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Optimal Cycle Length of MAGNOX Reactor for Weapons-Grade Plutonium Production

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Democratic People's Republic of Korea (DPRK) has produced weapon-grade plutonium in a graphite-moderated experimental reactor at the Yongbyon nuclear facilities. The amount of plutonium produced can be estimated using the Graphite Isotope Ratio Method (GIRM), even without considering specific operational histories. However, the result depends to some degree on the operational cycle length. Moreover, an optimal cycle length can maximize the number of nuclear weapons made from the plutonium produced. For conservatism, it should be assumed that the target reactor was operated with an optimal cycle length. This study investigated the optimal cycle length using which the Calder Hall MAGNOX reactor can achieve the maximum annual production of nuclear weapons. The results show that lower enrichment fuel produced a greater number of critical plutonium spheres with a shorter optimal cycle length. Specifically, depleted uranium (0.69wt%) produced 5.561 critical plutonium spheres annually with optimal cycle lengths of 251 effective full power days. This research is crucial for understanding DPRK's potential for nuclear weapon production and highlights the importance of reactor operational strategy in maximizing the production of weapons-grade plutonium in MAGNOX reactors.

Keywords: MAGNOX, Weapon-grade plutonium production, DPRK nuclear capabilities, Cycle length optimization, GIRM

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1. Introduction

It is well known that the Democratic People's Republic of Korea (DPRK) has produced weapon-grade plutonium at the Yongbyon nuclear facilities, which include a MAGNOX type experimental reactor [1]. Estimating the maximum number of nuclear weapons that the DPRK can make with the plutonium produced at the Yongbyon nuclear facilities is crucial for the denuclearization process of the DPRK. The Graphite Isotope Ratio Method (GIRM) [2, 3, 4, 5] has been explored as a tool for estimating the amount of plutonium production in a graphite-moderated nuclear reactor, such as MAGNOX reactor. GIRM has the advantage of being able to estimate the quantity of produced plutonium relatively accurately even when specific operational histories of the target reactor are not provided.

As the reactor operates, ^{235}U within the nuclear fuel is consumed, while plutonium accumulates. Furthermore, impurities within the graphite moderator also undergo changes in number density through nuclear reactions. For example, ^{10}B in the graphite moderator depletes while ^{11}B increases. In this process, the number densities of the nuclides are tightly correlated, and if the number density of ^{10}B is measured, then the number density of plutonium can be determined as long as the initial number densities are known. However, in reality, the initial amounts of impurities are unknown, and the amount of plutonium produced cannot be determined even though the number density of ^{10}B is measured. The main idea of GIRM is that the initial isotope ratio of impurities is known regardless of their absolute amount, and the amount of plutonium can be determined by measuring the isotope ratio of impurities instead of absolute number density of impurities. In GIRM, the quantity of plutonium produced in the reactor is determined using a relationship curve that links the amount of plutonium produced with the isotope ratios of impurity or indicator elements in the graphite moderator, such as $^{10}B/^{11}B$, $^{36}Cl/^{35}Cl$, $^{41}Ca/^{40}Ca$, and $^{235}U/^{238}U$. This relationship curve is pre-calculated using a simple geometric model composed of fuel and graphite moderator with indicator elements as impurities. Once the isotope ratio of the indicator elements is measured from the graphite moderator at the sampling locations in the target reactor, the amounts of plutonium produced at the sampling regions can be estimated using the relationship curve. The total amount of plutonium produced in the target reactor is calculated by a polynomial regression with the distribution of the cumulated plutonium at each sampling point.

However, the characteristics of the relationship curve itself depends on how the reactor has been operated, especially on the operation cycle length. The transmutation rate of plutonium from uranium remains constant while the consumption rate of plutonium increases as the operation time increases, eventually leading to saturation in the amount of plutonium produced. Therefore, a shorter cycle length is advantageous for producing a large amount of plutonium under the condition that the total operation time is the same. However, too short cycle length leads to a low availability of the reactor, resulting in a reduction in the annual production of plutonium. Not only does the annual plutonium production quantity, but also the quality of the produced plutonium is influenced by the reactor's cycle length. As the operation time increases, the proportion of ^{239}Pu in the total plutonium decreases and a shorter cycle length is advantageous for producing high-quality plutonium, which has a lower critical mass compared to low-quality plutonium. Therefore, there exists an optimal cycle length to maximize the number of nuclear weapons produced annually. For conservatism, it should be assumed that the cycle length was determined to maximize the annual production of nuclear weapons. By calculating the relationship curve with this optimal cycle length, the most conservative result could also be obtained in the plutonium production predicted by GIRM.

In this study, the impact of the cycle length of a MAGNOX reactor on both the quantity and quality (i.e., critical mass) of plutonium was assessed. Subsequently, the optimal cycle length of the reactor that maximize the annual

Table 1. Design parameters for Calder Hall MAGNOX reactor [6, 8]

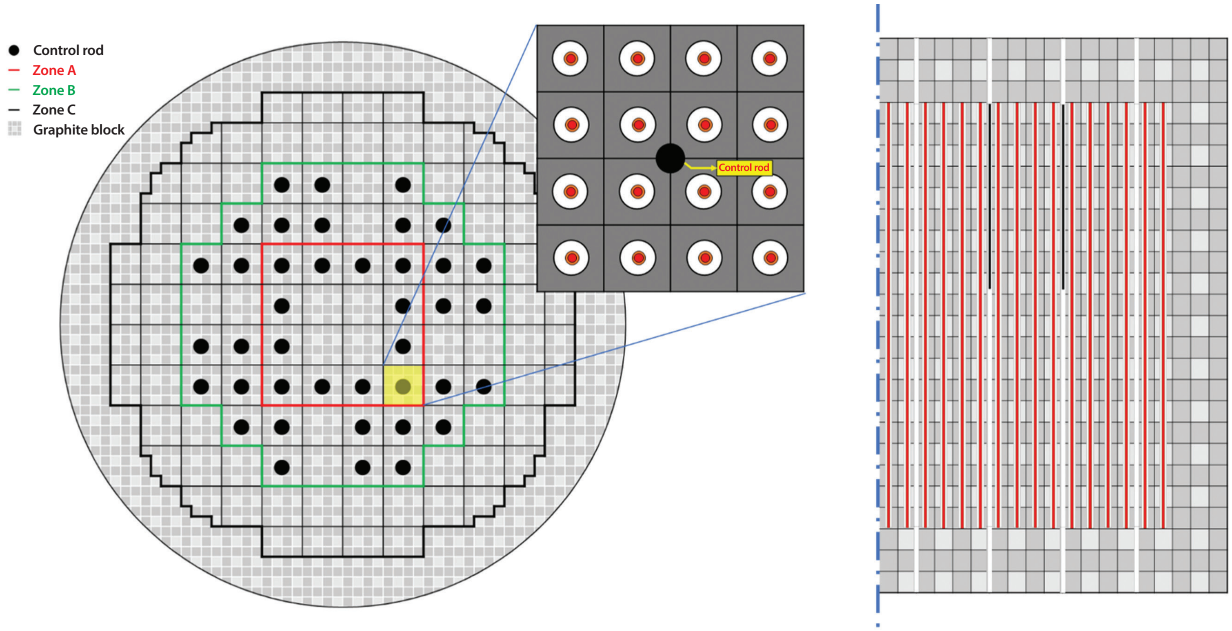
Parameter		Value
Power		182 MW_{th}
Active core height		640 cm
Active core diameter		945 cm
Fuel pin radius		1.4610 cm
Cladding radius		2.0400 cm
Coolant hole radius	Zone A	5.2080 cm
	Zone B	5.0165 cm
	Zone C	4.5847 cm
Control rod radius		3.87 cm
Control rod hole radius		4.125 cm
Average fuel temperature		425^{o}C
Average graphite temperature		250^{o}C
Number of fuel channels		1,696 EA
Number of control rods		40 EA
Uranium mass		120 tones
Fuel material		Natural U metal
Fuel density		17.98 $g \cdot cm^{-3}$
Clad material		Mg (1% Al, 0.05% Be)
Clad density		1.65 $g \cdot cm^{-3}$
Moderator material		Graphite
Moderator density		1.628 $g \cdot cm^{-3}$
Mean inlet gas temperature		140°C
Mean outlet gas temperature		336°C
Coolant direction		Upward

production of nuclear weapons was determined. The target reactor in this study was the Calder Hall MAGNOX reactor [6] and simulations were conducted using the Monte-Carlo code MCS developed at UNIST [7].

2. Optimal Cycle Length for Maximum Number of Nuclear Weapons

2.1 Calder Hall MAGNOX Reactor

The Calder Hall MAGNOX reactor is recognized as the world's first commercial nuclear reactor. The name 'MAGNOX' derives from the magnesium-aluminum alloy used as the cladding material for the nuclear fuel, highlighting its unique composition. This reactor's core has several distinctive features. It utilizes natural uranium for fuel, carbon dioxide as the coolant, and graphite as the moderator. Within the graphite, the coolant channels are laid out in a square grid, with fuel rods positioned centrally in these channels. These channels are organized in four-by-four sets, forming structures known as 'pans'. The reactor core is divided into three zones radiating outward from the center, with the coolant channels' diameter progressively decreasing



(a) Radial view (b) Axial view

Fig. 1. Geometry of Calder Hall MAGNOX reactor.

towards the outer zones. Fig. 1 illustrates the geometry of the Calder Hall MAGNOX reactor. In the outermost pans, certain channels are omitted to give the core a more cylindrical shape. Control rods, which are inserted from the top of the core, are strategically located at the center of selected pans to regulate the reactor's output. The coolant flows from the bottom to the top of the core, performing the vital role of heat removal generated by the reactor. Detailed specifications of the reactor are provided in Table 1 [6].

2.2 Depletion Calculation of the MAGNOX Reactor

Core burnup calculations were conducted employing MCS, utilizing a nuclear cross-section library based on ENDF/B-VII.1 and the HELIOS kappa library. The type of S(α,β) table was considered for the graphite crystal with zero porosity. The criticality calculations were performed with 70 inactive cycles and 50 active cycles, utilizing 100,000 histories of neutrons. This resulted in a standard deviation of k_{eff} less than 20 pcm.

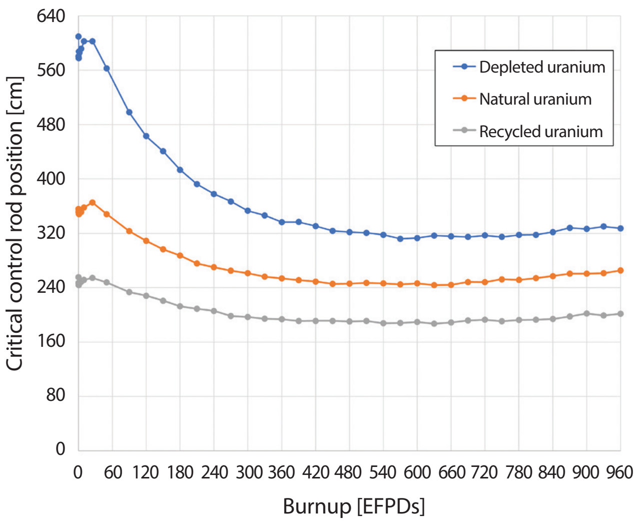


Fig. 2. Critical control rod positions for depleted, natural, and recycled uranium.

A burnup step of 30 Effective Full Power Days (EFPDs) was utilized except for the initial steps. It was assumed that after each operational cycle, the reactor undergoes a 30-day period of maintenance. During this interval, additional ^{239}Pu is generated, due to the presence of residual ^{239}U in the fuel. To incorporate this factor, an additional 30-day decay calculation was executed for the nuclear fuel at each stage of the analysis. This computational approach facilitated the comparison of outcomes among different uranium types: depleted (0.69wt%), natural (0.72wt%), and recycled (0.75wt%). It was assumed that the separation of minor actinides from the recycled fuel was perfect and that all fuel types contain only uranium isotopes ^{234}U, ^{235}U, and ^{238}U, without any other minor actinides. For ^{234}U, all fuel types maintain a consistent mass fraction of 0.0055wt%, while ^{238}U makes up the remaining mass ratio. The critical control rod positions from the bottom of the core under each of these conditions are depicted in Fig. 2. The standard deviations of critical control rod positions were less than 1 cm.

2.3 Effect of Cycle Length on the Annual Production of Plutonium

The net production rate of plutonium peaks at the start of the operation and diminishes as the operation progresses. This decline is due to the increase in the consumption rate, which is proportional to the plutonium accumulation. As a result, when the reactor operates with longer cycles, the annual plutonium yield is reduced. Conversely, with shorter cycles, the availability of the reactor decreases due to 30-day maintenance period after operation, leading to a decrease in annual plutonium production. Therefore, due to the interplay of these factors, there exists a specific cycle length for maximum annual plutonium production.

Fig. 3 shows the annual production of plutonium for the three cases. For evaluation of optimal cycle lengths, cubic interpolations are used with the points at 270, 300, 330, and 360 EFPDs. The calculations showed that the highest annual plutonium production using depleted uranium, was 57.04 kg·yr^{-1} at a cycle length of 295 EFPDs. For natural uranium, the maximum production was 55.00 kg·yr^{-1} at a cycle length of 300 EFPDs, and for recycled uranium, it was 53.67 kg·yr^{-1} at a longer cycle length of 318 EFPDs. Table 2 summarizes the maximum annual production of plutonium and the optimal cycle length. This trend of increased plutonium production in the fuel with lower enrichment levels can be attributed to the higher flux levels in the core with lower enrichment levels for maintaining the same power level.

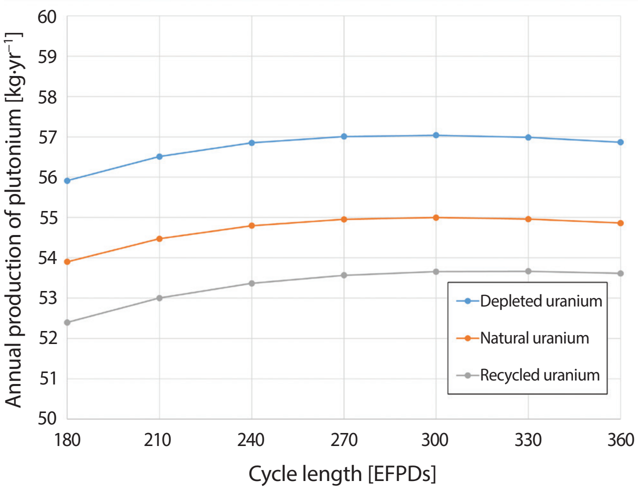


Fig. 3. Annual production of plutonium for various cycle length and fuel enrichment level.

Table 2. Maximum annual plutonium production and the optimal cycle length

Enrichment of ^{235}U in the fuel [wt%]	Maximum annual plutonium production [kg·yr^{-1}]	Optimal cycle length [EFPDs]
0.69	57.04	295
0.72	55.00	300
0.75	53.67	318

2.4 Effect of Cycle Length on the Critical Mass of Plutonium

As the cycle length increases, the consumption of ^{239}Pu and the transmutation of ^{240}Pu from ^{239}Pu increase, resulting in a degradation of plutonium quality and an increase of critical mass of the plutonium produced. The critical mass

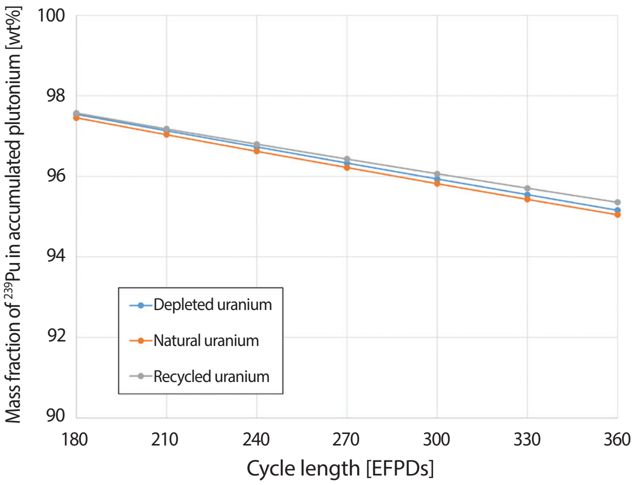


Fig. 4. Mass fraction of ^{239}Pu in plutonium for various cycle length and fuel enrichment level.

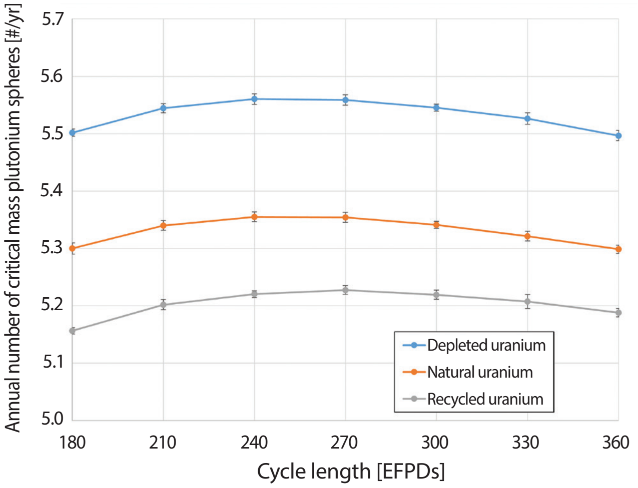


Fig. 6. Annual production of critical plutonium spheres for various cycle length and fuel enrichment level.

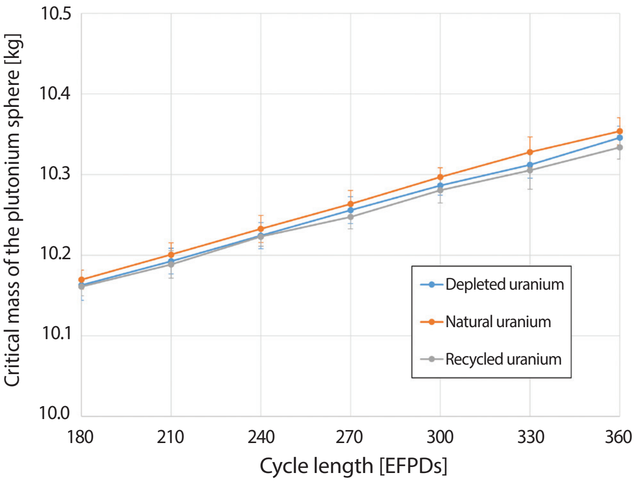


Fig. 5. Critical mass of plutonium spheres for various cycle length and fuel enrichment level.

was evaluated using the MCS code with a spherical model. Figs. 4 and 5 show the proportion of ^{239}Pu in total plutonium and the critical mass of the plutonium produced, respectively. As the cycle length increases, the proportion of ^{239}Pu in total plutonium decreases linearly and, as a consequence, the critical mass increases linearly. The standard deviations of critical mass are less than 0.015 kg, and the error bars in Fig. 5 represent a range of 2σ.

Additionally, it is observable that the critical mass varies somewhat depending on the enrichment level of the fuel. This variation appears to be due to factors such as the ratio of uranium isotopes and changes in neutron distribution caused by control rods, influencing the proportion of ^{239}Pu within the produced plutonium. However, these differences overlap within the 2-sigma error range of each data set and are minor compared to the previously discussed differences in annual plutonium production. Therefore, they are not likely to be a significant consideration.

Table 3. Maximum annual production of critical plutonium spheres and the optimal cycle length

Enrichment of ^{235}U in the fuel [wt%]	Maximum annual production of critical plutonium spheres [#/yr]	Optimal cycle length [EFPDs]
0.69	5.561	251
0.72	5.357	252
0.75	5.228	265

2.5 Effect of Cycle Length on the Number of Nuclear Weapons

The annual capability for nuclear weapons production is determined by considering both the annual plutonium production and the critical mass of plutonium at varying reactor cycle lengths. It is premised that nuclear weapons are made using plutonium at its critical mass. Fig. 6 shows the number of critical plutonium spheres produced annually. The standard deviation of annual number of critical plutonium spheres are less than 0.006 #/yr, and the error bars in Fig. 6 represent a range of 2σ. Since shorter cycles result in higher quality plutonium and a smaller critical mass, the optimal cycle length is correspondingly shorter for all three uranium types. Specifically, with depleted uranium, a cycle length of 251 EFPDs yields 5.561 critical spheres per year; natural uranium produces 5.357 critical spheres per year at a cycle length of 252 EFPDs; and recycled uranium generates 5.228 critical spheres annually at a cycle length of 265 EFPDs. Each value was calculated using cubic interpolation based on the top four points in the data. Although the critical mass varies with the enrichment level of uranium, this variation is relatively minor when compared to the annual plutonium production, indicating that depleted uranium is the most effective for producing plutonium among the three cases. Table 3 summarizes the maximum annual production of critical plutonium spheres and the optimal cycle length.

3. Conclusions

An in-depth analysis was performed to determine the optimal cycle length for maximizing the annual production of critical plutonium spheres in the Calder Hall reactor. The Monte-Carlo code MCS was utilized for this purpose. The maximum number of critical plutonium spheres annually produced was calculated, considering not just the quantity of plutonium produced at different cycle lengths but also its quality.

It was found that the annual production of plutonium reaches its peak at a specific cycle length. An increase in the critical mass of plutonium was notably observed with longer cycles, attributed to the changing ratio of ^{239}Pu to ^{240}Pu in the produced plutonium.

The study revealed optimal cycle lengths and the maximum number of nuclear weapons that could be produced, which varied depending on the uranium fuel's enrichment levels. For depleted uranium, an optimal cycle length of 251 EFPDs could produce 5.561 critical plutonium spheres per year. In contrast, for natural uranium, 252 EFPDs of cycle length resulted in 5.357 critical plutonium spheres annually. Meanwhile, recycled uranium reached its peak production of 5.228 critical plutonium spheres per year at an optimal cycle length of 265 EFPDs. Depleted uranium emerged as the most efficient material for weapon-grade plutonium production, considering both the yield and critical mass.

This research is crucial in understanding the DPRK's nuclear weapon development capabilities and plays a significant role in verifying its denuclearization efforts. Additionally, it underscores the importance of the operational cycle in the strategy to maximize the production of weapon-grade plutonium in MAGNOX reactors.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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