Preliminary Core Design of an Educational Tank-Type Critical Assembly for the Nuclear Joint Campus

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1. Introduction

An educational and research critical assembly plays a crucial role in cultivating future nuclear engineers. It can construct diverse reactor cores by arranging fuels and moderators for educational and research purposes. Through a range of reactor experiments, it facilitates a practical and innovative understanding of reactor physics.

Since the 2000s, educational training programs involving reactor experiments for domestic students have encompassed the international nuclear education program at the Kyoto University Critical Assembly (KUCA) [1] and the AGN-201K reactor experiment program at Kyung Hee University [2]. However, the KUCA is currently suspended due to the return of highly-enriched uranium fuels to the US. Additionally, the AGN-201K, the sole operational education program in Korea, faces challenges in altering its core configuration to suit diverse educational and research purposes.

The objective of this study is to conduct a preliminary conceptual design for two tank-type critical assemblies using rod-type UO_2 and plate-type U-7Mo fuels, and to serve as fundamental data for the future Korean educational critical assembly at the Nuclear Joint Campus within the Munmu Advanced Research Institute for Nuclear Science (MARINS). The preliminary design requirements are developed, and the neutronics parameters are evaluated by McCARD [3], a Monte Carlo neutron transport analysis code.

2. Design Requirements

The developed design requirements for an educational tank-type critical assembly are as follows:

1) Fuel: the rod-type UO_2 fuel or plate-type U-7Mo fuels will be applied. Fuel assemblies can be removed/installed during reactor shutdown.
2) Reactor type: it is an open-tank-in-pool type utilizing light-water as a moderator.
3) Power: while the typical critical assembly operates at the level of 1 W, it can be operated at a maximum thermal power of 10 W for neutron irradiation experiments.
4) First reactivity control system – control rod drive mechanism: the following equations have to be satisfied.

$$\rho_{ex} \leq 500 \text{ pcm}, \tag{1}$$

$$\rho_{ex} + 1000 \text{ pcm} \leq \sum_{i=1}^{6} \rho_{rod,i}, \tag{2}$$

$$\max\{\rho_{rod,i}\} \leq \frac{1}{3}\sum_{i=1}^{6} \rho_{rod,i}, \tag{3}$$

$$\rho_{SD} \geq 1.25\rho_{ex}, \tag{4}$$

where ρ_{ex} indicates excess reactivity, $\rho_{rod,i}$ indicates the i-th rod worth, and ρ_{SD} indicates total rod worth of safety rods.
5) Isothermal temperature coefficient (ITC)

$$\text{ITC} \leq 20 \text{ pcm/K} \tag{5}$$

6) Second shutdown system – moderator drain system

3. Core Design

The two tank-type critical assemblies are designed using the rod-type UO_2 fuel and the plate-type U-7wt%Mo dispersed in Al-5wt%Si matrix fuel (hereafter referred as U-7Mo) used in the KIJANG Research Reactor (KJRR) [4]. The fuel assemblies are designed to have a weight of under 10 kg and a length of less than 1 m, enabling students to handle them directly. The dimensions of the water tank include a radius of 2 m and a depth of 2 m.

3.1 The UO_2 Fuel-Loaded Core

3.1.1 Fuel Assembly

The UO_2 rod is enriched to 3 wt%, and its cladding material is Zr-4. Aluminum oxide (Al_2O_3) plenums are positioned at both the top and bottom of the rod. Following the PLUS7 model, the radii of the rod are as follows: 0.413 cm for the inner radius of the pellet, 0.4215 cm for the inner radius of the cladding, and 0.485 cm for the outer radius of cladding.

To determine the optimal pin pitch and the arrangement of fuel rods within a fuel assembly, preliminary calculations are performed for a single fuel assembly using arbitrary values for the active fuel length, as well as the lengths of the top and bottom plenum, which are set at 70, 20, 10 cm, respectively. In this configuration, the weight of a single preliminary fuel rod is 0.58 kg.

Considering both scalability and maximum weight, the fuel rod arrangement of 3×3 is selected, offering flexibility and a maximum weight of 5.2 kg. To determine the optimal pin pitch, the infinite multiplication factor of a single assembly with a 3×3 arrangement is calculated for various pin pitches ranging from 1.0 to 1.8 cm, including the PLUS7 model's pitch of 1.285 cm. McCARD eigenvalue calculations are performed on 400 active cycles with 10,000 histories per cycle with the ENDF/B-VIII.0 library [5]. For pin pitches greater than 1.4 cm, it is in an over-moderated state as shown in Fig. 1. In this study, considering an under-moderated state, the pin pitch of 1.285 cm from PLUS7 model is selected.

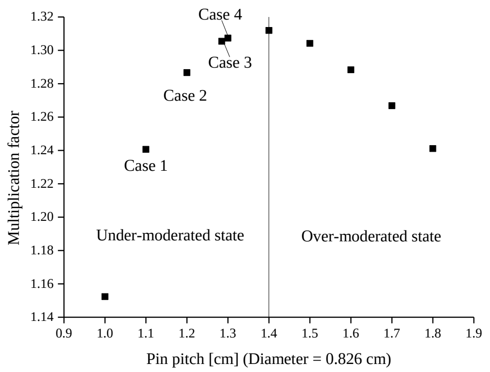

Fig. 1. The multiplication factor based on pin pitch

The UO_2 fuel-loaded core is designed in the shape of a scale-down cylinder, approximately one-ninth the size of APR1400. Furthermore, the ratio of the equivalent diameter (D_e) to the active core length (H) is set to 1. To achieve these conditions, the active fuel length is adjusted to 43 cm. The total length is 73 cm, as shown in Fig. 2, and the weight of a single UO_2 fuel rod is 0.37 kg. Figure 3 shows a cross-sectional view of the fuel assembly. To control neutron spectrum and critical mass, the number and arrangement of fuel rods within the fuel assembly can be changed.

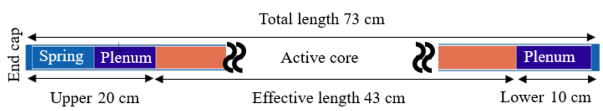

Fig. 2. The UO_2 pin configuration

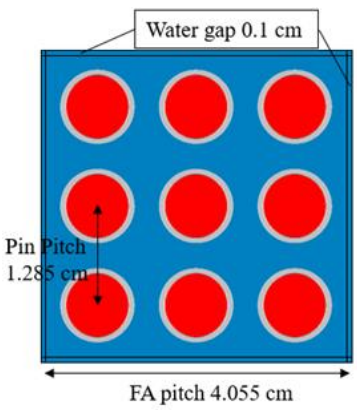

Fig. 3. The cross-sectional view of the UO_2 fuel assembly

When composed of 9 fuel rods, the total weight and the U-235 mass are 3.5 kg and 57.3 g, respectively. The pin pitch is 1.285 cm, resulting in the P/D and the $^{1}H/^{235}U$ values of 1.56 and 191.58, respectively. The dimensions of the fuel assembly are 4.055×4.055×73 cm, including a 0.1 cm water gap. The calculated infinite multiplication factor for the fuel assembly is 1.28248±0.00032.

3.1.2 Reactor Core

The UO_2 fuel-loaded core is designed in the shape of a cylinder, with dimensions about one-ninth the size of APR1400. The value of D_e/H is set to be close to 1. Additionally, the circularity, defined as 4π times the area divided by the circumference, is evaluated to determine how closely the cross-section of the core resembles a circle. To achieve a circularity similar to that of APR1400, the arrangement of the UO_2 rods within the core is adjusted.

Figure 4 illustrates the cross-sectional view of the UO_2 fuel-loaded core. A total of 732 fuel rods in the 88 fuel assemblies are loaded in the core. The value of D_e is 41.5 cm, which is approximately 1/8th that of APR1400, and the value of H is 43 cm, approximately 1/9th that of APR1400. The value of D_e/H is 0.96. Moreover, the circularity of the UO_2 fuel-loaded core is 0.618, closely aligned with that of APR1400, which is 0.613. The total U-235 mass within the UO_2 fuel-loaded core is 4.7 kg.

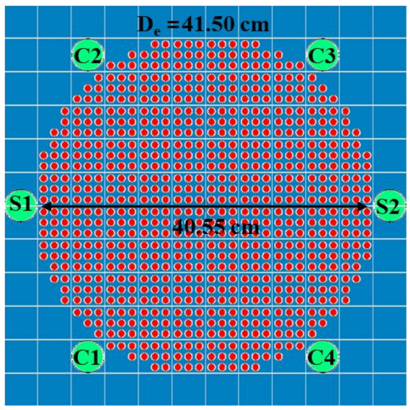

Fig. 4. The UO_2 fuel-loaded core configuration

3.1.3 Neutronics Parameters

For evaluating the neutronics parameters for the rod-type UO_2 fuel-loaded core, McCARD eigenvalue calculations are performed on 1,000 active cycles with 100,000 histories per cycle.

The excess reactivity is 185.7±14.0 pcm, satisfying Eq. (1). The effective delayed neutron fraction (β_{eff}) and the prompt neutron generation time (Λ) calculated by the MC forward eigenvalue calculations is 0.00778±0.00004 and 36.84±0.02 μsec, respectively.

As shown in Fig. 5, the neutron spectrum of the UO_2 fuel-loaded core indicates a thermal spectrum. Figure 6 shows the neutron flux distribution of the UO_2 fuel-loaded core. As neutrons move from the center toward its periphery, the fast neutrons decrease. For thermal neutrons, one can see a slight peak at the reflector boundary interface.

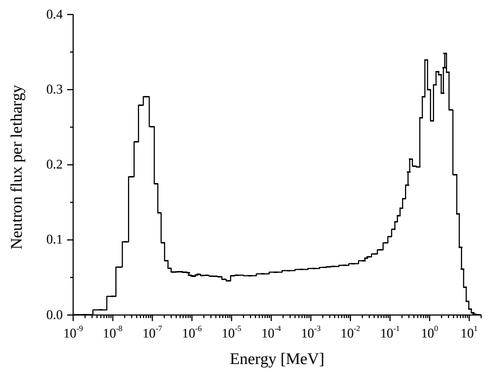

Fig. 5. The neutron spectrum of the UO_2 fuel-loaded core

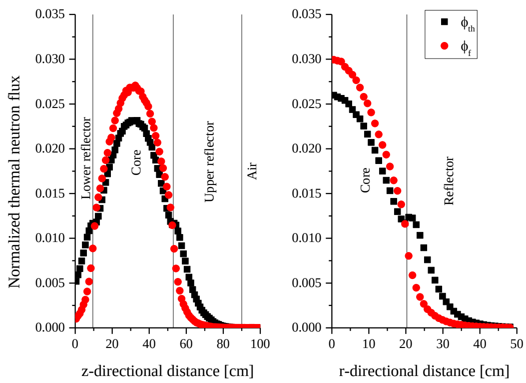

Fig. 6. The neutron flux distribution of the UO_2 fuel-loaded core

The temperature reactivity coefficient (TRC) is calculated by the MC adjoint-weighted perturbation method for a temperature variation of 1K. [6] For the analysis of the contribution of the thermal scattering library (TSL), the McCARD eigenvalue calculations are performed with two TSLs of the hydrogen in light-water. The ITC is estimated by summing up the effect of density changes and the microscopic cross-section changes. In this study, the thermal expansion of solid components in the core is negligible.

Figure 7 presents the fuel temperature coefficient (FTC), moderator temperature coefficient (MTC), and the isothermal temperature coefficient (ITC) at 283.6, 293.6, and 300.0K. The FTC is consistently -2.6 pcm/K, inserting the negative reactivity due to the Doppler-broadening effect. The reason for the linear decreases in the MTC is that the extent of density expansion becomes increases as the reference temperature increases. From the results, the UO_2 fuel-loaded core satisfies Eq. (5).

Based on the CROCUS core [7], the absorber of the control rod is selected with the B_4C absorber. To achieve a large control rod worth, the inner radius of the absorber rod is increased from 0.85 to 1.85 cm, corresponding to the B_4C mass of 1,946 g. The control rod can be withdrawn over a range of 80 cm from the lower grid plate. When arranged with the four control rods (C1, C2, C3, and C4) and two safety rods (S1 and S2) as shown in Fig. 4, the calculated rod worth is presented in Table II. From the results, the UO_2 fuel-loaded core satisfies Equations (2) to (4).

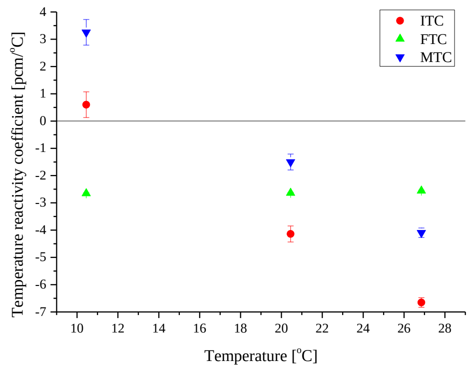

Fig. 7. The TRC of the UO_2 fuel-loaded core

Table I: Rod worth of the UO_2 fuel-loaded core

Contents	Rod worth
C1 rod worth	251±20 pcm
C2 rod worth	251±20 pcm
C3 rod worth	262±20 pcm
C4 rod worth	268±21 pcm
S1 rod worth	315±20 pcm
S2 rod worth	342±20 pcm
Total rod worth	1,829±20 pcm

3.2 The U-7Mo Fuel-Loaded Core

The U-7Mo fuel-loaded core is designed in a rectangular shape, approximately 30×30×60 cm in size like the KUCA light-water-moderated and -reflected core [1]. In this study, the U-7Mo with 6.5 g-U/cm^3 used in the KJRR [4] is applied to the designed core.

3.2.1 Fuel Assembly

The fuel plate consists of a homogeneous mixture of 19.75 wt% enriched U-7wt%Mo particles dispersed in Al-5wt%Si matrix as the fuel meat, encapsulated within an Al-6061 cladding material. The dimensions of the fuel meat are 62.0×0.51×600 mm, and the overall dimensions of the fuel plate are 70.7×1.27×640 mm. In this configuration, the U-235 mass in a single fuel plate is 24.4 g, and the total weight is 287.4 g.

Figure 8 shows the schematic diagram of the U-7Mo fuel assembly. The dimensions of the fuel assembly are 8.0×8.0×73.5 cm. When the fuel assembly is loaded into the tank, the gaps between the fuel plates are filled with water.

To derive the optimal number of nuclear fuel plates and fuel pitch, the infinite multiplication factor of a single U-7Mo fuel assembly is calculated based on varying the number of fuel plates. Figure 9 shows the infinite multiplication factor with the number of the fuel plates. As shown in Fig. 9, one can see that the number of fuel plates divided into an over-moderated state and an under-moderated state with 22 plates. In this study, the number of the U-7Mo fuel plates is set to 24 at which the infinite multiplication factor is maximized within the under-moderate state. In this configuration, the water channel thickness and the fuel pitch are 0.174 and 0.311 cm, respectively.

When the fuel assembly consists of 24 U-7Mo fuel plates, the infinite multiplication factor is 1.56886±0.00062. The U-235 mass within a single fuel assembly is 584.5 g, and the total weight of the fuel assembly is 9.1 kg, which is less than 10 kg. The $^{1}H/^{235}U$ ratio is 83.2, which is approximately half that of the UO_2 fuel assembly.

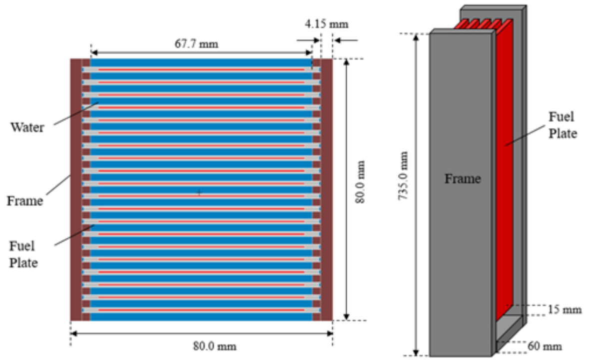

Fig. 8. The configuration of the U-7Mo fuel assembly

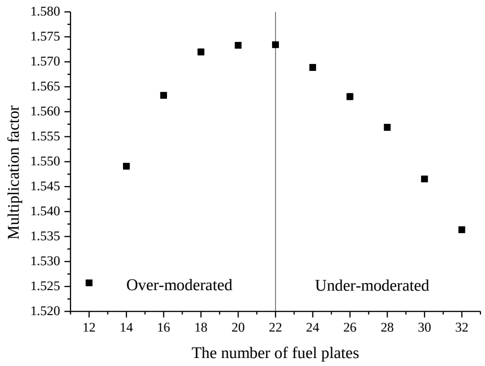

Fig. 9. The multiplication factor with the number of the U-7Mo fuel plate within the fuel assembly

3.2.2 Reactor Core

With the fuel pitch fixed at 0.311 cm, the number of the U-7Mo fuel plates is adjusted to reach critical mass. Figure 10 shows the core configuration of the U-7Mo fuel-loaded core. In Fig. 10, ‘F24’ and ‘F18’ denote the U-7Mo fuel assemblies with 24 and 18 fuel plates, respectively. The total number of U-7Mo fuel plates in the core is 270, corresponding to the U-235 mass of 6.6 kg, which is significantly 1.4 times larger than that of the UO_2 fuel-loaded core. The active core size is 24.3×29.9×60.0 cm.

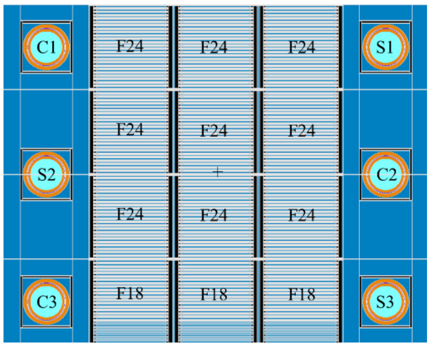

Fig. 10. The core configuration of the U-7Mo fuel-loaded core

3.2.3 Neutronics Parameters

For evaluating the neutronics parameters for the plate-type U-7Mo fuel-loaded core, McCARD k-eigenvalue calculations are performed on 1,000 active cycles with 100,000 histories per cycle.

The excess reactivity is 441.0±17.8 pcm, satisfying Eq. (1). The values of β_{eff} and Λ calculated by the MC forward eigenvalue calculations are 0.00794±0.00003 and 33.45±0.02 μsec, respectively.

As shown in Fig. 11, the neutron spectrum of the U-7Mo fuel-loaded core is harder than that of the UO_2 fuel-loaded core illustrated in Fig. 5.

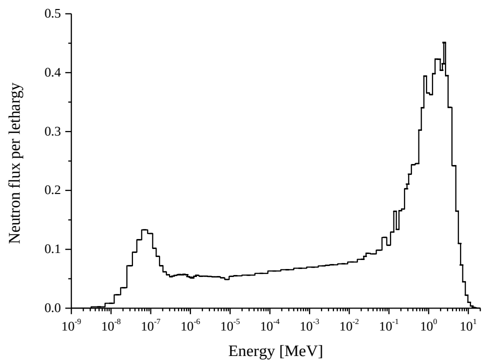

Fig. 11. The neutron spectrum of the U-7Mo fuel-loaded core

Figure 12 shows the neutron flux distribution of the U-7Mo fuel-loaded core. The overall graph is similar to that of the UO_2 fuel-loaded core illustrated in Fig. 6, but one can see that the thermal neutron peak at the reflector boundary interface in the U-7Mo fuel-loaded core is larger than that of the UO_2 fuel-loaded core. It is attributed to the harder neutron spectrum of the U-7Mo fuel-loaded core.

Figure 13 shows TRCs at 283.6, 293.6, and 300.0K with a temperature change of 1K. The error bars in Fig. 13 indicate the 95% confidence interval. Significantly, the ITC of the U-7Mo fuel-loaded core is larger than that of the UO_2 fuel-loaded core. It is attributed to the more hardening neutron spectrum and the smaller core size, which result in the spectral shift effect and neutron leakage. [8] Despite the positive ITC values for all three reference temperatures, it confirmed that the core satisfies the ITC regulations specified in Eq. (5).

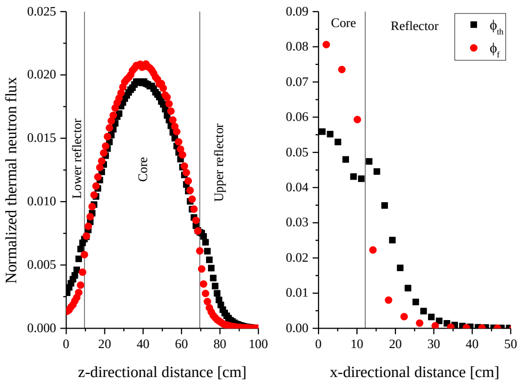

Fig. 12. The neutron flux distribution of the U-7Mo fuel-loaded core

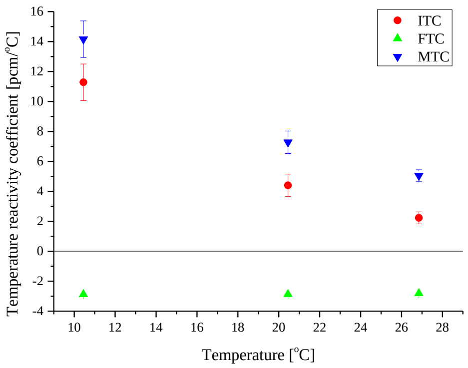

Fig. 13. The TRC of the U-7Mo fuel-loaded core

In this design, the control rods utilizing the Cd absorber of the KUCA light-water-moderated and -reflected core [1] are implemented. When arranged the three control rods (C1, C2, and C3) and three safety rods (S1, S2, and S3) as shown in Fig. 10, the calculated rod worth is presented in Table II. From the results, the U-7Mo fuel-loaded core satisfies Equations (2) to (4).

Table II: Rod worth of the U-7Mo fuel-loaded core

Contents	Rod worth
C1 rod worth	361±25 pcm
C2 rod worth	651±25 pcm
C3 rod worth	266±24 pcm
S1 rod worth	356±25 pcm
S2 rod worth	661±25 pcm
S3 rod worth	274±24 pcm
Total rod worth	2,591±26 pcm

4. Conclusions

In this study, the tank-type core designs are carried out for the rod-type UO_2 and plate-type U-7Mo fuel-loaded cores. The UO_2 fuel-loaded core is designed with an equivalent diameter of 41.5 cm and an effective length of 43 cm. The core consists of 732 fuel rods with 3 wt% uranium enrichment, resulting in the U-235 mass of 4.7 kg. The U-7Mo fuel-loaded core is designed with the 19.75 wt%-enriched U-7Mo fuel with 6.5 g-U/cm^3 used in the KJRR. The active core size is 24.3×29.9×60.0 cm, utilizing a total of 270 U-7Mo fuel plates. In this configuration, the U-235 mass is 6.6 kg, which is significantly 1.4 times larger than that of the UO_2 fuel-loaded core. Furthermore, it is confirmed that the neutronics parameters of both cores satisfy the developed design requirements.

This study is anticipated to provide foundational data for the establishment of a future Korean educational critical assembly at the Nuclear Joint Campus.

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