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Original Article

Benchmark Analysis of a Prismatic Type-high Temperature Gas-cooled Reactor with the ENDF/B-VII.0, ENDF/B-VII.1 and ENDF/B-VIII.0 Nuclear Data Libraries

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Abstract: In this work we performed a benchmark analysis of the High Temperature Engineering Test Reactor (HTTR) fully-loaded start-up critical core with a 30-bundle loading configuration using the Monte Carlo code Serpent 2 with the recently released nuclear data libraries ENDF/B-VII.0, ENDF/B-VII.1 and ENDF/B-VIII.0. The purpose of the work is to reveal the impacts of using different ENDF nuclear data libraries on neutronics calculations of a prismatic high temperature gas-cooled reactor (HTGR). The benchmark results obtained with Serpent 2 were compared against the available experimental values and those attained by different computer codes (MCNP5 and SCALE) using the nuclear data library ENDF/B-VII.0. The comparative results showed good agreement between Serpent 2, the experimental values, MCNP5 and SCALE. The results also exhibited a notable difference between using ENDF/B-VII.0, ENDF/B-VII.1 and ENDF/B-VIII.0 in predicting the neutronics parameters of the HTTR that suggests further investigation in future work.

Keywords: HTGR, HTTR, ENDF/B-VII.0, ENDF/B-VII.1, ENDF/B-VIII.0.

1. Introduction

The high temperature gas-cooled reactor (HTGR) or very high temperature reactor (VHTR), which is a candidate for Generation IV reactors, has the capability of producing high coolant temperature

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output up to about 1,000 ^{o}C for high efficiency electricity generation and nuclear heat applications including hydrogen production [1]. HTGR uses the TRISO coated particle fuel, full ceramic core structure and helium as coolant that can withstand the high temperature environment. In addition, HTGR can provide inherent safety features that help simplify its safety systems. Therefore, HTGR has been widely researched, developed and operated around the world for cogeneration of electricity and heat for non-electric applications. The High Temperature Engineering Test Reactor (HTTR) is a 30 MWt test HTGR utilizing graphite moderation, helium coolant, and prismatic TRISO fuel [2, 3]. It was designed and constructed by the former Japan Atomic Energy Research Institute (JAERI) (now is Japan Atomic Energy Agency (JAEA)) in order to establish and upgrade the technology basis for HTGRs as well as develop the technology for high temperature nuclear heat applications.

In this work we performed a benchmark analysis of the HTTR fully-loaded start-up critical core with different ENDF nuclear data libraries including ENDF/B-VII.0 [4], ENDF/B-VII.1 [5] and ENDF/B-VIII.0 [6]. These three widely-used libraries were released in 2006, 2011 and 2018. ENDF/B-VII.0 has neutron cross-section library for 393 isotopes and thermal scattering law libraries for 20 materials; while ENDF/B-VII.1 cover 423 isotopes and 21 materials; and for the newest version, ENDF/B-VIII.0, those cover 557 isotopes and 34 materials, respectively. The continuous-energy Monte Carlo code Serpent 2 [7] was used for the analysis. The purpose of the study was to reveal the impacts of using different nuclear data libraries on neutronics calculations of a prismatic-type HTGR. The input data for building the HTTR simulation model with Serpent 2 were obtained from the publicly available resources for the HTTR [8-10]. The results obtained with Serpent 2 including effective neutron multiplication factor, excess reactivity, shutdown margin and axial fission reaction rate distribution using ENDF/B-VII.0, ENDF/B-VII.1 and ENDF/B-VIII.0 were compared with the available experimental values and those obtained with the other computer codes (MCNP5 and SCALE) [9, 10] using the nuclear data library ENDF/B-VII.0.

2. Methodology

The HTTR was chosen herein thanks to the publicly available resources of the HTTR. The benchmark for the initial fully-loaded start-up critical core of the HTTR [9] in preparation for further evaluation of HTTR experimental physics data was therefore selected in this study. The Monte Carlo code Serpent 2 and the nuclear data libraries ENDF/B-VII.0, ENDF/B-VII.1 and ENDF/B-VIII.0 were then used to model the HTTR fully-loaded start-up critical core with a 30-bundle loading configuration. For the analysis, the HTTR fully-loaded core model with Serpent 2 was significantly improved from the sample input for HTTR with Serpent 2 provided in [8]. In addition, the detailed geometry and material information of the above-mentioned benchmark for the HTTR [9] was used in this HTTR full core model with Serpent 2.

The active HTTR fully-loaded core to be modeled has a height of 290 cm with an effective diameter of 230 cm and consists of a total of 30 fuel columns. Each column has five hexagonal fuel blocks that are 58 cm high and 36 cm across flats. Control rod guide blocks, replaceable reflector blocks and irradiation blocks, which have the same dimensions, are stacked vertically within the core. The fuel compacts containing TRISO particles with twelve different enrichment levels are placed in graphite sleeves and inserted into coolant channels within the fuel blocks. Sixteen control rods are used for reactor core reactivity control. Further details can be found in [9]. The radial layout of the HTTR full core model with Serpent 2 is presented in Fig. 1.

Benchmark parameters of the HTTR to be determined and analyzed with Serpent 2 include the effective neutron multiplication factor (k-eff) of the critical and subcritical configurations, the excess reactivity, the shutdown margin, and the axial neutron fission reaction rate distribution in the instrumentation columns. These above parameters obtained with Serpent 2 using ENDF/B-VII.0, ENDF/B-VII.1 and ENDF/B-VIII.0 were compared against the experimental values [9] and those obtained with MCNP5 [9] and SCALE [10] as provided in the benchmark. It is noted that the nuclear data library ENDF/B-VII.0 was used with MCNP5 [9] and SCALE [10]. The comparative results are expected to elucidate the impacts of using different nuclear data libraries in neutronics analysis of a prismatic HTGR.

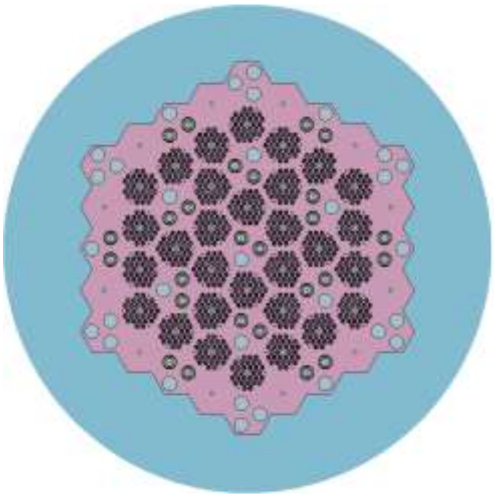

Figure 1. The HTTR core model with Serpent 2.

3. Results and Discussion

The k-eff values of the critical and subcritical configurations of the HTTR calculated by Serpent 2 using ENDF/B-VII.0, ENDF/B-VII.1 and ENDF/B-VIII.0 are presented in Table 1. The excess reactivity and the shutdown margin of the HTTR obtained by Serpent 2 with these three libraries are shown in Table 2. The neutron spectra of the HTTR calculated by ENDF/B-VII.0, ENDF/B-VII.1 and ENDF/B-VIII.0 are represented in Fig. 2. The axial fission rate distribution (normalized neutron flux) along the instrumentation channels of the HTTR was attained by Serpent 2 using ENDF/B-VII.0, ENDF/B-VII.1 and ENDF/B-VIII.0 and shown in Table 3 and Fig. 3. These above results calculated with Serpent 2 were compared against the available experimental (benchmark) values [9] and those attained with MCNP5 [9] and SCALE (CE- Continuous Energy model) [10] (both MCNP5 and SCALE using ENDF/B-VII.0).

Table 1 indicates that the k-eff results obtained with Serpent 2 using ENDF/B-VII.0, ENDF/B-VII.1 and ENDF/B-VIII.0 are in good agreement with MCNP5 and SCALE (both using ENDF/B-VII.0) and were within the standard deviation of experimental values. However, there was a notable difference (within about 1,000 pcm) between the results obtained with Serpent 2 using different libraries. In particular, the results with ENDF/B-VII.1 were consistent with the experiment while those with ENDF/B-VII.0 and ENDF/B-VIII.0 were significantly different, which are consistent with that reported in [11]. The comparison of the neutron spectra of the HTTR calculated with ENDF/B-VII.0, ENDF/B-VII.1 and ENDF/B-VIII.0 (Fig. 2) also shows significant differences in the thermal energy region. These differences in the k-eff values and neutron spectra are mainly due to the differences in the neutron capture cross section of carbon in the thermal energy range between the ENDF/B-VII.1 and ENDF/B-VII.0 and the updates of the U-235 and U-238 cross sections in the ENDF/B-VIII.0 [11, 12]).

Table 1. Comparison of the effective multiplication factors of the HTTR

Configuration		Critical		Subcritical	
		k-eff	Difference with benchmark (%)	k-eff	Difference with benchmark (%)
Benchmark [9]		1.0025 ± 0.1		0.6876 ± 0.1	
MCNP5 (ENDF/B-VII.0) [9]		1.0229 ± 0.0001	2.03	0.6999 ± 0.0001	1.78
SCALE (ENDF/B-VII.0) [10]		1.01847 ± 0.0009	1.59	0.69760 ± 0.0009	1.45
Serpent 2	ENDF/B-VII.0	1.02004± 0.00041	1.75	0.70122 ± 0.00042	1.98
	ENDF/B-VII.1	1.00985 ± 0.00040	0.73	0.69640 ± 0.00040	1.28
	ENDF/B-VIII.0	1.01635 ± 0.00041	1.38	0.70423 ± 0.00040	2.42

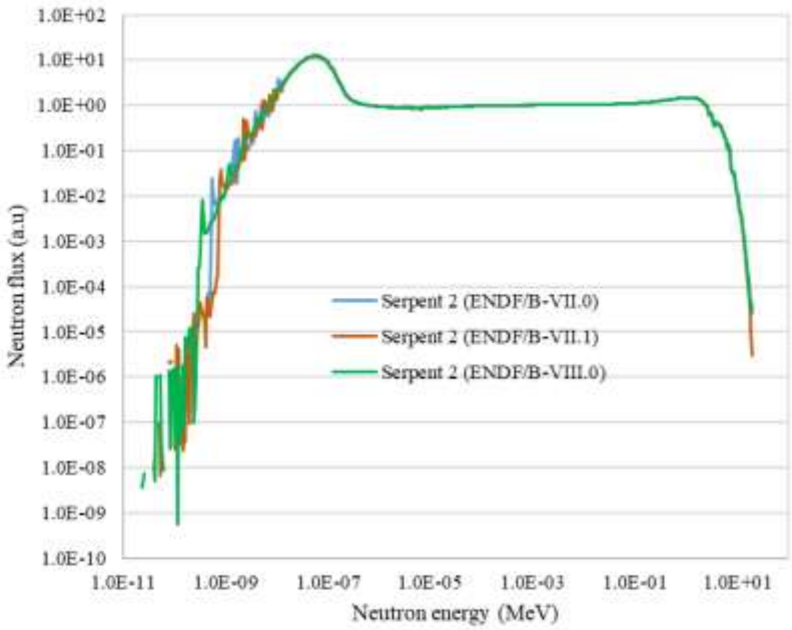

Figure 2. Comparison of neutron spectra obtained with ENDF/B-VII.0, ENDF/B-VII.1 and ENDF/B-VIII.0.

Table 2 indicates that the reactivity results obtained with Serpent 2 (ENDF/B-VII.0 and ENDF/B-VII.1) were closer to the measured ones than those attained with Serpent 2 (ENDF/B-VIII.0). Tables 2 also exhibits that most of the calculated reactivity values were within the standard deviations of the experimental ones except the shutdown margin calculated with Serpent 2 (ENDF/B-VIII.0). The above results also imply that further investigation is needed when using different ENDF libraries for neutronics analysis of the HTTR.

Additionally, Table 3 and Fig. 3 exhibit a good agreement between Serpent 2 (ENDF/B-VII.0), Serpent 2 (ENDF/B-VII.1), Serpent 2 (ENDF/B-VIII.0) and the measured axial fission reaction rate distributions along the HTTR's instrumentation channels and those calculated with MCNP5 (ENDF/B-VII.0). It is also noted that both the experimental data and calculated results were normalized to their maximum values. The difference in the position of the peak axial fission rate may be due to the reported experimental values at shifted height values (about 10 cm) as discussed in [10].

Table 2. Comparison of the reactivity values for the HTTR

Parameter		Excess reactivity		Shutdown reactivity	
		Reactivity (%dk/k)	Difference with benchmark (%)	Reactivity (%dk/k)	Difference with benchmark (%)
Benchmark [9]		12.0 ± 3.3		-46.3 ± 1.2	
MCNP5 (ENDF/B-VII.0) [9]		11.38	-11.79	-46.59	0.60
SCALE (ENDF/B-VII.0) [10]		11.44	-4.67	-45.16	-2.46
Serpent 2	ENDF/B-VII.0	11.55	-3.75	-44.57	-3.74
	ENDF/B-VII.1	11.80	-1.67	-44.65	-3.56
	ENDF/B-VIII.0	11.54	-3.83	-43.61	-5.81

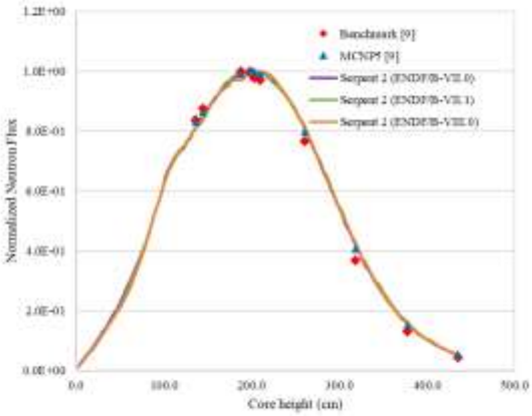

Figure 3. Measured and simulated axial fission rate distributions along the HTTR's instrumentation columns.

Table 3. Comparison of axial fission rate distributions along the HTTR's instrumentation columns

Data Point	Height (cm)	Benchmark [9]	MCNP5 (ENDF/B-VII.0) [9]	Serpent 2		
				(ENDF/B-VII.0)	(ENDF/B-VII.1)	(ENDF/B-VIII.0)
1	19.68	0.8381 ± 0.0127	0.8307 ± 0.0013	0.8022 ± 0.0062	0.8002 ± 0.0053	0.8051 ± 0.0053
2	28.47	0.8759 ± 0.0126	0.8650 ± 0.0014	0.8555 ± 0.0059	0.8455 ± 0.0051	0.8592 ± 0.0051
3	71.81	0.9991 ± 0.0128	0.9918 ± 0.0015	0.9927 ± 0.0065	1.0000 ± 0.0061	0.9733 ± 0.0059
4	82.53	1.0000 ± 0.0116	1.0000 ± 0.0015	0.9917 ± 0.0064	0.9959 ± 0.0061	0.9850 ± 0.0060
5	86.52	0.9784 ± 0.0242	0.9989 ± 0.0015	0.9988 ± 0.0062	0.9971 ± 0.0059	0.9943 ± 0.0059
6	93.61	0.9703 ± 0.0306	0.9920 ± 0.0015	1.0000 ± 0.0068	0.9968 ± 0.0059	1.0000 ± 0.0060
7	144.22	0.7673 ± 0.0277	0.7981 ± 0.0013	0.7980 ± 0.0058	0.8063 ± 0.0053	0.8036 ± 0.0052
8	202.28	0.3695 ± 0.0158	0.4070 ± 0.0009	0.4205 ± 0.0042	0.4305 ± 0.0040	0.4293 ± 0.0040
9	261.19	0.1302 ± 0.0094	0.1505 ± 0.0006	0.1544 ± 0.0026	0.1616 ± 0.0024	0.1570 ± 0.0024
10	319.13	0.0440 ± 0.0057	0.0552 ± 0.0004	0.0523 ± 0.0014	0.0504 ± 0.0012	0.0524 ± 0.0013

4. Conclusion

In summary, we performed a benchmark analysis of the HTTR fully-loaded start-up critical core with a 30-bundle loading configuration with Serpent 2 using ENDF/B-VII.0, ENDF/B-VII.1 and

ENDF/B-VIII.0 in order to comprehend the potential impacts of using these nuclear data libraries on neutronics calculations of a prismatic HTGR. The neutronics parameters including the k-eff values for the critical and subcritical configurations, the excess reactivity, the shutdown margin and the axial fission rate distribution were calculated and compared against the experimental and computational values published with the benchmark. The comparative results showed good agreement between Serpent 2 (ENDF/B-VII.0), Serpent 2 (ENDF/B-VII.1) and Serpent 2 (ENDF/B-VIII.0), MCNP5 (ENDF/B-VII.0) and SCALE (ENDF/B-VII.0) where the results with Serpent 2 using the ENDF/B-VII.1 were closest to the experiment data. The results also revealed a significant difference between using ENDF/B-VII.0, ENDF/B-VII.1 and ENDF/B-VIII.0 in predicting the neutronics parameters of the HTTR that needs further investigation in future work. In addition, the approximations in the HTTR simulation model will also be evaluated to figure out the relevant uncertainties in the calculated neutronics results.

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