Sensitivity Study on Plutonium Production Potential from 5MWe YongByon Reactor using McCARD simulation

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1. Introduction

North Korea conducted six nuclear tests from 2006 to 2017, making them a major challenge in preventing nuclear proliferation around the world. Most of these tests are believed to have used weapons-grade (WG) plutonium and enriched uranium. Plutonium is produced at the reactor, and the 5 MWe Yongbyon reactor is considered the main WG plutonium production facility. From a national security perspective, it is essential to prepare for the asymmetric power of another country. Thus, it is necessary to estimate the amount of plutonium that can be extracted from the nuclear fuel of the Yongbyon reactor to predict for the size of their nuclear weapons.

The 5 Mwe Yongbyon reactor is a nuclear reactor that produces weapons-grade plutonium required for North Korea to build nuclear weapons. The Yongbyon reactor uses graphite reflectors to stack perforated graphite bricks and load nuclear fuel into the hole, and cool with carbon dioxide (CO_2). The reactor core consists of fuel channels, control rod channels, and reflector, with a thermal power of 25 MWt and an electrical power of 5 MWe, and no enrichment process is required using natural U as fuel.

Based on the information obtained by analyzing the operation records of the reactor from 1986 to 2007 and various previous research cases, the amount of plutonium produced during the operation of the reactor was investigated. The channel arrangement of the core was referenced by the paper calculating the amount of plutonium produced in the Yongbyon reactor through MCNP6 [3]. In order to compensate for the too large range of plutonium production presented in this paper, more information was collected so that accurate calculations could be made. And the material composition of the fuel rod was determined based on the contents presented in the paper that calculated the amount of tritium produced in the Yongbyon reactor using McCARD [4]. Although it is not revealed that tritium was produced in the Yongbyon reactor, it is referred to in that it dealt with the same reactor as this study.

McCARD(Monte Carlo Code for Advanced Reactor Design and Analysis) was used as a calculation code for estimating the inventory of plutonium. The Monte Carlo method refers to a method of mathematically approximating the value of a function using repeated random sampling, and McCARD simulates the random motion of individual neutrons [1]. The results are statistically processed to quantify the average value of the nuclear characteristic factor and the error in its calculation. This Monte Carlo method is mainly used for approximate calculations when the value to be calculated is complex and has high accuracy in studying the characteristics of neutrons. It was confirmed that McCARD is suitable for the analysis of neutronics enough to be used for the calculation of the criticality prediction of the JRTR core, a research reactor in Jordan [2]. In addition, a series of calculations were performed using the ENDF/B-VII.1 nuclear library.

Uncertainty exists for the input variables by designing the core based on the collected data rather than the officially disclosed information. Therefore, it is necessary to supplement the uncertainty of the McCARD's own program, such as the number of neutrons sampled for the Monte Carlo method. Sensitivity analysis was performed by selecting the reactor power, core and coolant temperature, and the number of neutron samples as sensitivity analysis variables. In this paper, we present McCARD basic calculation results for plutonium production in 5MWe Yongbyon reactor and sensitivity analysis results to compensate for uncertainty.

2. Base case analysis

To write the McCARD input for calculating the plutonium production amount in the 5 MWe Yongbyon reactor, the shape of the core and the operation history were investigated. The reactor information was written by borrowing the necessary information from the reference paper or assuming some of it.

2.1 Core design of 5MWe Yongbyon reactor

5MWe Yongbyon reactor is a research reactor that produces weapons-grade plutonium required for North Korea to build nuclear weapons. 5MWe Yongbyon reactor is located next to the Kuryong River in Yongbyon, about 100km north of Pyongyang. The Yongbyon reactor is modeled after the UK's Magnox

Calder Hall reactor, which is a graphite decelerator, and the exterior is modeled after Japan's Tokai-1 reactor.

In this study, two documents [3], [4] were referenced to set appropriate values for the reactor structure and the core. In both documents, the 5 MWe Yongbyon reactor uses 25 MWt of heat power, 5 MWt of electric power, Mg as a cladding material, CO_2 as a coolant, natural uranium as fuel, and graphite as a moderator. However, there are some differences because the detailed specifications are not known exactly. The total number of channels was set at 877 and all 76 other than 801 fuel rod channels were assumed to be control rod channels, and the control rod was assumed to be made of CO_2 with a diameter of 8 cm. In addition, the ratio of components, weight, and thickness of the coating material were referred to [5].

The inside of the reactor vessel consists of the fuel rod channel, the control rod channel, and the reflector. The fuel rod channel consists of a fuel rod and a moderator, and the control rod channel consists of a control rod and a moderator. Both channels are composed of a square with a side length of 20 cm, with a fuel rod and a control rod in the center. Natural uranium is located at the innermost side of the fuel rod channel, cladding surrounds the fuel, and a coolant with CO2 occupies the outermost part. In case of the control rod channel, the inside is filled with a coolant and the cladding surrounds it. Each fuel rod and control rod are wrapped with a graphite moderator, and the reactor container surrounds it [3]. The outer part of the reactor vessel is composed of air, and the air acts as a coolant and at the same time blocks heat, and the part composed of air is surrounded by a heat shield.

Table 1 is the detailed specifications of 5 MWe Yongbyon reactor assumed in this study.

Table 1: Characteristics of the 5 MWe Yongbyon reactor

	Parameter	Value
Core power	Thermal power	25 MWt
	Electric power	5 MWe
Core	Number of channels	877
	Number of fuel channels	801
	Number of control channels	76
	Number of fuel rods per channel	10
	Distance between channels	20 cm
	Radius of fuel channel	3.6 cm
	Radius of control channel	8 cm
Reflector	Mass of graphite reflector	300 t
Fuel	Uranium loaded	50 t
	Uranium enrichment	0.71 wt%
	Fuel composition	Nat U (0.5% Al)
	Length of fuel rod	52 cm
	Radius of fuel rod	2.866 cm
	Uranium per fuel rod	6.24 kg
Cladding	Cladding composition	Mg (1% Al)
	Thickness of cladding	0.35 cm
Coolant	CO_2	
Moderator	Graphite	

2.2 Operational history of 5MWe Yongbyon reactor

In order to know the potential amount of plutonium North Korea possesses, it is important to evaluate fuel burnup based on the operating records of the 5 MWe Yongbyon reactor. North Korea started operating the reactor in 1986 and the operation was suspended from 1994 to 2002 due to the conclusion of the Agreed Framework, and then restarted in January 2003 when the Agreed Framework was invalidated at the end of 2002. In 2005, a fuel rod was withdrawn to extract plutonium, and a new fuel rod was inserted and operated again. After that, at the six-party agreement in February 2007, it was decided to deactivate the nuclear facility in Yongbyon, so the operation was stopped. Operation data from show that the reactor power was not constant and operated over various ranges.

In this study, since the integrated thermal energy is important in calculating the amount of plutonium produced, EFPD (Effective Full Power Day) was determined according to the integrated thermal energy value after assuming the power of 25 MW. Table 2 shows the integrated thermal energy, number of operating days, and EFPD for each specific period.

Table 2: Integrated thermal energy, Operation days, and EFPD by Operational period

Operational period		Integrated thermal energy (MWd)	Operation days	EFPD(Integrated thermal energy/25 MWt)
Period 1	1986.01.05. – 1994.04.10	33,641	2,5787.7	1345
Period 2	2003.02.23. – 2005.03.31	18,380	690.6	735
Period 3	2005.06.16 – 2007.07.14.	8,570	533.5	347

2.3 Calculation result of base case

The amount of nuclear weapons-grade Pu-239 was calculated by executing the McCARD input based on the records of the structure and fuel burnup of the 5 Mwe Yongbyon reactor. The McCARD input simulated the reactor of the 1/4 core model (200.25 channels) of the Yongbyon reactor, and the burnup calculation was performed by dividing it into 45 burnup steps for 1345 days. In addition, ENDF/B-VII.1 was used for the neutron reaction cross-sectional calculation, and 300 repetitive calculations were performed using 150,000 samples of neutron particles, 100 of which correspond to inactive calculations. And the temperature of the nuclear fuel channel was assumed to be 600 K, and the temperature of the coolant, moderator, and reflector was assumed to be 300 K.

The value to be derived in this analysis is the total amount of plutonium extracted, which can be derived by adding the amount of plutonium extracted for each period. In addition, since the 1/4 core model was calculated, the amount of plutonium produced in the entire reactor was derived by quadrupling the amount of plutonium produced for the total operating period.

Figure 1 is a graph showing the amount of plutonium produced according to EFPD as a base case analysis result, which is the result of the total core. Plutonium production over the entire period can be obtained by adding the amount of plutonium produced for each of the three previously defined operating periods. It can be seen that 26.68 kg was produced in period 1, 15.48 kg in period 2, and 7.60 kg in period 3, resulting in a total of 49.76 kg.

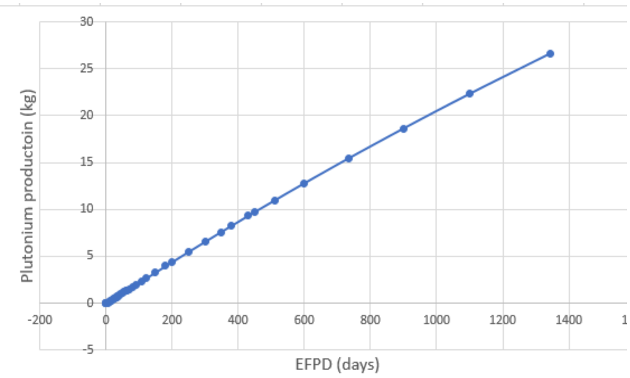

Fig. 1. Plutonium production vs. EFPD

3. Sensitivity analysis

The base case analysis has uncertainty because the information on the Yongbyon reactor structure and operation are established based on various literature investigations, and different parts are also visible for each literature. It is not easy to find the exact value of variables related to the operation of the reactor based on the uncertain information recorded. There is also the uncertainty of McCARD's input. For example, it is the number of neutrons sampled for the Monte Carlo method. Therefore, sensitivity analysis is required for the main variables for a basic estimation of this uncertainty. In this study, the reactor full power (SA-A), reactor integrated thermal energy (SA-B), number of neutron samples and repetitive calculations (SA-C), fuel channel temperature (SA-D), coolant/reflector temperature (SA-E), and nuclide cross section libraries (SA-F) were selected as information that may affect the results as shown in Table 3.

3.1 Reactor full power (SA-A)

In the reactor operational history of the 5 MWe Yongbyon reactor, the maximum full power of the reactor is not kept constant during the period of the analysis [6]. In the basic case analysis, it was performed in consideration of EFPD by assuming 25 MWt and dividing the integrated thermal energy with it. This is based on the prediction that there will be no significant change in the total plutonium production even if the EFPD is adjusted according to the change in full power, assuming that the integrated thermal energy is the same. In this sensitivity analysis, the analysis was performed by adjusting 25 MWt to 20 MWt to confirm the validity of this premise. Accordingly, the power value created in the burnup input was modified from 6.25 to 5.0 (1/4 core), and the McCARD input was modified and executed to reflect the increased number of operating days due to the reduced maximum power.

Table 3 shows the results of SA-A sensitivity analysis. For the total reactor operation period, the amount of plutonium produced in the entire core was 49.72kg, a 0.08% decrease from the value of 49.76kg derived by performing the calculation with a maximum power of 25 MWt.

Table 3: Sensitivity analysis list

		Variables	Base case	Sensitivity analysis
SA-A		Reactor full power	25 MWt	20 MWt
SA-B		Reactor integrated thermal energy	60,591 MWd	54,639 MWd
SA-C	SA-C1	Number of neutron samples and repetitive calculations	150,000 neutrons 300 calculations (100 inactive)	75,000 neutrons 150 calculations (50 inactive)
	SA-C2			200,000 neutrons 500 calculations (200 inactive)
SA-D		Fuel channel temperature	300 K	400 K
SA-E		Coolant/reflector temperature	600 K	700 K
SA-F		Nuclide cross section library	ENDF/B-VII.1	ENDF/B-VII.0

Table 4: Plutonium production in SA-A

Operational period	Integrated thermal energy (MWd)	EFPD (days)	Plutonium production(kg)		
			Base case (A)	SA-B(B)	Change rate (B-A)/A
Period 1	33,641	1,682	26.68	26.68	+0.00%
Period 2	18,380	919	15.48	15.52	+0.26%
Period 3	8,570	429	7.60	7.52	-1.05%
Total			49.76	49.72	-0.08%

Table 5: Plutonium production in SA-B

Operational period	Integrated thermal energy (MWd)	EFPD (days)	Plutonium production(kg)		
			Base case (A)	SA-A(B)	Change rate (B-A)/A
Period 1	33,641	1,345	26.68	26.68	+0.00%
Period 2	12,428	497	15.48	10.72	-30.75%
Period 3	8,570	347	7.60	7.52	+0.00%
Total			49.76	45.00	-9.57%

Table 6: Plutonium production in SA-C

Operational period	Integrated thermal energy (MWd)	EFPD (days)	Plutonium production(kg)				
			Base case (A)	SA-C1 (B1)	SA-C2 (B2)	Change rate (B1-A)/A	Change rate (B2-A)/A
Period 1	33,641	1,345	26.68	26.64	26.61	-0.15%	-0.26%
Period 2	18,380	735	15.48	15.48	15.48	+0.00%	+0.00%
Period 3	8,570	347	7.60	7.60	7.59	+0.00%	-0.13%
Total			49.76	49.72	49.68	-0.08%	-0.16%

Table 7: Plutonium production in SA-D

Operational period	Integrated thermal energy (MWd)	EFPD (days)	Plutonium production(kg)		
			Base case (A)	SA-D(B)	Change rate (B-A)/A
Period 1	33,641	1,345	26.68	26.72	+0.15%
Period 2	18,380	735	15.48	15.52	+0.26%
Period 3	8,570	347	7.60	7.60	+0.00%
Total			49.76	49.84	+0.16%

Table 8: Plutonium production in SA-E

Operational period	Integrated thermal energy (MWd)	EFPD (days)	Plutonium production(kg)		
			Base case (A)	SA-E(B)	Change rate (B-A)/A
Period 1	33,641	1,345	26.68	26.48	-0.75%
Period 2	18,380	735	15.48	15.52	+0.26%
Period 3	8,570	347	7.60	7.68	+1.05%
Total			49.76	49.68	-0.16%

Table 9: Plutonium production in SA-F

Operational period	Integrated thermal energy (MWd)	EFPD (days)	Plutonium production(kg)		
			Base case (A)	SA-F(B)	Change rate (B-A)/A
Period 1	33,641	1,345	26.68	26.60	-0.30%
Period 2	18,380	735	15.48	15.45	-0.19%
Period 3	8,570	347	7.60	7.57	-0.39%
Total			49.76	49.63	-0.26%

3.2 Reactor integrated thermal energy (SA-B)

According to the 2009 KAERI report "Analysis of reactor operation data and estimation of plutonium production by period" [6], it was confirmed that the amount of plutonium produced from 2003 to March 2005 significantly exceeded the predicted value. This is based on the difference that the integrated thermal energy calculated through the comparison between the power value and the steam production, the temperature change of the coolant and the heat power calculation by the flow rate is higher than it actually is as a result of analyzing the reactor operation data. Therefore, the plutonium production calculated in the base case analysis was compared with the plutonium production obtained with the new integrated thermal energy value estimated by calculating several variables.

A sensitivity analysis is needed to confirm the range of uncertainties in the amount of plutonium produced due to the uncertainty in the integrated thermal energy. The estimated value of the integrated thermal energy in Period 2, which corresponds to 2003 to 2005, was revised to 12,428 MWd, and burnup calculations were performed by correcting the EFPD accordingly.

Table 4 shows the results of SA-B sensitivity analysis. For the total operation period of the reactor, the amount of plutonium generated in the entire core was 45.00kg, which was a difference of 4.76kg compared to 49.76kg as the integrated thermal energy decreased by about 6,000MWd, showing a decrease of about 10% compared to the previous one. This was very similar to the 9.82% decrease in the integrated thermal energy from 60,591 MWd to 54,639 MWd, and accordingly, it can be seen that the total amount of plutonium generated is proportional to the integrated thermal energy, as shown in Figure 2.

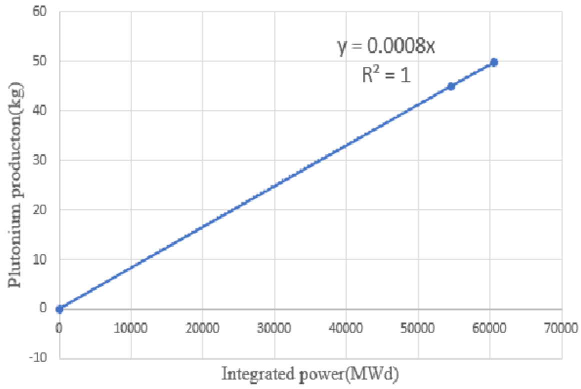

Fig. 2. Linear model of Plutonium production with integrated thermal energy

3.3 Number of neutron samples and repetitive calculations (SA-C)

McCARD uses the Monte Carlo method, which samples numerous neutrons and repeatedly calculates their motions to produce statistically significant results. Therefore, the number of neutron samples and the number of repetitive calculations must be sufficiently large to reasonably perform the analysis of the core. Sensitivity analysis was performed on the fact that sufficient number could only be confirmed by analysis experience. In the base case analysis, 150,000 neutrons were sampled, a total of 300 repetitive calculations were performed, of which 100 were Inactive. SA-C dealt with two cases: 75,000 neutrons were sampled in SA-C1, a total of 150 repetitive calculations including 50 inactive calculations were performed, and 200,000 neutrons were sampled, and a total of 500 repetitive calculations including 200 inactive calculations were performed in SA-C2.

Table 4 shows the results of sensitivity analysis for the number of neutron samples and repetitive calculations. In the case of SA-C1, the amount of plutonium generated in the total core for the total reactor operation period was 49.72kg, showing a 0.08% decrease from the previous one to 0.04kg compared to the 49.76kg derived by calculating the base case input. And in the case of SA-C2, the amount of plutonium generated in the total core for the total reactor operation period was 49.68kg, showing a 0.16% decrease from the previous one. This means that the basic analysis of 150,000 neutron sampling and 300 repetitive calculations are sufficient number at a reasonable level.

3.4 Fuel channel temperature (SA-D),

Neutron reactions have different reaction cross-sections depending on the temperature of the material. Therefore, the sensitivity of plutonium production to nuclear fuel temperature was analyzed by varying the temperature of the previous nuclear fuel. In the base case, the temperature of the fuel channel was 600 K, so the calculation was performed by increasing 100 K to 700 K.

Table 5 shows the results of sensitivity analysis according to the temperature of the fuel channel. When the temperature of the fuel channel increases by 100 K, the total plutonium production amount is 49.84 kg, which increases by 0.08 kg compared to 49.76 kg derived by calculating the base case input. Figure 2 is a graph when the correlation of the amount of plutonium production according to the temperature change of the fuel channel is assumed to be linear through sensitivity analysis.

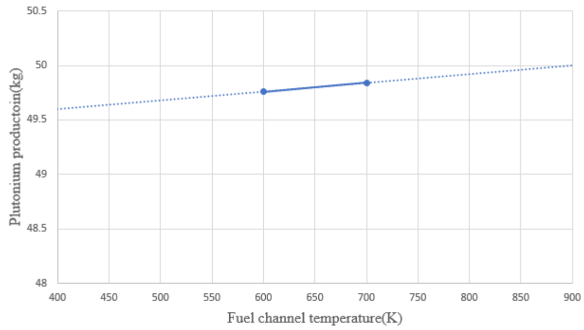

Fig. 3. Linear model of Plutonium production with fuel channel temperature

3.5 Coolant/reflector temperature (SA-E)

For the same reason as the sensitivity according to the temperature of the fuel channel (SA-D), the sensitivity analysis according to the temperature change of the coolant/reflector was performed. In the base case input, the temperature other than the nuclear fuel was 300 K, so the calculation was performed by increasing 100 K and setting it to 400 K.

Table 6 shows the results of sensitivity analysis to changes in coolant/reflector temperature. When the temperature of the coolant/reflector increases by 100 K, the total plutonium production amount is 49.68 kg, which is 0.08 kg decreased compared to 49.76 kg derived by calculating the basic input. Figure 3 is a graph when the correlation between the amount of plutonium production according to the temperature change of the coolant/reflector is assumed to be linear through sensitivity analysis.

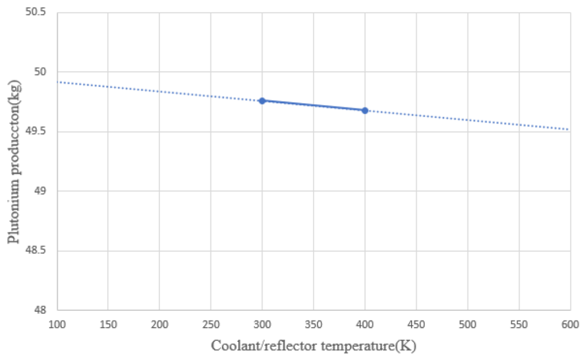

Fig. 4. Linear model of Plutonium production with coolant/reflector temperature

3.6 Nuclide cross section libraries (SA-F)

The ENDF library used in Monte Carlo calculations contains information on the cross section of particle interactions in nuclear reactions occurring in nuclear reactors. As the version was updated from ENDF/B-VII.0 to ENDF/B-VII.1, there was a significant change in carbon (C). Since a reactor using graphite reflectors and CO_2 coolant was designed, a sensitivity analysis was performed to confirm the difference indicated by the change in the ENDF version. In the base case analysis, calculations were performed using ENDF/B-VII.1. In the sensitivity analysis SA-F, calculations were performed using ENDF/B-VII.0.

Table 7 shows the results of sensitivity analysis to the change of the nuclide cross section library. When calculated using ENDF/B-VII.0, the total plutonium production amount was 49.63 kg, indicating a difference of 0.13 kg decrease compared to the 49.76 kg derived by calculating the basic input, resulting in a decrease of 0.26% compared to the previous one.

3.7 Summary of result

The orange bar graph in Figure 5 shows the amount of plutonium production calculated as a result of the base case and the sensitivity analysis result. SA-B shows a significantly lower amount of plutonium produced compared to the rest of the cases, but this can be seen to be due to the modified integrated thermal energy. Therefore, there is no significant difference in plutonium production as long as the integrated thermal energy remains the same. In each case, all of them showed small rates of change, but the variables that were more affected were the reactor full power (SA-A) and fuel channel temperature (SA-D).

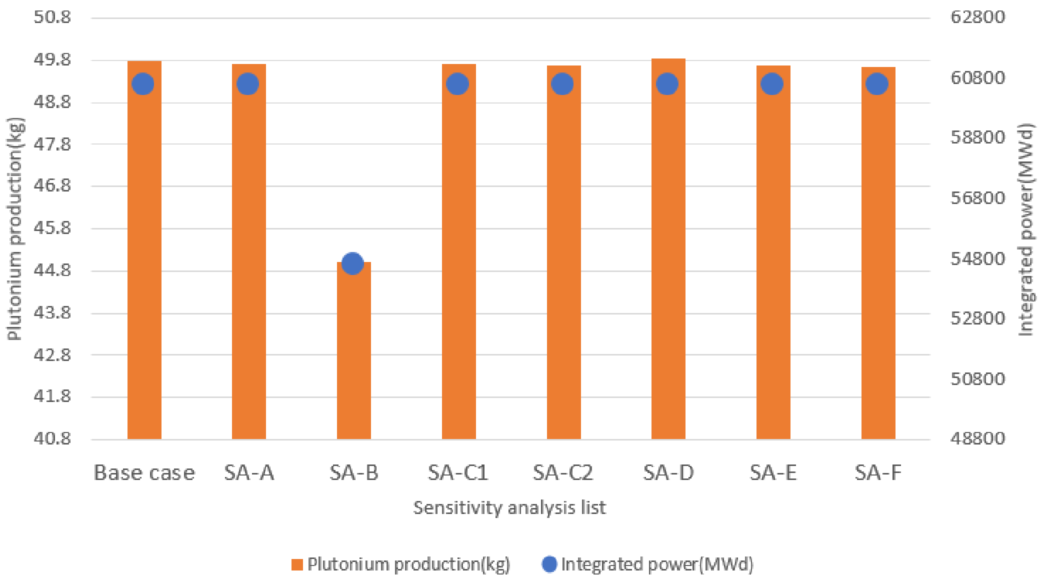

Fig. 5. Result of sensitivity analysis

4. Conclusions

In this study, an analysis was performed using the McCARD code to estimate the potential reserves considering the possibility that North Korea extracted plutonium from the 5 MWe Yongbyon reactor. For this analysis, the shape and burnup information of reactor were identified through literature research, and based on this, the amount of plutonium produced was quantified by developing the McCARD input.

The 5 MWe Yongbyon reactor is a Magnox-type nuclear fuel using natural uranium and is composed of about 8,000 fuel rods, graphite reflectors, and CO_2 coolant. Burnup of nuclear fuel was based on the operational history from 1986 to 2007, and the total plutonium production that can be potentially extracted was about 49.76 kg from McCARD.

However, sensitivity analysis was performed to compensate for the uncertainty of the information collected based on various literature studies. As a result of performing the calculation by changing each variable, if the value of the integrated thermal energy was maintained, a very small change rate was found compared to the result of the bas case analysis. However, when the integrated thermal energy changes, the amount of plutonium produced changes accordingly. This means that the amount of plutonium produced is a function of the integrated thermal energy, and securing accurate integrated thermal energy information is important to know the exact value.

Even with a 100K temperature difference between the fuel channel and the coolant/reflector, only around a 0.1% change rate is observed, and significant differences are not evident even when other variables besides integrated thermal energy change. Through this sensitivity analysis, it has been confirmed that the plutonium production is not significantly impacted even if assumptions are made for input design based on available information about the 5 MWe Yongbyon reactor.

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