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McCARD Analysis for Molten Salt Reactor Experiment Benchmark

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1. Introduction

The Molten Salt Reactor (MSR), representing one of the Generation IV reactors, is currently being researched by various countries and research institutions. To operate MSR safely, it is crucial to determine appropriate safety margins, and computational analysis plays a significant role in this process. Since MSR has a different configuration from conventional reactors like PWR, it's important to verify through reliable benchmark whether computational analysis is performed well. Thus, this paper uses reliable data from the Molten Salt Reactor Experiment (MSRE). The MSRE, which operated from 1965 to 1969 at the Oak Ridge National Laboratory, is included as a benchmark in the "International Handbook of Evaluated Reactor Physics Benchmark Experiments" (IRPhEP handbook) [1] in 2019.

This paper aims to analyze the MSRE core by McCARD [2], a Monte Carlo (MC) neutron transport analysis code, and to confirm the capability of McCARD in the analysis of MSRs. This paper briefly introduces the MSRE benchmark, and conducts a comparison between numerical and experimental results for three neutronics parameters: effective multiplication factor (k_{eff}), control rod worth, fuel temperature coefficient (FTC).

2. Benchmark Modeling

Figure 1 shows the vertical view of the MSRE. As shown in Fig. 1, the MSRE consists of a reactor vessel, lower head, upper head, graphite core, distributor, inlet pipe, and outlet pipe. The overall height of the reactor is 255.91 cm, with the graphite core occupying a height of 179.46 cm. The internal molten salt consists of LiF-BeF_2-ZrF_4-UF_4 with a uranium enrichment of 33 %, and the temperature is 911 K. The molten salt enters the core from outside the vessel through the distributor, which is attached in a half-torus shape, and is discharged through the outlet pipe located above the reactor. The upper head, distributor, and pipes are filled with fuel, while the lower head contains a mixture of fuel and graphite in a volume ratio of 90.8% and 9.2%, respectively.

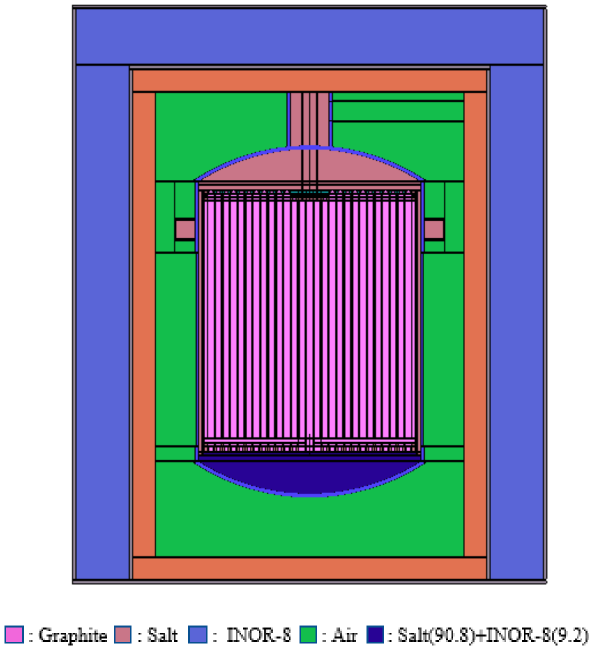

Fig. 1. Vertical cross sectional view of MSRE

The graphite core is divided into five main sections. Starting from the bottom, there is the dowel section with a height of 3.86 cm, followed by the bottom layer and top layer of the horizontal graphite lattice, each with a height of 2.54 cm. Next is the vertical graphite lattice with a height of 159.25 cm, and finally, there is the taper region with a height of 7.33 cm.

The horizontal graphite lattice consists of a bottom layer and a top layer, each with a height of 2.54 cm, and their shapes are depicted in Fig. 2. Each graphite block has a width of 4.13 cm, and there is a gap of 0.95 cm between adjacent blocks. Moreover, the graphite stringers are centrally positioned within the core.

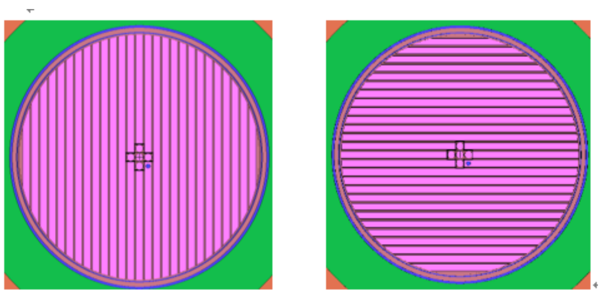

Fig. 2. Horizontal Cross Section of Horizontal Graphite Lattice

The vertical graphite lattice consists of 541 full vertical graphite stringers, 72 vertical graphite stringers with partial channels, 3 control rods, and 1 sample basket. The overall shape is depicted in Fig. 3. Each stringer has the shape shown in Figure 3 with a length of 5.08 cm. It is a square shape with fuel channels drilled on each side. The fuel channels have a radius of 0.51 cm, creating rounded corners, and the length of the longer side is 3.05 cm, while the length of the shorter side is 2.04 cm.

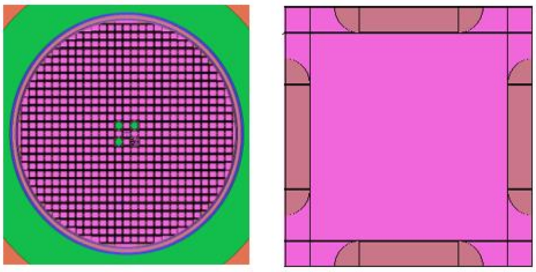

Fig. 3. Horizontal Cross Section of Vertical Graphite Lattice (left) and Vertical Graphite Stringers (right)

The control rod consists of an Inconel cable at the center, surrounded by stainless steel, inner and outer Inconel shells, and a poison shell. The poison shell is composed of alternating layers of gadolinia poison and Inconel seal. The sample basket consists of six graphite blocks and twelve INOR-8 cylinders, with the INOR-8 cylinders enclosing them. The positions of the control rods and the sample basket are depicted in Fig. 4.

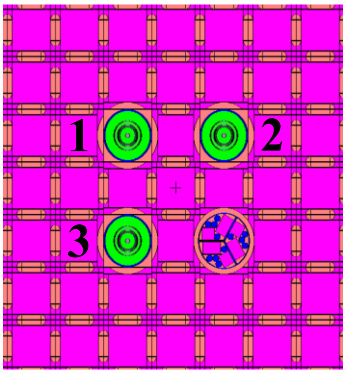

Fig. 4. Control Rod and Sample Basket

3. Methodology and Result

In this paper, McCARD eigenvalue calculations are performed on 200 inactive and 1,000 active cycles with 100,000 histories per cycle with the ENDF/B-VII.1 cross section library [3].

3.1. k_{eff}

The control rods are adjusted to match the critical state provided by the benchmark. The positions of the two control rods attached to the sample basket are located 161.77 cm and 149.59 cm above the bottom surface of the horizontal graphite lattice, respectively. The k_{eff} is calculated by McCARD for three scenarios: first, with a thermal scattering library (TSL) at 800 K; second, with a thermal scattering library at 1000 K; and finally, with a stochastic mixing of the two libraries mentioned above to achieve 911 K. The numerical results are presented in Table 1, compared with results from Serpent2 [4]. As a result of the calculation, there was a difference of about 40 to 80 pcm.

Table 1. $\boldsymbol{k_{eff}}$ comparisons between Serpent2 and McCARD calculations

Case	**Serpent2 (SD)**	**McCARD (SD)**	**Difference [pcm] (SD)**
TSL at 800 K	1.02723 (3.5)	1.02682 (9)	41 (9.7)
TSL at 1,000 K	1.01640 (3.5)	1.01563 (9)	77 (9.7)
stochastic mixing	1.02132 (3.5)	1.02051 (9)	81 (9.7)

3.2. Rod worth

The rod worth was calculated under the following conditions: all three control rods inserted, only one control rod inserted for rod 2, and two control rods inserted for rods 1 and 2. These values were then compared with benchmark value [5]. The control rod numbers are indicated in Fig. 4, and the results are shown in Table 2. The numerical results by McCARD reveal good agreement with benchmark values within their 95% confidence intervals.

Table 2. Rod worth comparisons between McCARD and Benchmark

Case	**Benchmark [pcm] (SD)**	**McCARD [pcm] (SD)**	**Difference [pcm] (SD)**
Rod 2	2,252 (19)	2,261 (13)	9 (23)
Rod 1, 2	4,099 (116)	4,141 (13)	52 (117)
Rod 1, 2, 3	5,596 (158)	5,812 (13)	216 (159)

3.3. FTC

When the fuel temperature is changed from 861 K to 961 K, the inserted reactivity is calculated for the condition with all control rod withdrawn. The density expansion of the fuel is considered. These results were compared with the values obtained from benchmark[4]. As shown in Table 3, The numerical results by McCARD reveal good agreement with experimental results within their 95% confidence intervals.

Table 3. FTC comparisons between McCARD and Benchmark

Benchmark [pcm/°F] (SD)	**McCARD [pcm/°F] (SD)**	**Difference [pcm/°F] (SD)**
-4.70 (0.7)	-4.23 (0.08)	0.47 (0.7)

4. conclusion

In this study, the MSRE benchmark is analyzed by McCARD with the ENDF/B-VII.1 library. Three key parameters were analyzed: k_{eff}, rod worth, and FTC. While there was a discrepancy of approximately 40 to 80 pcm in the k_{eff} due to differences between Serpant2 and McCARD, both the control rod worth and FTC. The numerical results by McCARD reveal good agreement with benchmark values within their 95% confidence intervals. Through these results, we confirmed McCARD's ability to analysis MSR

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