McCARD Analysis for Molten Salt Reactor Experiment Benchmark

Korea Nuclear Society
May 9^{th}, 2024

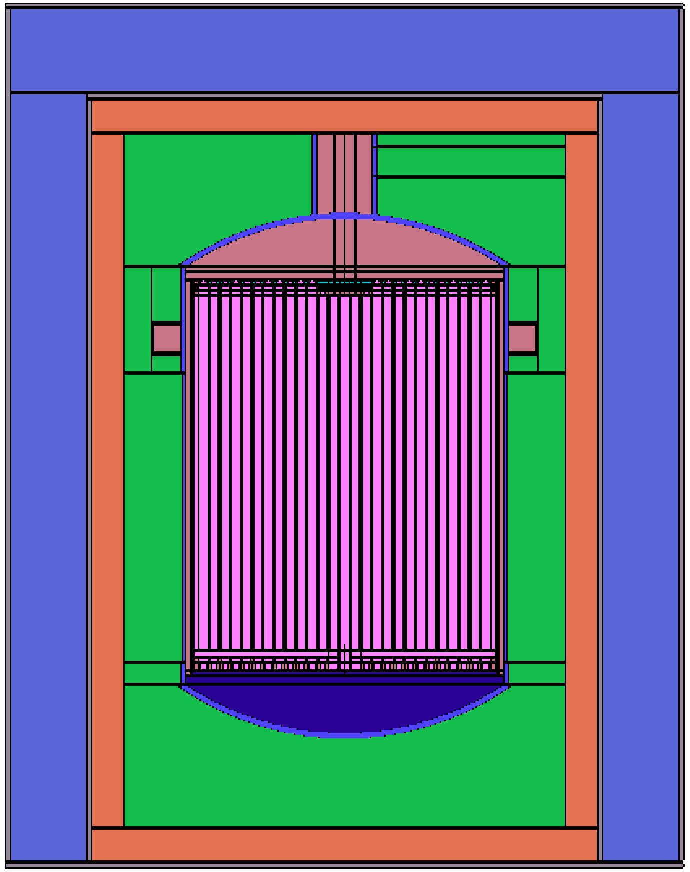
Kwon, Jae Yong and Shim, Hyung Jin

Monte Carlo Laboratory
Seoul National University

Contents

Introduction(1/2)

◆ Research background and purpose



: graphite : salt : INOR-8 : Air : Salt+INOR-8

Fig. 1. Vertical cross sectional view of MSRE

- The Molten Salt Reactor (MSR) is currently being researched by various countries and research institutions.

- Since MSR has a different configuration from conventional reactors like PWR, it's important to confirm whether conventional codes can be used for analyzing MSRs.

- This paper aims to analyze the MSRE, which included as a benchmark in the "International Handbook of Evaluated Reactor Physics Benchmark Experiments" (IRPhEP handbook) [1] by McCARD [2], a Monte Carlo (MC) neutron transport analysis code, and to confirm the capability of McCARD in the analysis of MSRs.

Introduction (2/2)

◆ Introduction to MSRE

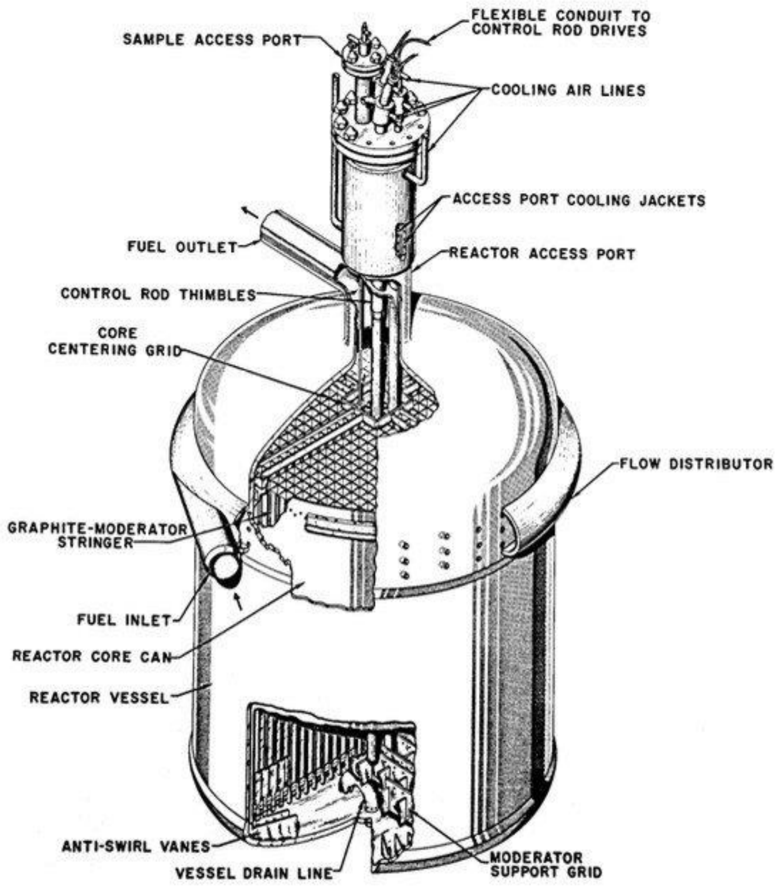


Fig. 2. The structure of the MSRE

- MSRE(Molten-Salt Reactor Experiment) was built at the Oak Ridge National Laboratory(ORNL) and was operated between 1965 and 1969.
- Its purpose was to demonstrate key features of the molten-salt liquid fuel reactor concept and to prove the practicality of the molten salt reactor (MSR) technology.
- The molten salt enters the core from outside the vessel through the distributor and exits through the outlet pipe.

MSRE Specification (1/6)

◆ Reactor specification and modelling

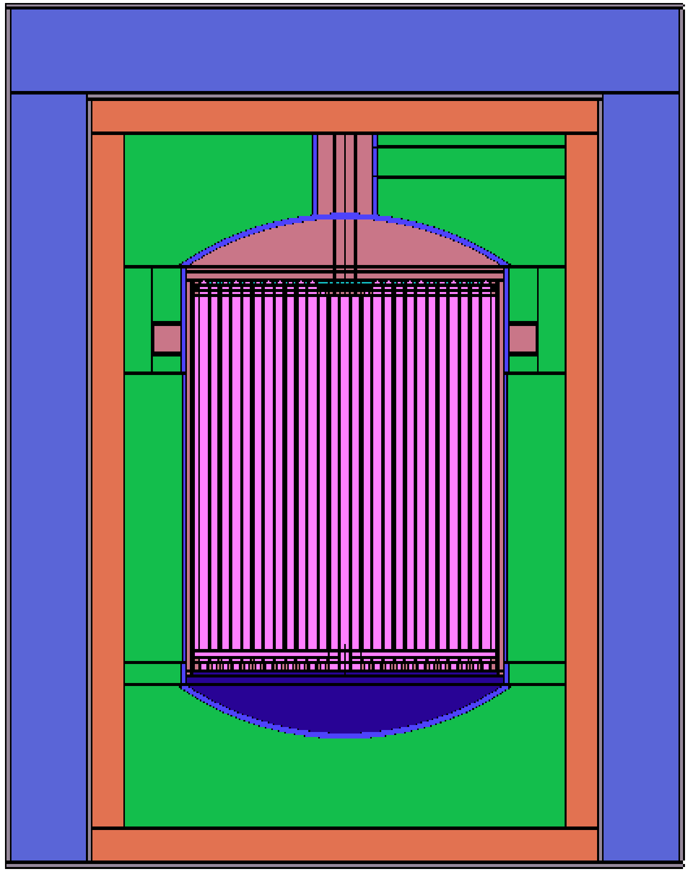


Fig. 3. Vertical cross sectional view of MSRE

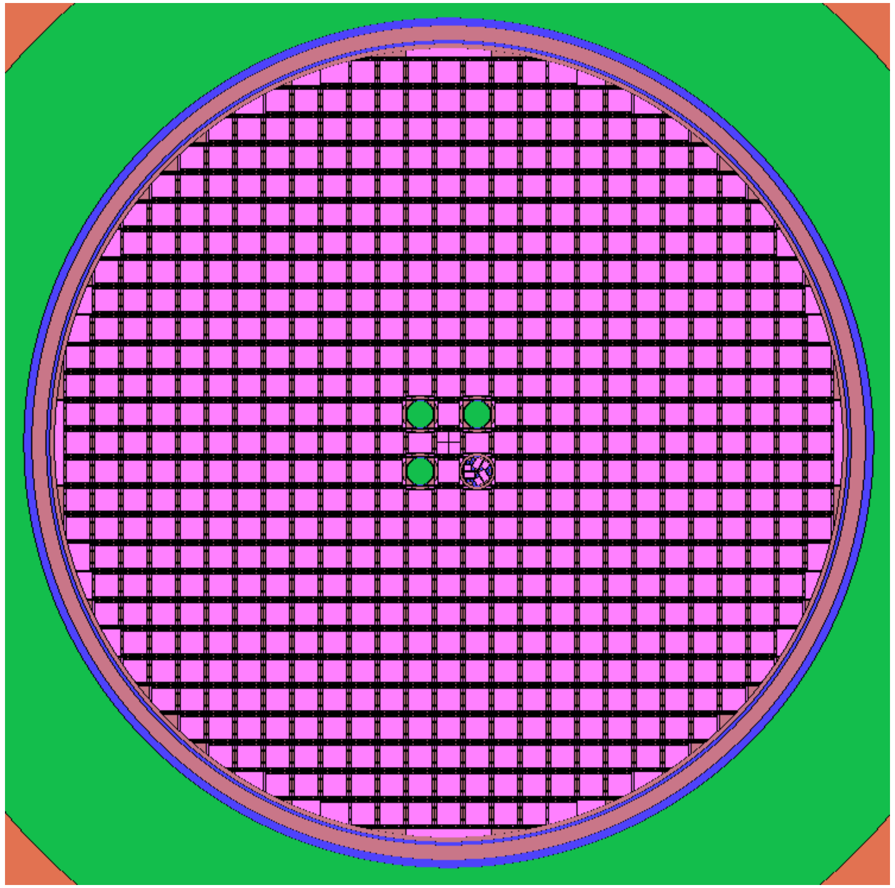
Table. 1. Reactor specification of MSRE

Category	Contents
Reactor type	MSR
Fuel	Li-BeF_2-ZrF_4-UF_4
Temperature	911 K
Reactor power	10 MWth
Reactor height	235.93 cm
Graphite height	179.46 cm

❖ The MSRE consists of a reactor vessel, lower head, upper head, graphite lattice, distributor, inlet pipe, and outlet pipe.

MSRE Specification (2/6)

◆ Vertical graphite lattice specification and modelling



: graphite : salt : INOR-8 : Air

Fig. 4. Horizontal cross sectional view of vertical graphite lattice

Table. 2. Core specification

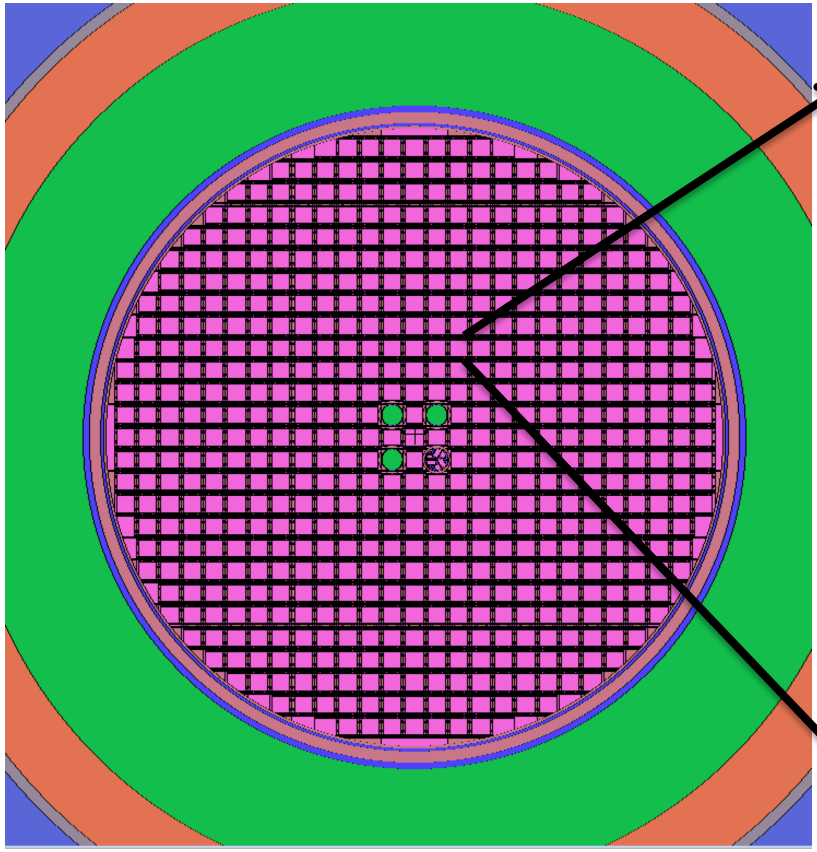
Category	Contents
Core radius(graphite)	70.29 cm
Core radius(Salt)	71.01 cm
Can radius(in, out)	74.30, 76.86 cm
Vessel radius(in, out)	74.30, 76.86 cm

❖ The left figure depicts a horizontal cross-section of the active core. The core consists of 541 full stringers, 72 partial stringers, 3 control rods, and 1 sample basket.

❖ The active core is enclosed by a can and a vessel.

MSRE Specification (3/6)

◆ Graphite stringer modeling and specification



: graphite : salt : INOR-8

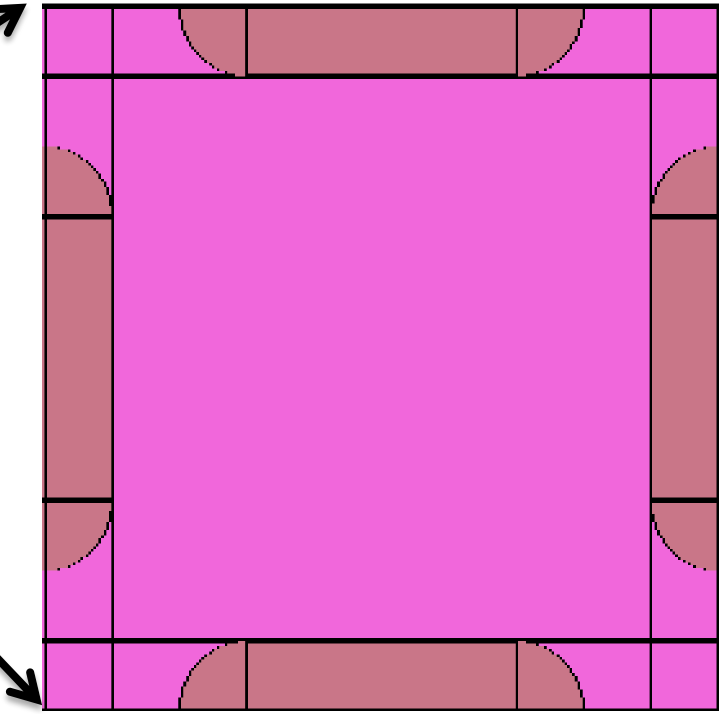


Fig. 5. Horizontal cross sectional view of graphite stringer

Table. 3. Fuel lattice specification

Category	Contents
Lattice length	5.08 cm
Salt length(long)	3.05 cm
Salt length(short)	2.04 cm

❖ Each stringer consists of a graphite and 4 fuel channels

❖ Each channel has ends that are quarter-circles with a radius of 0.51 cm

MSRE Specification (4/6)

◆ Horizontal graphite lattice modeling and specification

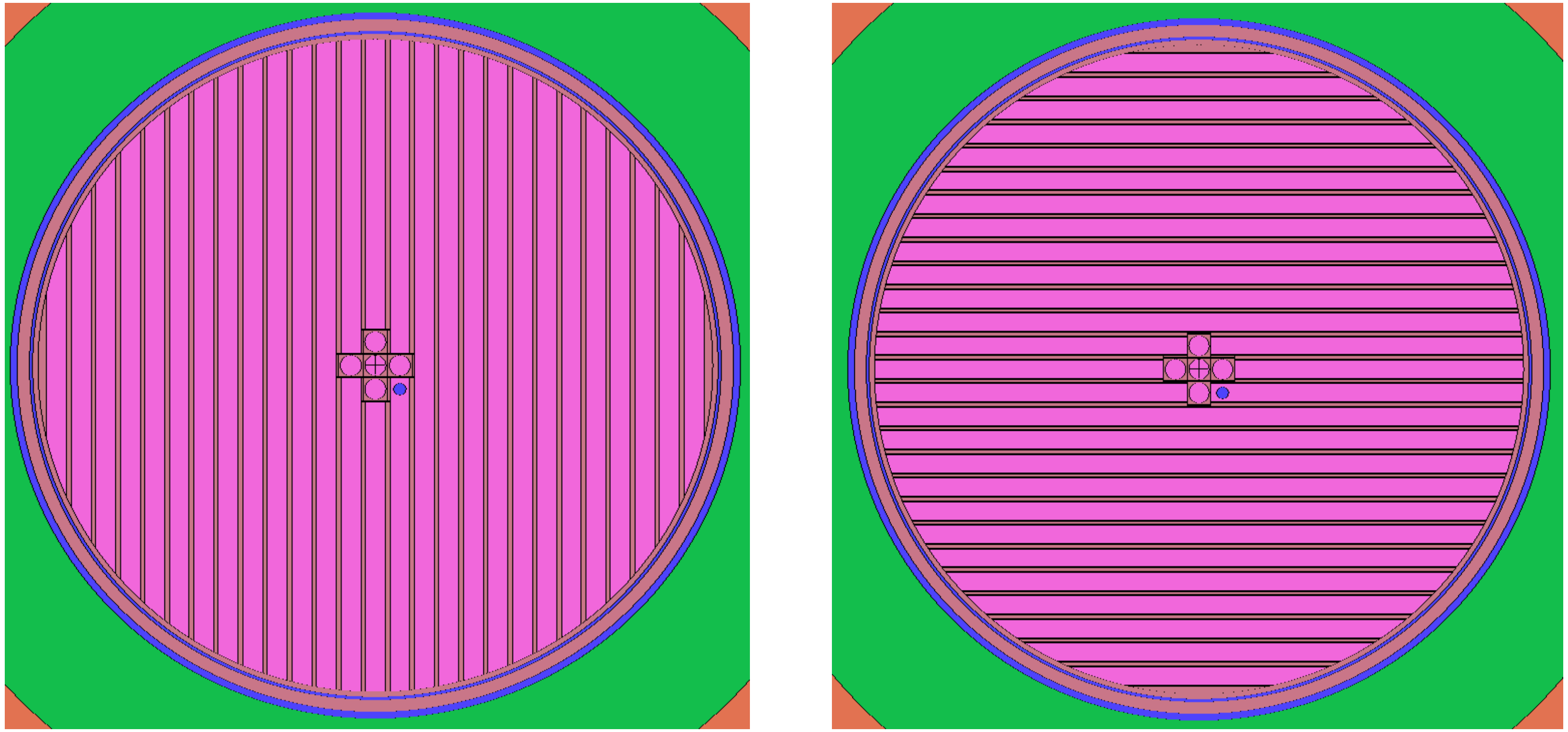


Fig. 6. Horizontal Cross Section of horizontal graphite lattice

❖ Below the vertical graphite lattice, there is a horizontal graphite lattice

❖ The graphite lattice consists of 27 graphite blocks each, and there are two layers: a bottom layer and a top layer.

MSRE Specification (5/6)

◆ Top and bottom of graphite lattice

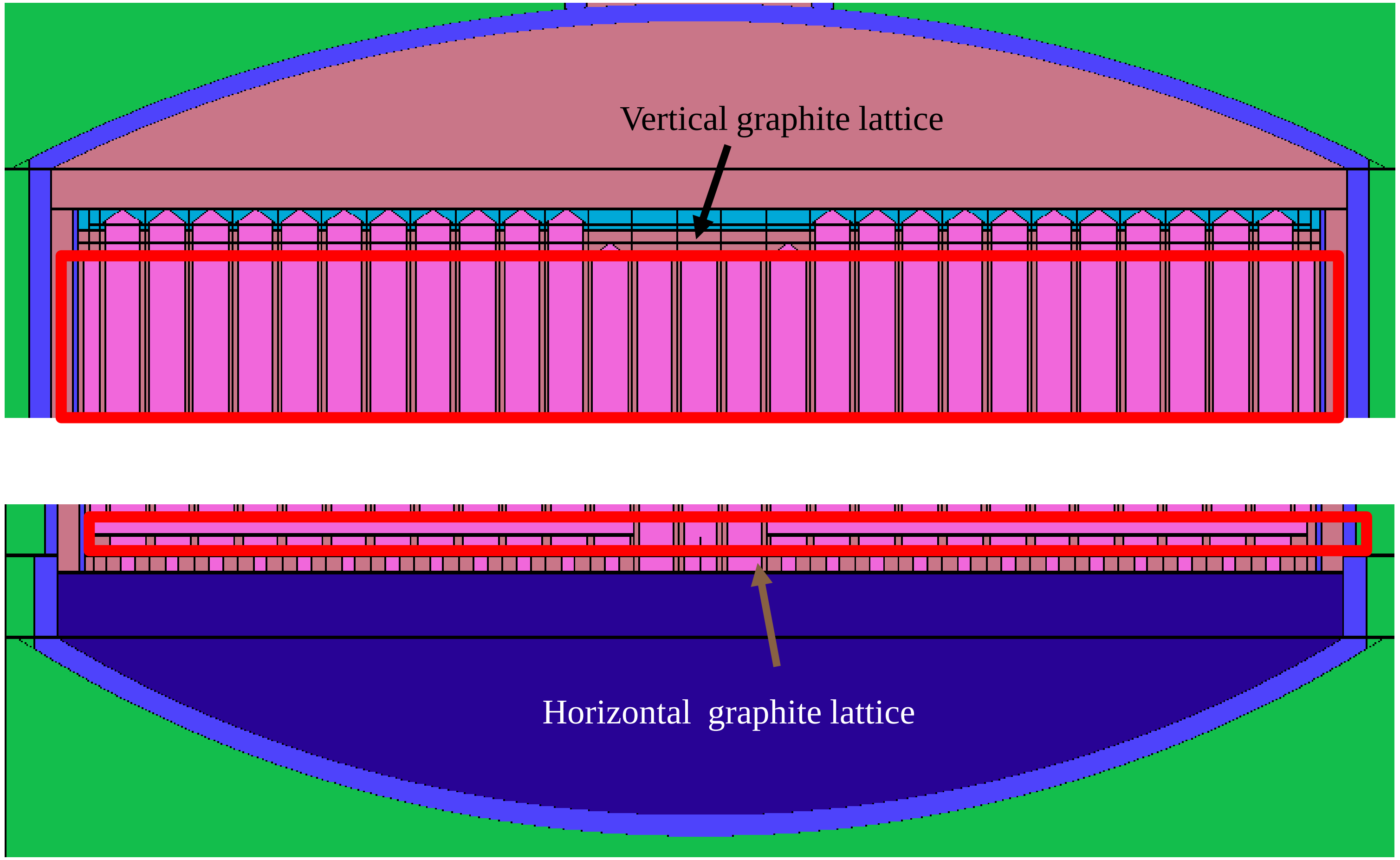


Fig. 7. Top and bottom of graphite lattice

- Above the graphite lattice, the graphite is tapered into a cone shape. This area is called the cetering bridge, and due to the difficulty in separately modeling the presence of INOR-8 in this region, it is modeled as a homogenized mixture of fuel and INOR-8.

- Below the lattice, there exists a dowel section, and beneath each stringer, there is a graphite cylinder with a diameter of 2.54 cm.

MSRE Specification (6/6)

◆ Control rod and sample basket modeling and specification

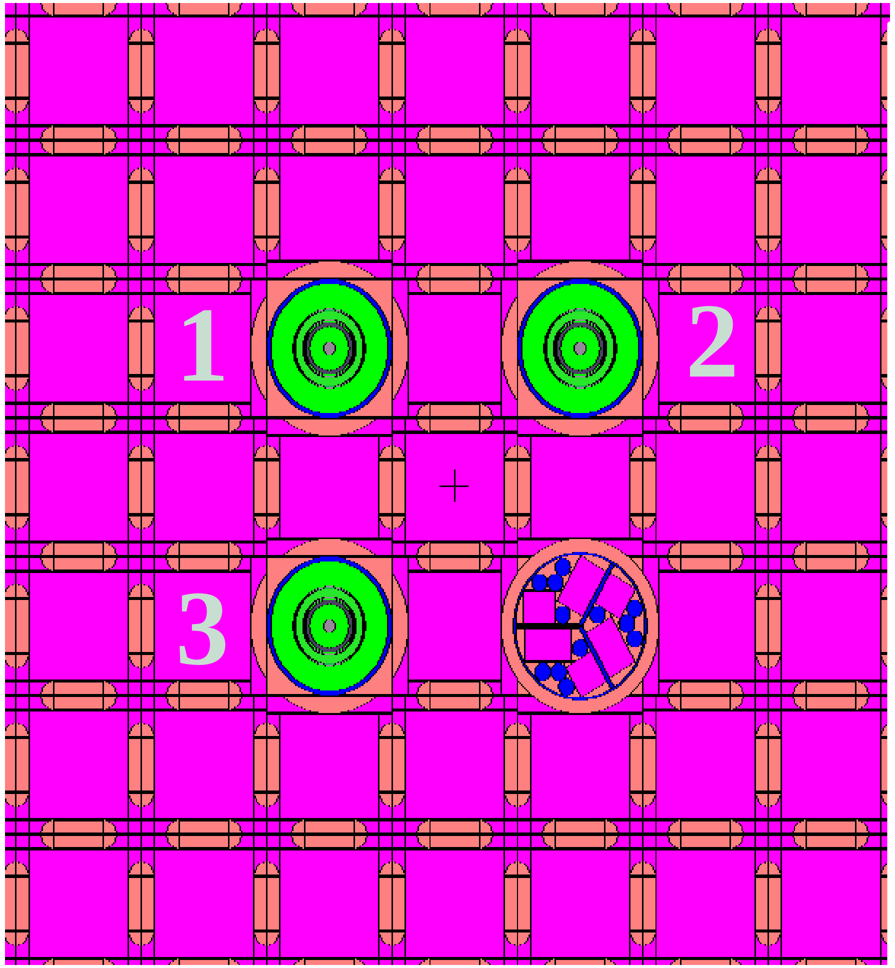
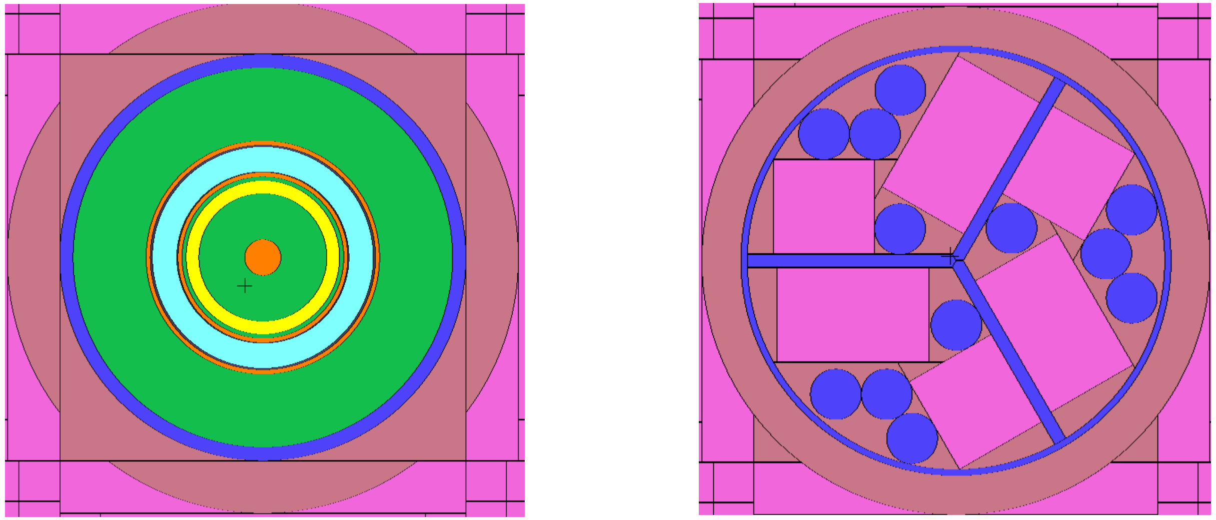


Fig. 5. Horizontal cross sectional view of control rods and basket



: Inconel : Poison : Stainless steel : graphite : salt : INOR-8

Fig. 8. Horizontal cross sectional view of control rod and sample basket

❖ The control rods are composed of Inconel wrapped with stainless steel and poison. The sample basket consists of 6 graphite blocks and 12 INOR-8 cylinders

McCARD Calculation Option (1/2)

- Calculate the effective multiplication factor for the thermal scattering library at 800 K, 1000 K and 911 K with stochastic mixing.
  - Control rod position : 51(rod 2,3), 19(rod 1) inch
  - compare with the data from Serpent 2

- Calculate the differential control rod worth
  - calculate from 1 inch to 49 inches, with a Δx of 4 inches
  - compare with the data from the benchmark

- Calculate the total control rod worth
  - calculate the total rod worth of one, two, or three control rods
  - compare with the data from the benchmark

- Calculate the fuel temperature coefficient and isothermal temperature coefficient
  - Calculate the k_{eff} for temperatures ± 50 K from the original temperature and then compute the ITC and FTC
  - compare with the data from the benchmark

McCARD Calculation Option (2/2)

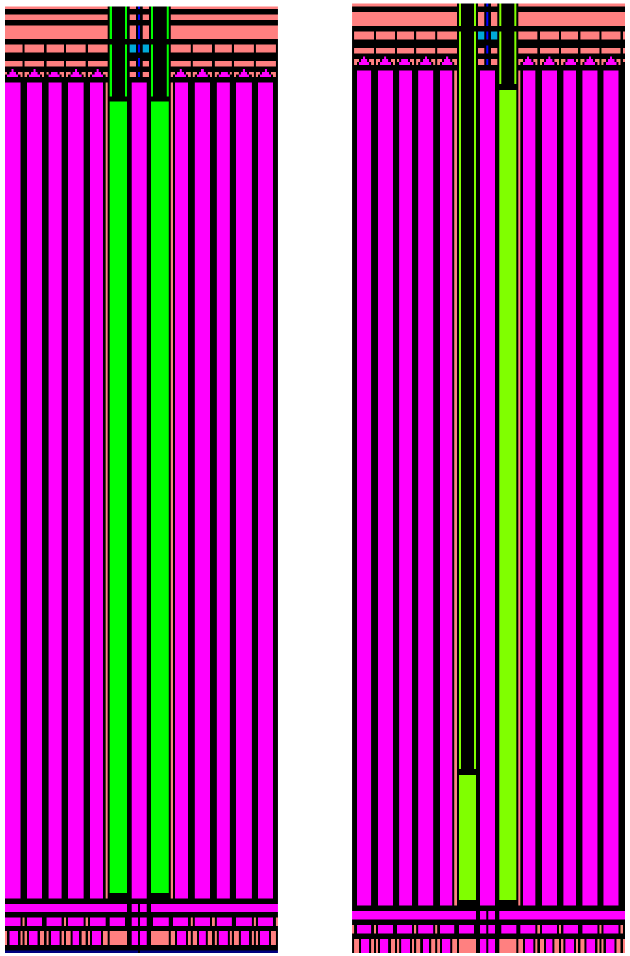


Fig. 9. Vertical cross sectional view of control rod

❖ The calculation options for all calculations are as follows :

- Library : ENDF/B-VII.1[3]
- Neutron histories : 100,000
- Inactive cycle : 200
- Active cycle : 1,000

❖ All calculations were performed using McCARD, and for control rod worth, calculations were conducted by moving the control rod up and down as shown in the left figure. The effective multiplication factor and control rod worth were then calculated.

Calculation Result

- k_{eff} calculation

Table. 4. k_{eff} of MSRE with TSL at 800, 1000 K and using stochastic mixing to simulate 911 K

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)

- When using the thermal scattering library for graphite at 800 K, 1000 K and using stochastic mixing to simulate 911 K the k_{eff} calculated with McCARD differed by 41, 77, 81 pcm respectively from that calculated with SERPENT2[4].
- The differences between Serpent 2 and McCARD calculations does not match within the 95% confidence interval, suggesting that there may be some ambiguous modeling contributing to this differences.
- Example : air outside the vessel, centering bridge, cone graphite

Result

◆ Differential rod worth calculation

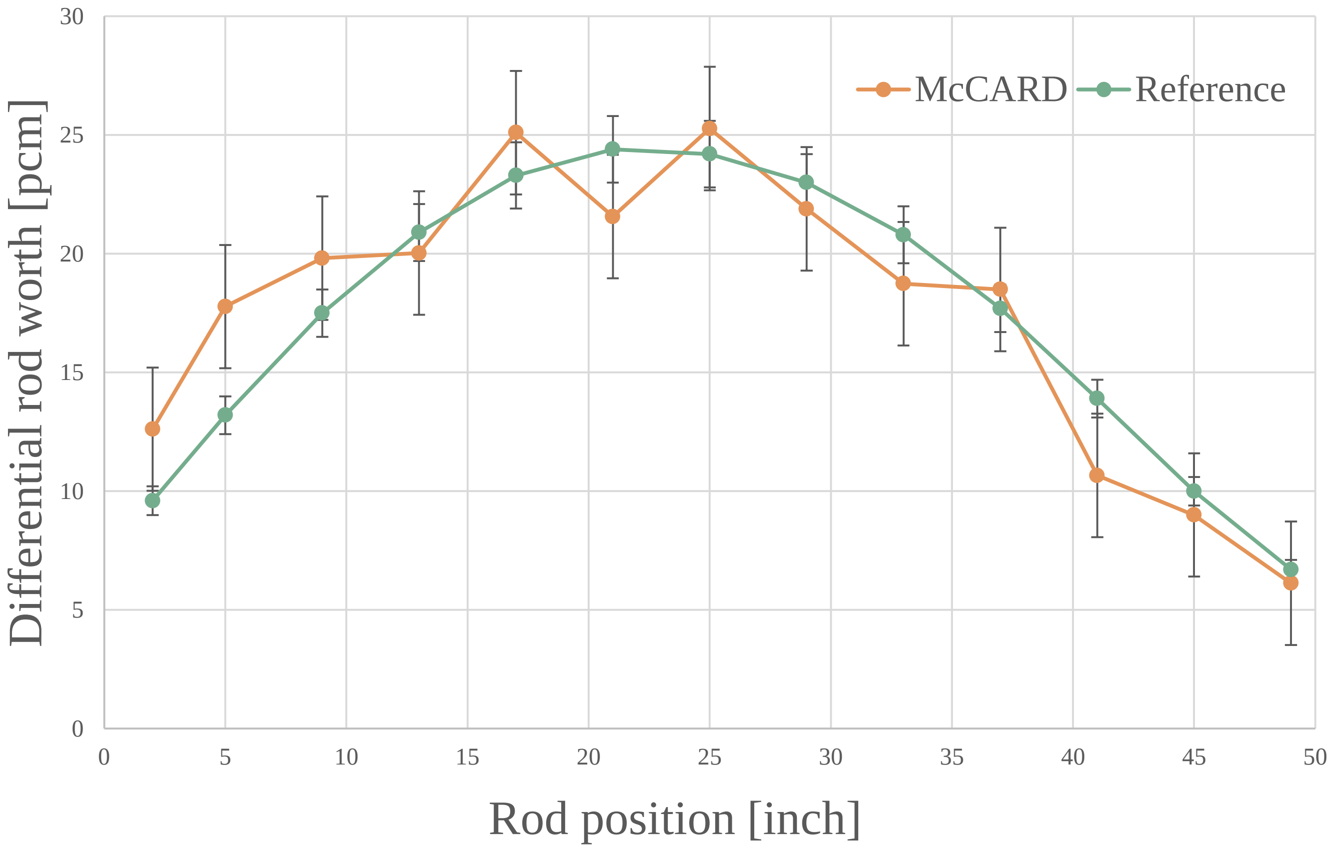


Fig. 10. Differential rod worth of control rod 2

- The results are computed by moving the control rod from 1 inch to 49 inches with a Δx of 4 inches
- Both the benchmark results and the McCARD calculations exhibit a cosine shape
- Excluding the result at 5 inches, the benchmark[5] values and the McCARD values match within a 95% confidence interval.

Result

◆ Total rod worth calculation

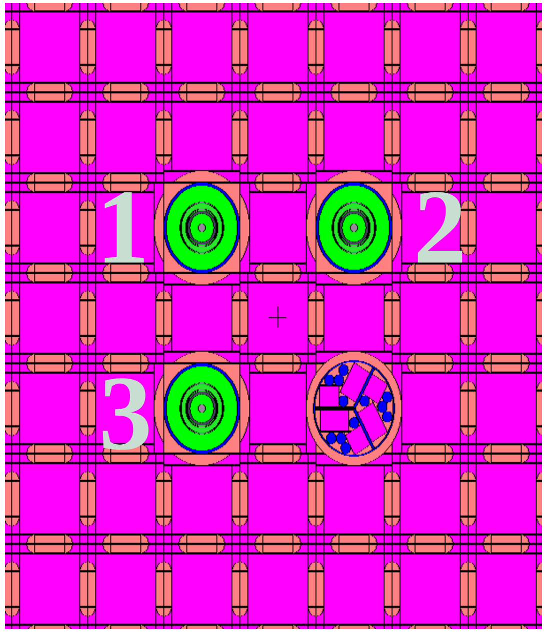


Table. 5. Total rod worth of control rods

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)

❖ The differences in total control rod worth between the benchmark and McCARD for one, two, and three control rods are 9, 52, and 216 pcm respectively

❖ The benchmark values and the McCARD values match within a 95% confidence interval.

Result

◆ Isothermal temperature coefficient and fuel temperature coefficient calculation

Table. 5. ITC and FTC of MSRE

Case	Benchmark [pcm/° F] (SD)	McCARD [pcm/° F] (SD)	Difference [pcm/° F] (SD)
ITC	-7.45 (0.85)	-7.51 (0.08)	0.06 (0.85)
FTC	-4.7 (0.7)	-4.23 (0.08)	0.47 (0.7)

❖ Calculate the k_{eff} values for temperatures of 961 K and 861 K and then determine the ITC and FTC

❖ The benchmark values and the McCARD values match within a 95% confidence interval.

Conclusion and Future Works

- The MSRE benchmark was solved using McCARD
  - For k_{eff} , the calculated values from McCARD and Serpent 2 did not match within the 95 percent confidence interval.
  - However, for both rod worth and temperature coefficient, the calculated values from McCARD matched the benchmark values.

- By analyzing MSR, a different type compared to conventional PWRs, it has been confirmed that McCARD can also analyze MSRs.

- As a future work, we plan to simulate the flow of fuel with updating the position of delayed neutrons and conduct calculations accordingly.

References

[1] Shen D., Fratoni M., Ilas G., Powers J., “Molten-Salt Reactor Experiment (MSRE) Zero-Power First Critical Experiment with U-235,” NEA/NSC/DOC(2006)1; MSRE-MSR-EXP-001 CRIT, OECD/NEA, 2019.

[2] H. J. Shim et al., “McCARD: Monte Carlo code for Advanced Reactor Design and Analysis,” Nuclear Engineering and Technology, vol. 44, no. 2, pp.161-176, 2012.

[3] M. B. Chadwick, et al., “ENDF/B-VII. 1 nuclear data for science and technology: cross sections, covariances, fission product yields and decay data,” Nuclear data sheets, Vol. 112, No. 12, p. 2887, 2011.

[4] Shen D., Ilas G., Powers J., Fratoni M., “Reactor Physics Benchmark of the First Criticality in the Molten Salt Reactor Experiment,” Nuclear Science and Engineering, vol. 195, pp. 825-837, 2021

[5] Fratoni M., Shen D., Ilas G., Powers J., “Molten Salt Reactor Experiment Benchmark Evaluation (Project 16-10240),” University of California, Berkeley, 2020