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The Effects of the Thermal Scattering Law of ENDF/B-VIII.0 on the VHTR Criticality Analysis

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1. Introduction

The very high temperature gas-cooled reactor (VHTR), one of the candidates for the Generation IV reactor, typically uses graphite as a moderator and reflector material. Since graphite occupies most of the VHTR core volume, it is very important to analyze the behavior of neutrons in the graphite medium for accurate neutronics analysis. In addition, since silicon carbide (SiC) is being considered as a matrix material for the VHTR fuel compact, its analysis is also important.

In ENDF/B-VII.1 [1] published in 2011, thermal scattering law (TSL) [2] sub-libraries for graphite existed. After that, ENDF/B-VIII.0 [3] published in 2018 included TSL sub-libraries for reactor-grade graphite with porosity of 10% and 30% as well as crystalline graphite. In addition, in ENDF/B-VIII.0, TSLs for Si and C of SiC were newly evaluated.

In this paper, the effects of TSL of each porosity of graphite, Si and C of SiC included in ENDF/B-VIII.0 were confirmed on the VHTR core analysis. As a target problem, the 3D core of the Very High Temperature Reactor Critical assembly (VHTRC) benchmark [4] and a single pin, single block, and two-dimensional core of the VHTR-350 benchmark [5] were selected. Since the VHTR-350 benchmark uses SiC in only one layer of TRISO, the results were also compared for the problem of changing the fuel compact matrix from graphite to SiC to measure the effect of TSL on SiC.

Neutronics calculations were performed using McCARD [6], a Monte Carlo (MC) code developed at Seoul National University, and TSLs were produced through NJOY21 code [7].

2. Problem Descriptions

In this section, brief descriptions of the cores used in this research are given. The detailed specifications of the benchmarks are listed in References 4 and 5.

2.1 VHTRC core

VHTRC is a critical assembly [4] using BISO-type carbon-coated particle fuels with 2.0 and 4.0 wt% of U-235 enrichment. Except for fuel such as graphite rods, graphite matrix, and graphite blocks, most of the rest are composed of graphite. As shown in Figure 1, there are HP, HC-1, and HC-2 cores according to the core configuration. The temperature of the HP core is 25.5, 71.2, 100.9, 150.5, 199.6℃ at five points, HC-1 is 8.0℃ and HC-2 is 200.3℃.

The densities of graphite used in the matrix and blocks of VHTRC are about 1.69-1.71 g/cm^3. Since the density of ideal crystalline graphite is 2.25 g/cm^3 [8], the porosities of VHTRC graphite are about 24-26%.

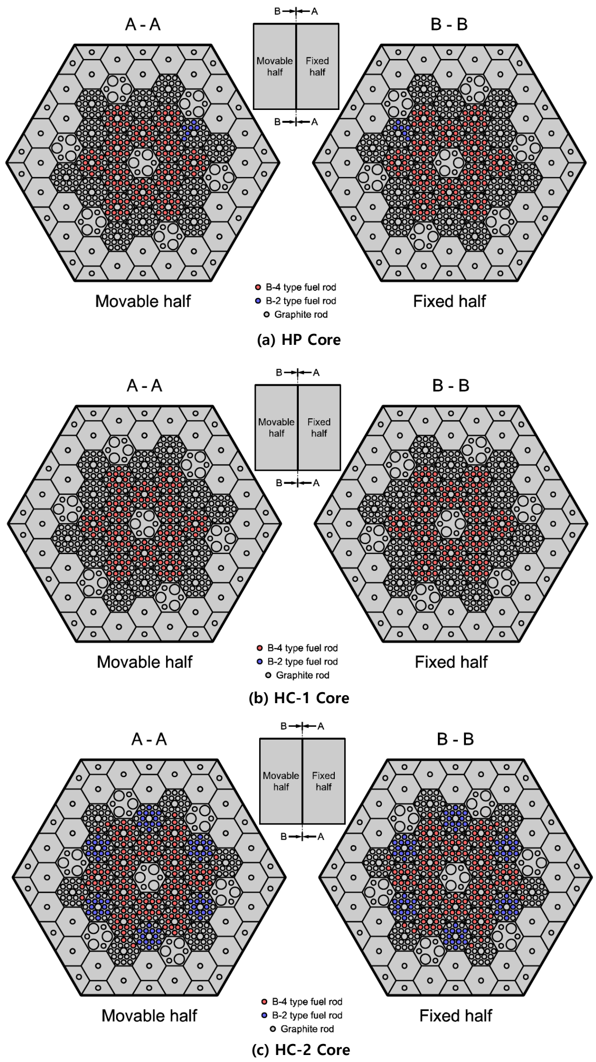

Fig. 1. Loading Patterns of VHTRC. (Taken from reference 4)

2.2 VHTR-350 benchmark

VHTR-350 benchmark is a conceptual core design of 950℃ VHTR being proposed by KAERI to verify the VHTR core analysis code [5]. TRISO particle fuel is randomly distributed in SiC matrix, the packing fraction of fuel compact is 30%.

The radius of the fuel compact and the hole are 0.6225 cm and 0.635 cm, respectively, and the pitch of the single pin is 1.8796 cm. There are 6 single pin problems depending on U-235 enrichment, 5.0, 7.0, 9.0, 11.0, 14.0, and 15.5 wt%.

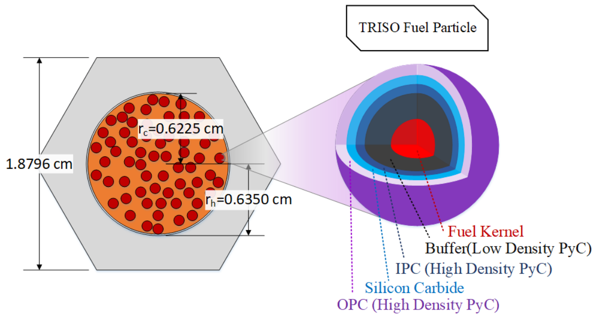

Fig. 2. Single pin problem of VHTR-350.

There are several types of fuel blocks according to enrichment zoning. In this study, six types of fuel blocks A0, A1, A2, A3, A4, and A6 were selected. Figure 3 shows the configurations of fuel blocks. The graphite block pitch is 36.0 cm and the case including the gap is 36.2 cm. Figure 4 shows the loading pattern of 1/6 core.

The densities of graphite used in VHTR-350 core are 1.85-1.90 g/cm^3, and their porosities are about 15-18%.

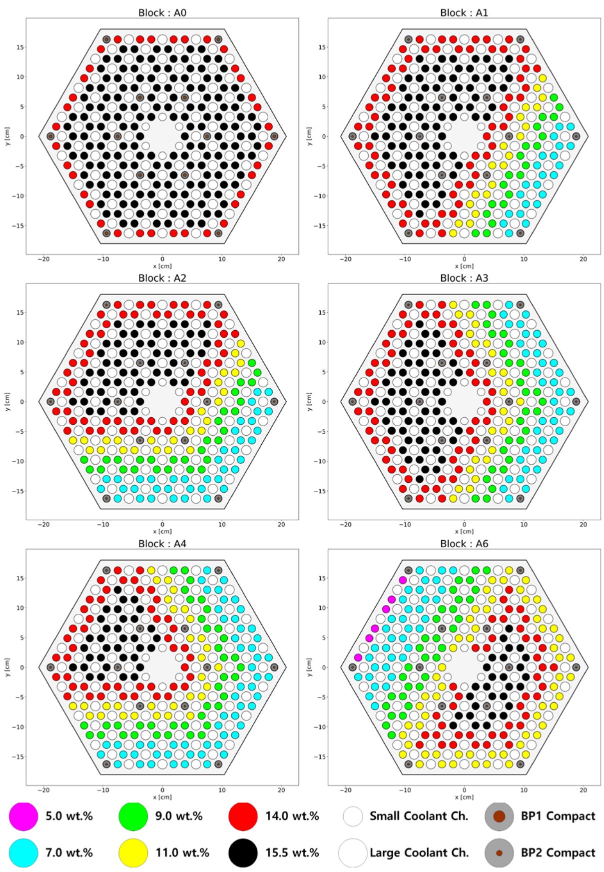

Fig. 3. Radial configuration of fuel blocks of VHTR-350.

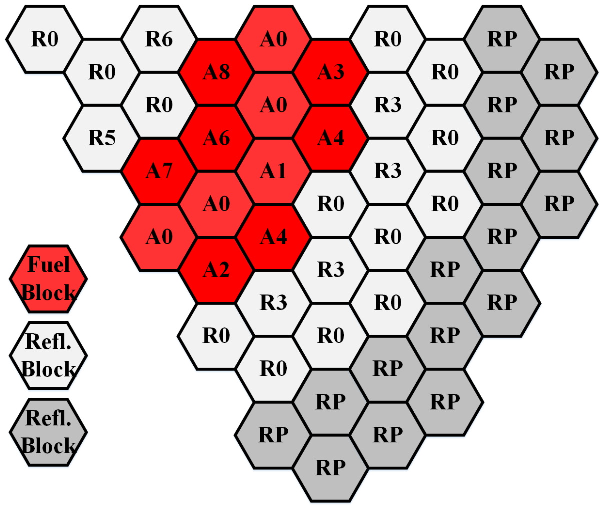

Fig. 4. Loading pattern of VHTR-350 1/6 core.

3. Numerical Results

All MC calculations are performed during 100 inactive cycles and 500 active cycles with 100,000 histories per cycle. From this, all k_{inf} and k_{eff} results have a standard deviation of 11-12 pcm. The ENDF/B-VIII.0 libraries processed by NJOY21 were used for the continuous energy neutron cross section. In addition, differences from calculation results using ENDF/B-VII.1 (E71) are additionally listed for simple reference.

Table I shows the problem cases according to the use of TSLs. In the VHTRC benchmarks, the results using 30% porous graphite TSL (P30) were used as a reference case because the graphite porosity was close to 30% among 0, 10, and 30%. On the other hand, in the VHTR-350 problems, it was close to 10%, so the results using 10% porous graphite TSL (P10) were used as a reference.

Table I: Problem Cases According to the Use of TSLs

Case Name	Graphite TSL	SiC TSL
P00	(0% porous) crystalline graphite	Si, C
P10 SiC	10% porous graphite	Si, C
P30	30% porous graphite	Si, C
noGrp	-	Si, C
Si	10% (VHTR-350), 30% (VHTRC)	Si
C	10% (VHTR-350), 30% (VHTRC)	C
noSiC	10% (VHTR-350), 30% (VHTRC)	-
E71	graphite from ENDF/B-VII.1	-

3.1 VHTRC core

Figure 5 and Table II shows the effect of TSL on k_{eff} according to graphite porosity in the VHTRC core problem. There was a difference of at least 100 pcm and a maximum of 507 pcm depending on the graphite TSL selection. In a core with a lower temperature, the effect on TSL by porosity is significant. When the graphite TSL was not used, it shows an error of up to 813 pcm.

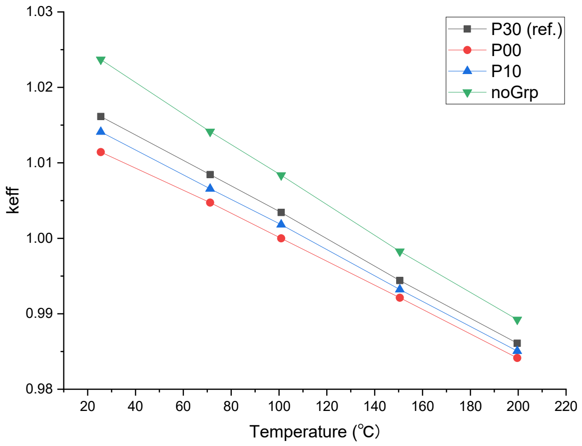

Fig. 5. the k_{eff} results of the VHTRC HP core.

3.2 VHTR-350 benchmark

All of VHTR-350 benchmark problems were calculated assuming that the temperature of all regions was 1200K. The upper rows of Tables III and IV and the left columns of Table V show the effects of TSL on k_{inf} in the single pin, single block, and 2-D core of VHTR-350, respectively.

In the single pin problem, the maximum difference according to the graphite porosity of TSL is about 28 pcm. Considering that the standard deviation of the calculation is about 11-12 pcm, it can be seen that there is little difference according to the TSL. On the other hand, in the single block problem, the differences are about 90-150 pcm according to the graphite porosity of the TSL. For the 2-dimensional core problem, the difference according to the graphite porosity of TSL is up to 81 pcm. If TSL of graphite is not used, an error of 223 pcm is shown.

The maximum error according to the use of the SiC TSL is about 40 pcm in the all cases. For SiC, no significant difference can be found with or without TSLs.

3.3 Modified VHTR-350 benchmark using SiC Matrix

The VHTR-350 benchmark problems use SiC in only one layer of TRISO fuel particle. In order to check whether the effects of SiC TSL were small because SiC occupies a small proportion in the problem, calculations were performed on the problem of changing the matrix material of fuel compacts from graphite to SiC. For the calculation, TSL for 10% porous graphite was used. The calculation using both TSL for Si and C of SiC was used as a reference case, and the effects of each were investigated.

The lower rows of Tables III and IV and the right columns of Table V show the effects of SiC TSL on k_{inf} in the single pin, single block, and 2-D core of the modified VHTR-350 benchmark. The single pin problem showed an error of up to 25 pcm depending on the use of SiC TSL, and the single block problem showed an error of up to about 69 pcm. The 2-D core problems show an error of 27-28 pcm, showing no significant difference compared to the MC standard deviation of 11-12 pcm.

Table II: The k_{eff} Results of the VHTRC Core

Core		HP core					HC-1 core	HC-2 core
Temperature [°C]		25.5	71.2	100.9	150.5	199.6	8.0	200.3
k_{eff}	P30	1.01614	1.00844	1.00342	0.99440	0.98610	1.01710	1.01184
Diff. [pcm]	P00	-471	-370	-343	-228	-195	-507	-176
	P10	-204	-187	-161	-118	-104	-218	-109
	noGrp	755	570	494	386	313	813	300
	E71	-749	-732	-690	-642	-645	-752	-614

Table III: The k_{inf} Results of the Single Pin of VHTR-350

Problem	U-235 Enrichment [wt%]		5.0	7.0	9.0	11.0	14.0	15.5
VHTR-350 (Section 3.2)	k_{inf}	P10	1.13542	1.17677	1.20357	1.22351	1.24652	1.25650
	Diff. [pcm]	P00	-7	-15	-4	-20	-19	-25
		P30	10	2	-12	-4	-1	3
		noGrp	39	31	32	44	42	26
		Si	9	17	-6	-9	16	-7
		C	2	-10	12	16	5	11
		noSiC	26	-11	3	-3	16	-5
		E71	-78	25	114	193	280	272

Modified VHTR-350 (Section 3.3)	k_{inf}	SiC	0.96007	1.02960	1.07508	1.10872	1.14712	1.16274
	Diff. [pcm]	Si	18	-8	22	13	-8	16
		C	3	-16	0	4	-9	-25
		noSiC	14	-1	18	10	-23	3

Table IV: The k_{inf} Results of the Single Block of VHTR-350

Problem	Block Type		A0	A1	A2	A3	A4	A6
VHTR-350 (Section 3.2)	k_{inf}	P10	1.04800	1.08834	1.06489	1.06489	1.04052	1.04295
	Diff. [pcm]	P00	-19	-48	-29	-19	-48	-34
		P30	128	63	73	74	51	72
		noGrp	337	279	298	295	281	297
		Si	40	-18	-11	-1	12	10
		C	21	0	0	-11	-9	22
		noSiC	30	-3	12	-4	-6	5
		E71	-238	-222	-251	-272	-364	-310
Modified VHTR-350 (Section 3.3)	k_{inf}	SiC	0.99171	1.02011	0.99472	0.99478	0.96858	0.97111
	Diff. [pcm]	Si	50	23	55	46	26	53
		C	-15	12	22	24	-22	3
		noSiC	33	46	69	67	23	54

Table V: The k_{inf} Results of the 2-D Core of VHTR-350

VHTR-350 (Section 3.2)			*Modified VHTR-350 (Section 3.3)*		
Case	k_{inf}	Diff. [pcm]	Case	k_{inf}	Diff. [pcm]
P10 (ref.)	1.03023	0	SiC	0.96809	0
P00	1.03011	-12	Si	0.96782	27
P30	1.03092	69	C	0.96755	-27
noGrp	1.03315	292	noSiC	0.96810	28
Si	1.03024	1			
C	1.03017	-6			
noSiC	1.03030	7			
E71	1.02648	-375			

4. Conclusions

In this study, the effects of the TSL of ENDF/B-VIII.0 on the VHTR criticality were investigated. In ENDF/B-VIII.0, TSL of graphite was provided in three types: crystalline graphite, reactor-grade graphite with 10% and 30% porosity.

As a result of applying in the VHTRC and VHTR-350 problems, the criticality result may differ by several hundred pcm depending on the use of graphite TSL. For accurate analysis, it is necessary to calculate using TSL of porosity suitable for the problem.

On the other hands, the k_{inf} results in the VHTR-350 benchmarks according to the use of SiC TSL were negligible compared to the MC standard deviation of 11-12 pcm.

Acknowledgements

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