values, taking into account the uncertainty.

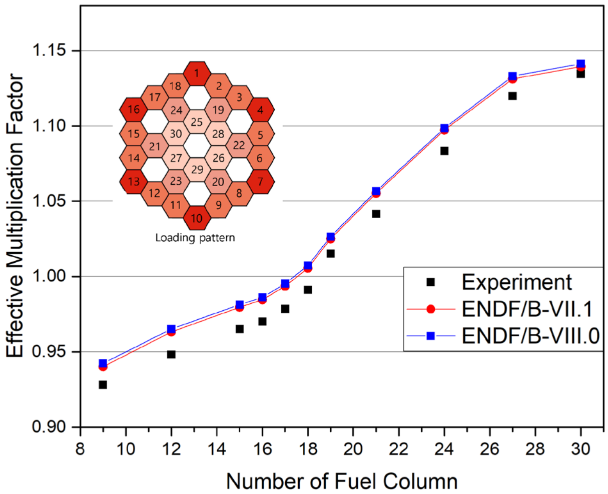

Figure 1. Effective multiplication factor as a function of fuel loading

Table 3. Comparison of measured and calculated excess reactivity

Fuel column	ρ_E (%$\Delta k/k$)	ENDF/B-VII.1		ENDF/B-VIII.0	
		ρ_C (%$\Delta k/k$)	ρ_C-ρ_E (%$\Delta k/k$)	ρ_C (%$\Delta k/k$)	ρ_C-ρ_E (%$\Delta k/k$)
19	1.5	2.4	0.9	2.6	1.1
21	4.0±1.1	5.2	1.2	5.4	1.4
24	7.7±2.1	8.9	1.2	9.0	1.3
27	10.7±3.0	11.6	0.9	11.7	1.0
30	12.0±3.3	12.2	0.2	12.4	0.4

The shutdown margin was calculated by performing two-step insertions of control rods in the fuel and reflector regions, as shown in Table 4. The relative errors between the measured and calculated reactivity worth for the insertion of control rods in the fuel and reflector regions were estimated to be within 2 % and 26 %, respectively. Similar to the core with dummy blocks, a significant difference of 26 % was observed in the graphite reflector region. The calculated shutdown margin agrees with the measured value with discrepancies of -4.8 % for ENDF/B-VII.1 and -6.0 % for ENDF/B-VIII.0.

Table 4. Comparison of measured and calculated shutdown margin

Control rod insertion	ρ_E (%$\Delta k/k$)	ENDF/B-VII.1		ENDF/B-VIII.0	
		ρ_C (%$\Delta k/k$)	C/E-1 (%)	ρ_C (%$\Delta k/k$)	C/E -1 (%)
Reflector region only	-12.1	-9.2	-23.6	-9.0	-25.4
Fuel region only	-34.2	-34.8	1.8	-34.5	0.8
All control rods	-46.3	-44.1	-4.8	-43.5	-6.0

The comparison of the measured and calculated isothermal temperature coefficients is shown in Table 5 and Figure 2. The calculated and measured values of the lowest two temperatures measured under the zero-power warm critical condition are almost the same. For the other four temperatures, the calculated values are within two times the uncertainty of the measured values. The measured value at 421 K has a large uncertainty of 13.0 pcm/K and the slope of the measured values above 421 K is steeper than that of the calculated values. Since the measurement at high temperatures were carried out up to 20 MW, there is a possibility that unaccounted-for factors contributed to the results.

Table 5. Comparison of measured and calculated isothermal temperature coefficient

Temperature (K)	ITC_E (pcm/K)	ENDF/B-VII.1		ENDF/B-VIII.0	
		ITC_C (pcm/K)	C/E-1 (%)	ITC_C (pcm/K)	C/E-1 (%)
346	-12.3±3.2	-11.8	-4.4	-11.8	-4.3
407	-13.2±3.3	-12.9	-2.3	-12.7	-3.9
421	-21.7±13.0	-12.9	-40.5	-12.7	-41.6
533	-16.5±2.9	-13.0	-20.9	-12.7	-23.2
642	-10.3±2.8	-12.4	20.5	-12.5	21.2
736	-8.6±2.7	-12.0	40.1	-11.9	38.7

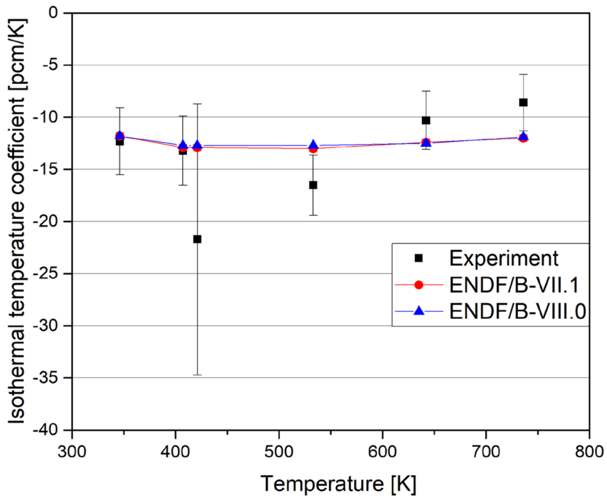

Figure 2. Isothermal temperature coefficient

4. Conclusion

The HTTR core physics benchmark was evaluated using McCARD with the nuclear libraries of ENDF/B-VII.1 and ENDF/B-VIII.0. The McCARD calculation was performed for criticality, excess reactivity, shutdown margin, and isothermal temperature coefficient. The calculated effective multiplication factors were found to be greater than the measured values. As the number of fuel columns increases, the difference between calculation and measurement decreases. In particular, the results of McCARD closely match the measurements for the fully-loaded core. The results of this study are expected to serve as a reference for the calculation model of HTTR to validate the

DeCART2D/CAPP code system for VHTR core design and analysis.

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