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An Estimation of Plutonium Inventories of 5MWe Yongbyon Reactor with MCNP6

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1. Introduction

North Korea has conducted six nuclear tests in 2006, 2009, 2013, twice in 2016, and in 2017, which has been a key challenge for the global nuclear nonproliferation regime. Through these nuclear tests, it is expected that North Korea used the enriched uranium or weapon grade (WG) plutonium for achieving nuclear chain reactions. So, it is very important to accurately estimate the WG plutonium and highly enriched uranium inventories in order to figure out the capability of North Korea for producing nuclear bombs.

In 1993, the U.S. CIA leaked its assessment that North Korea might have enough plutonium for one or two nuclear weapons. Shortly thereafter, many other analysts have announced their various estimates of the weapon-grade (WG) plutonium inventories of 5MWe Yongbyon reactor which is considered as the unique facility producing WG plutonium. For example, D. Albright [1], [2] estimated the annual WG plutonium production using the following simple formula

$$Pu(kg/year) = 365 \times 0.9 \times 10^{-3} PC, \qquad (1)$$

where P and C represent reactor thermal power and capacity factor, respectively. The factor 0.9×10^{-3} in Eq. (1) represents the plutonium conversion factor which means the amount of plutonium production per unit energy (kg/MWt·day). However, the use of the single fixed conversion factor can give considerable uncertainties in the estimation of WG plutonium inventories due to the fact that the plutonium conversion factor varies depending on the burnup.

The objective of this work is to give more accurate estimation of the inventory and fissile plutonium contents from 5MWe Yongbyon reactor with consideration of detailed core modeling using MCNP6 [3]. In particular, we suggest the range of the WG plutonium inventory depending on the burnup and excess reactivity.

2. Material and Methods

In this work, the MCNP6 code developed by LANL (Los Alamos National Laboratory) was used to perform the depletion analysis for 5MWe Yongbyon reactor and these results are compared with a simple estimation of WG plutonium inventory and fissile plutonium contents with the ORIGEN-S code [4] to show the suitability of the simple method using ORIGEN-S point depletion calculation. ORIGEN-S is the depletion and decay module in the SCALE code system which was developed at Oak Ridge National Laboratory. The specific power used in the ORIGEN-S calculation was obtained by dividing the thermal power with the initial reactor loading. We used the cross section library 'magnox' provided in SCALE 6.1 in the ORIGEN-S depletion calculations. The main design parameters of 5MW Yongbyon reactor are given in Table 1. The thermal power of this reactor is 25MWt and its initial uranium loading is about 50tons of natural uranium. The reactor is classified as the Magnox type because it uses the Magnox cladding composed of 1% Al and 99% Mg and uses CO_2 as the coolant. The core consists of 812~877 fuel channels and each fuel channel is composed of axially 10 fuel rods. In this work, we adopted 801 fuel channels such that the initial uranium loading is consistent to the value given in the literature. [5] The active core height is 592 cm and each fuel rod is 60 cm long. For each fuel channel, the fuel rod and coolant are embedded in the graphite moderator block. In particular, it is noted that the specific power of ~0.5MWt/tHM is much lower by a factor of 0.013 than those of the typical PWRs. Fig. 1 shows the radial layout of the reactor. [5]

Table 1. Design Specification of 5MWe Reactor

Parameter	Value
Thermal power (MWth)	25
Electric power (MWe)	5
Specific power (MWth/tHM)	0.50
Uranium loaded (ton)	49.47
Number of channels	812−877
Number of fuel channels used in this work	801
Number of control rod channels	44
Number of fuel rods per channel	10
Distance between channels (cm)	20
Radius of channel (cm)	6.50
Effective core radius (cm)	643
Effective core height (cm)	592
Upper reflector (cm)	77.50
Bottom reflector (cm)	66.50
Fuel composition	U(0.5% Al)
Diameter of fuel meat (cm)	2.90
Length of fuel meat (cm)	52
Length of fuel rod (cm)	60
Uranium per fuel rod (kg)	6.24
Clad composition	Mg(1% Al)
Clad thickness (cm)	0.05

The active core region is surrounded by the graphite reflector zone followed by the reactor vessel.

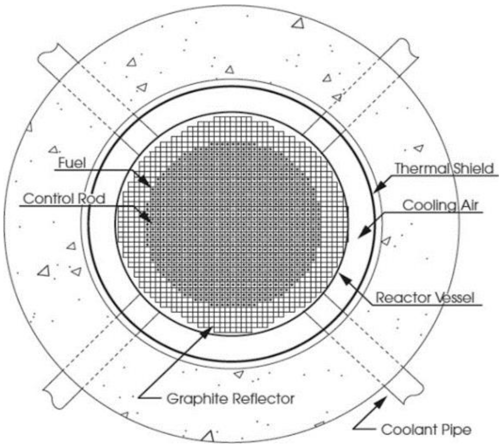

Fig. 1. Radial layout of 5MWe Yongbyon Reactor

We modelled 5MWe Yongbyon reactor core using a quarter core symmetry. The radial and axial MCNP core models are shown in Figs. 2 and 3, respectively. For detailed depletion analysis, we treated each of 10 axial fuel zone for each fuel channel as the depletion zone in the MCNP calculations, which led to total 2140 depletion zones because each fuel channel is composed of axially 10 fuel rods stacked vertically. In addition, we modelled the empty and control channels as the same zone filled with CO_2 coolant for simplicity and all the external regions outside the core was modelled as a single graphite reflector region. The axially external regions above and below fuels are also treated as the graphite reflector.

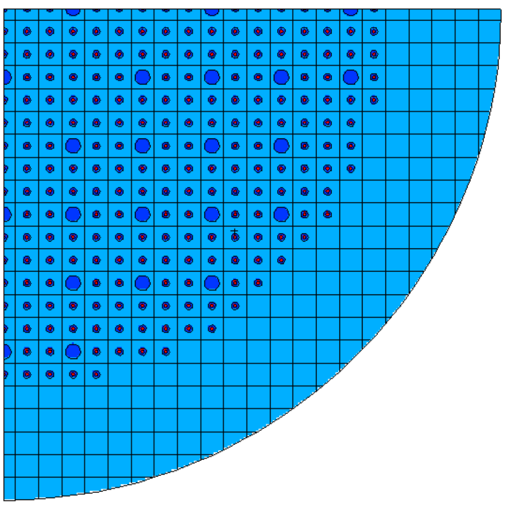

Fig. 2. Radial MCNP6 Model of 5MWe Yongbyon Reactor

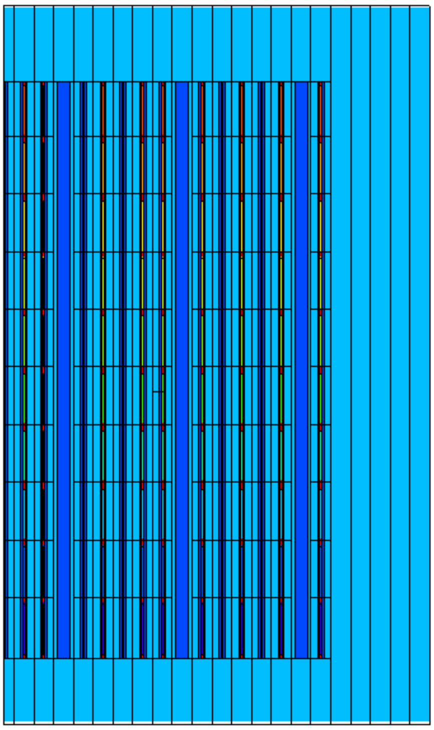

Fig. 3. Axial MCNP6 Model of 5MWe Yongbyon Reactor

The depletion time up to 4000 days corresponding to 2000 MWD/MTU burnup was divided into 15 time steps. The first five time steps of 40 days up to 200 days are much more fine than the subsequent depletion time steps in order to show the detailed change of the burnup characteristics in the initial stage of the depletion. The next depletion time interval from 200 to 400 days is treated as a single time step and then the one from 400 to 4000 days are uniformly divided into nine steps. To show the validity of $0.9\text{x}10^{-3}$ given in the literature, we calculate the change of plutonium conversion factor as depletion time using the following formula

$$\text{C.F.}\,(\text{kg/MWth day}) = \frac{{}^{tot}Pu(kg)}{P(MWt) \times t(day)} \quad (2)$$

3. Results

First, we estimated the changes of the fissile plutonium contents, which are compared in Fig. 4. Fig. 4 shows that the fissile plutonium content monotonically decreases as the depletion time and there are considerable differences in fissile plutonium contents between MCNP6 and ORIGEN-S. In general, the plutonium having higher Pu-239 content than 93wt% is classified as the WG plutonium. Pu-241 is also considered as fissile plutonium isotope but its content is quite low (0.0002~1.86wt%) and so the fissile content given in Fig. 4 can be considered as Pu-239 content. The times at which the fissile plutonium contents decrease down to 93wt% are estimated by ORIGEN-S and MCNP6 to be 835 and 1247 MWD/MTU, respectively. So, MCNP6 and ORIGEN-S give considerable differences in fissile plutonium contents and this difference increases as time. In particular, MCNP6 gives higher fissile plutonium contents than ORIGEN-S for all the burnup ranges. For example, MCNP6 overestimates the fissile plutonium content by 0.018 (1.89%) at the typically assumed burnup of 800 MWD/MTU

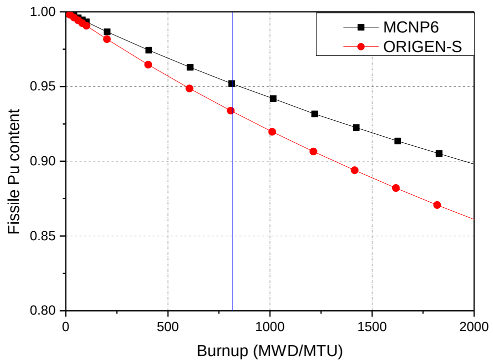

Fig. 4. Comparison of changes of fissile plutonium contents as burnup

Fig. 5 compares the evolutions of the effective multiplication factor (k_{eff}) estimated by MCNP6. Fig. 5 shows that k_{eff} initially increases due to the breeding of natural uranium but monotonically decreases as burnup. k_{eff} decreases below 1.0 from 3542 MWD/MTU and so this burnup is the maximum burnup up to which the reactor can keep criticality. The fissile plutonium content at this burnup is estimated to be 84.8wt% by MCNP6 but the actual burnup will be much smaller than this burnup to keep high fissile plutonium content. The typical burnup is assumed to be 800 MWD/MTU

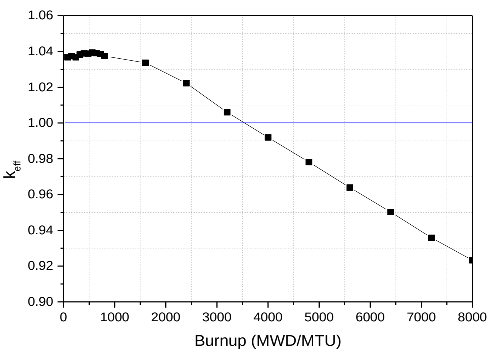

Fig. 5. Comparison of k_{eff} evolutions as burnup

The evolutions of the plutonium conversion factors as burnup is shown in Fig. 6. As shown in Fig. 6, the plutonium conversion factor considerably changes as burnup and so the fissile plutonium inventories estimated with a single plutonium conversion factor can be considerably different from the actual value. Also, it is noted in Fig. 6 that MCNP6 gives significantly lower plutonium conversion factors than ORIGEN-S and the values estimated with MCNP6 are considerably lower than 0.9×10^{-3} given in the literature. [1] The maximum plutonium conversion factors by ORIGEN-S and MCNP6 are estimated to be 1.061×10^{-3} and 8.85×10^{-4} at 80 and 100 MWD/MTU, respectively.

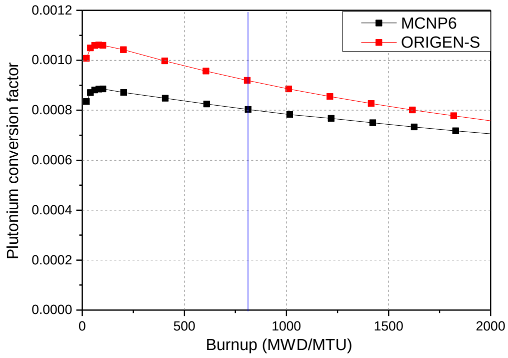

Fig. 6. Comparison of changes of plutonium conversion factors as burnup

The evolutions of the plutonium inventories are compared in Fig. 7. Fig. 7 shows that MCNP6 considerably underestimates plutonium inventories than ORIGEN-S. For example, MCNP6 underestimates the plutonium inventory by 4.652 kg (14.49%) at the assumed burnup of 800 MWD/MTU.

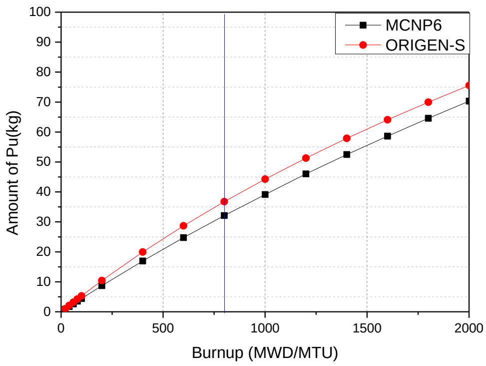

Fig. 7. Comparison of changes of plutonium inventories as burnup

Next, we applied the ORIGEN-S and MCNP6 results to estimate the WG plutonium inventories produced from Yongbyon 5MWe reactor up to 2015. For this purpose, we used the basic estimation given in Ref. 6 as the reference. Table 2 shows the estimations of separated WG plutonium. First, the burnup range for each time interval during which the reactor is considered to be operated were calculated using the operation history, the reference separated WG plutonium inventories, and the following formula

$$\mathbf{Pu}(kg/year) = M \times burnup \times 0.9 \times 10^{-3} \quad (3)$$

Eq. (3) is a variation of Eq. (1), where M represent the amount of initial fuel charge(ton) and the unit of burnup is MWD/MTU. Then, the calculated burnup ranges are used to estimate the separated WG plutonium with ORIGEN-S and MCNP6. Table 2 shows that ORIGEN-S over-estimates the upper bound in WG plutonium inventory by ~5.03 kg until 2015 while MCNP6 under-estimates it by ~4.57 kg in comparison with the reference value given in Ref. 6.

Table 2. Comparison of WG plutonium inventories with the different methods

Operation and shutdown	Separated WG Pu (kg)	Burnup range (MWD/MTU)	ORIGEN-S (kg)	MCNP6 (kg)
Op.1986~1989 Shutdown 1989 (70~100 days)	Less than 2kg Possibly<100g		Less than 2kg Possibly<100g	Less than 2kg Possibly<100g
Op.1989~1994 Shutdown 1994	20~30	444~666.7	21.69~31.09	18.5~26.94
Op.2003~2005 Shutdown 2005 (~70 days)	10~14	222~311	11.37~15.56	9.53~13.15
Op.2005~2007 Shutdown July 2007	~8	~178	~9.19	~7.67
Op.2013~2015 Shutdown 2015	5.5~8	122~177.8	6.37~9.19	5.32~7.67
Op.2016~	In reactor			
Sum	42~63		47.12~68.03	39.52~58.43

4. Conclusion

In this work, the depletion characteristics of 5MWe Yongbyon reactor are analyzed using MCNP6 and the results are compared with a simple point depletion calculation using ORIGEN-S. In particular, we developed a detailed core model with a large number of depletion zones and depletion steps to produce a reference data on the plutonium inventory change as burnup. From the results of the analysis, it was found that MCNP6 gives considerably higher fissile plutonium contents, lower plutonium conversion factors, and lower plutonium inventories than ORIGEN-S. In particular, it was found that the simple calculations with a single plutonium conversion factor as in the literature and a point depletion using ORIGEN-S can significantly overestimate the plutonium inventories. Also, the WG plutonium inventory estimated with detailed MCNP6 model is smaller by 4.57kg (7.3%) until 2015 than the reference value given in the literature [6] while ORIGEN-6 considerably over-estimates WG plutonium inventory by 5.03kg (8.0%).

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