FEASIBILITY STUDY OF THE CONVERSION OF IRT-DPRK RESEARCH REACTOR FROM HEU TO LEU FUEL

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1. Abstract

Democratic People's Republic of Korea (DPRK) currently uses 80 wt% ^{235}U enriched fuel in their research reactor (8MWth-IRT), which is not under the International Atomic Energy Agency (IAEA) safeguards because DPRK retreated away from the treaty on the non-proliferation of nuclear weapons (NPT). Conversion of fuel in nuclear research reactors from highly enriched uranium (HEU) to low enriched uranium (LEU) is a global trend for meeting the objectives of nuclear non-proliferation. A computational feasibility study was conducted to convert DPRK's 8MWth-IRT reactor fuel from HEU to LEU. Comparisons were made of the reactor performance, such as neutron flux, effective neutron multiplication factor, neutron reactivity, temperature dependent coefficients, reactor operation time, etc., with the current 80 wt% ^{235}U enriched HEU fuel type (UAl: uranium aluminum alloy) and potential 19 wt% ^{235}U LEU fuel types (UAl and U_3Si_2: uranium silicide). Potential proliferation risk of plutonium was assessed and compared by performing fuel depletion simulation for both types of ^{235}U enrichments (HEU and LEU fuel). The neutronic simulation and analysis of fuel depletion, buildup of fission products and other actinides, including plutonium were carried out using the Monte Carlo radiation transport code, MCNP6.2. The MCNP6.2 code was selected because it is suitable to model complex geometry of the reactor fuel as well as it uses very accurate energy dependent neutron interaction point cross sections. Two potential LEU fuels showed suitable performance with sufficient excessive reactivity and the thermal neutron flux to replace the HEU fuel from a neutronics perspective. These results can form the basis for further research regarding the peaceful use of nuclear material and for the discussion on the nuclear weapons denuclearization of DPRK.

2. INTRODUCTION

Democratic People's Republic of Korea (DPRK) currently uses highly enriched uranium (HEU) with 80 wt% ^{235}U fuel in their research reactor (8MWth-IRT). [1] This 8MWth-IRT reactor of DPRK is not under the International Atomic Energy Agency (IAEA) safeguards since its withdrawal from the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). [2] Considering potential diversion of HEU fuel to nuclear weapon development, conversion of fuel in nuclear research reactors from HEU to low enriched uranium (LEU) is a global trend for meeting the objectives of nuclear non-proliferation. Given DPRK's history of sharing nuclear technology with other nations, it is crucial for the international community to take action to minimize the risk of nuclear proliferation. As such, concerted efforts must be made to reduce potential threats posed by DPRK's HEU fuel of IRT-DPRK research reactor. The main objective of this study is to assess the feasibility of the conversion of a research reactor (IRT-DPRK) from using HEU fuel to LEU fuel. The goal is to analyze the performance of potential LEU fuel and to validate that this fuel can be a suitable candidate for the fuel conversion of the IRT-DPRK from the view of neutronic analysis. In addition, predictions for potential proliferation risk due to the conversion to LEU, plutonium production, was conducted through fuel burnup simulations. In this work, estimation of neutronic key parameters, fuel depletion, buildup of plutonium, and fission product inventory were carried out for the comparison of the original HEU core with the potential LEU cores using the Monte Carlo N-Particle radiation transport code, MCNP6.2. [3]

3. IRT-8MWth REACTOR AND FUEL DESCRIPTION

In the Yongbyon nuclear complex of DPRK, IRT-2000 type nuclear research reactor has operated since 1965. There were several reactors which are similar to IRT-DPRK, for example in Libya, Uzbekistan, and Russia. [4] This Soviet Union-designed and supplied IRT-2000 is a pool type nuclear reactor that is fueled with enriched uranium and cooled and moderated by light water; the light water is also used as a reflector and biological shielding of the reactor. The rated power with 80 wt% ^{235}U HEU fuel is 8MWth and the thermal neutron flux is in the range from 10^{13} to 10^{14} $n.cm^{-2} \cdot s^{-1}$ at the center of the core and 10^{12} to 10^{13} $n.cm^{-2} \cdot s^{-1}$ in the water surrounding the core. [5] However, since access to detailed information of IRT-DPRK is not available in open literature, physical characteristics for this study were gathered from the same type of reactor in other countries. IRT-2000 research reactor in Libya [6] was the world's only IRT type research reactor that used the same 80 wt% ^{235}U HEU as the DPRK's research reactor.

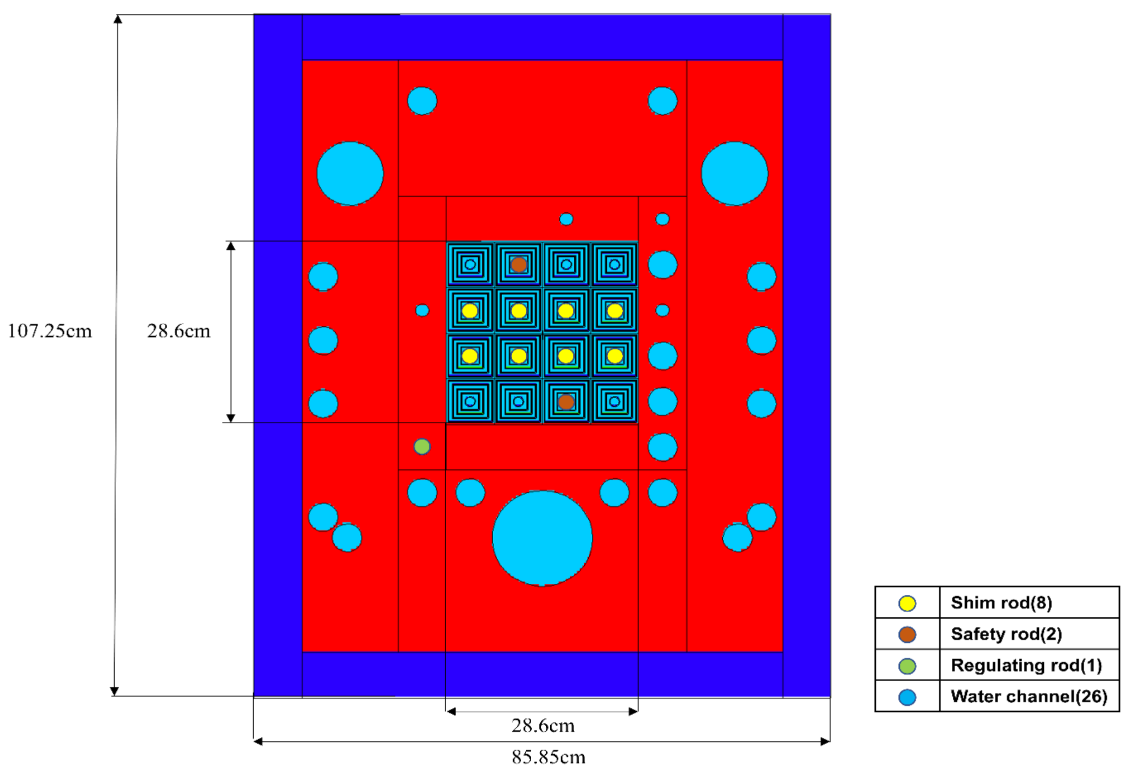


Figure 1. 2-Dimensional horizontal cross section of IRT research reactor

The base of the core is a square grid plate with 36 identically formed places with a lattice pitch of 7.15 cm. The fuel assemblies (FA), the removable beryllium units, and guide tubes of the control rods (8 shim control rods, 2 safety rods and one automatic regulating rod) can be put into these places on the grid. The absorbing material in all of the rods is boron carbide enclosed in a stainless-steel cladding. The compact core loading of the reactor consists of 16 FAs. The FAs are surrounded by 20 removable beryllium units. Stationary beryllium reflector surrounds the removable core units. The active fuel length is 58 cm. The fuel is cooled by the pumped flow of water from top to bottom of the core. The stationary beryllium reflector contains a number of vertical irradiation channels called VCR and it can be plugged with beryllium plugs when they are not utilized. The cross section of the core is shown in Figure 1.

The old HEU fuel of the IRT-DPRK is of the IRT-2M type. The fuel is an alloy (matrix) of aluminum and uranium aluminum-eutectic (UAl–Al) with aluminum cladding. There are two types of fuel assemblies which are 3 fuel tubes (3TFA) and 4 fuel tubes (4TFA) as shown in Figure 2. The coaxial fuel tubes are 2.0 mm thick, which consists of 0.4 mm of fuel between two 0.8 mm thicknesses of cladding. The thickness of the water gap between adjacent fuel tubes is 4.5 mm; the half-thickness of the water space outside of the outermost fuel tube (between fuel assemblies) is 2.25 mm. Interior to the innermost fuel tube in the 4-tube assembly is a circular tube having an 8.0 mm outer radius. The interior of the innermost fuel tube in the 3-tube assembly is a tube having the same outer dimensions as the innermost tube of the 4-tube assembly as a guide for the control rod.

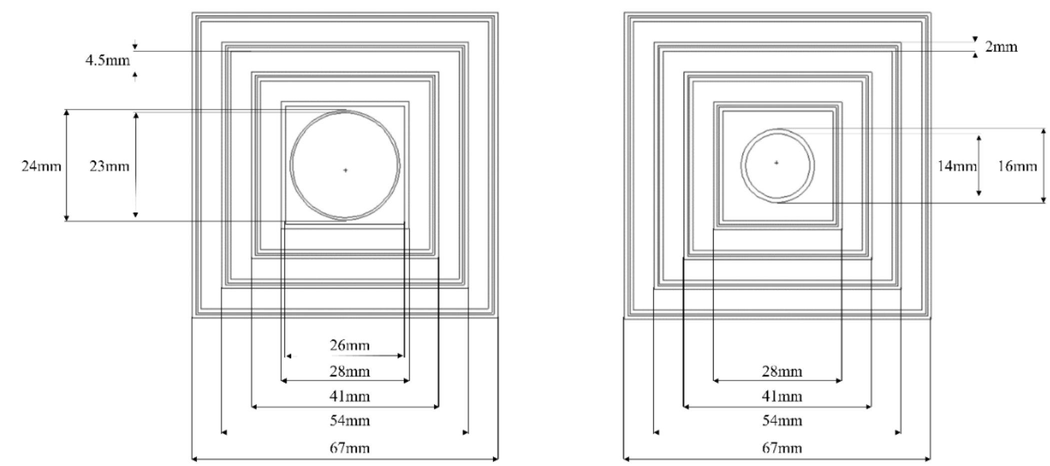


Figure 2. Cross section of IRT-2M (80wt%) fuel assembly (left: 3-tube, right: 4-tube)

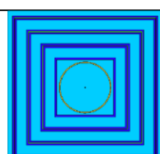
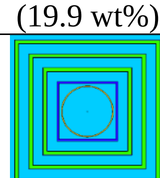
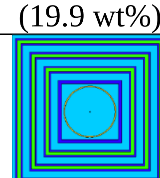
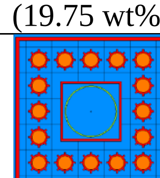
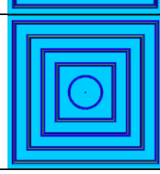
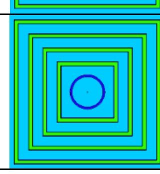
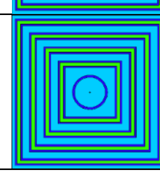
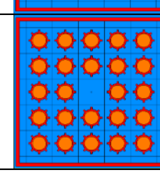
4. METHDOLOGY

The procedure of core conversion from HEU to LEU is normally conducted by maintaining the overall design and dimension of the fuel and core. Therefore, it is vital to model potential LEU fuel assemblies with the same dimensions as those of the HEU fuel, while the fundamental structure does not change. Several potential assemblies were assessed for neutronic feasibility in this study including HANARO LEU fuel [7] of Republic of Korea. Fuel conversion from HEU to LEU core was studied by increasing fertile material, ^{238}U weight percent preserving the ^{235}U mass. As a condition for exhibiting the same performance of research reactor, the mass of fissile material (^{235}U) was maintained, and the mass of fertile material (^{238}U) was adjusted to reduce the degree of uranium enrichment. Accordingly, the volume of the fuel meat increased physically, and the volume of the cladding or moderator was changed in order to find an optimal size within the limited space. The optimal dimension to achieve an enrichment within 20% was calculated analytically. Due to the objective of exploring the initial neutronic feasibility for potential LEU fuel, variables such as density changes and additional material use were minimized. Due to the limited information of the DPRK reactor, design of a research reactor in Libya, most similar in type and performance, was used as substitute. Although the neutron flux in the core and irradiation channels was expected to decrease when using LEU, potential LEU fuel had to not only meet non-proliferation goals but also preserve basic reactor performance and research productivity as much as possible. Neutronics code, MCNP6.2 was used to perform neutron transport calculations, particularly criticality and fuel burnup calculations using MCNP utilizing its KCODE feature, tally (detector) functions, and fuel burnup simulation features. The fuel burnup calculations were performed using the CINDER90 depletion module of MCNP6.2 code.

5. RESULTS AND DISCUSSION

Through preliminary scoping fuel design calculations, three LEU candidates were proposed and information about them is presented together with HEU fuel in Table 1. First, the 19.9 wt% enriched ^{235}U fuel assembly, which is the maximum amount that can physically reduce the cladding thickness, was selected as the cladding thickness reduction model, and the 19.9 wt% enriched ^{235}U model that reduce the least amount of water was selected as the moderator thickness reduction model, considering the importance of the moderation effect in the thermal reactor. The HANARO fuel assembly was designed with the fuel pin within the same dimension as the IRT fuel by applying the optimal fuel pin pitch.

Table 1. Summary of proposed LEU fuels

	HEU (80 wt%)	LEU A (19.9 wt%)	LEU B (19.9 wt%)	HANARO (19.75 wt%)
Cross section of FA (With Control Rod)				
Cross section of FA (Without Control Rod)				
^{235}U mass per FA (g) (With CR/Without CR)	162.8/190	162.8/190	162.8/190	183/274
^{238}U mass per FA (g) (With CR/Without CR)	40.7/47.5	655/765	655/765	743/1114
^{235}U mass per core (g)	2,768	2,768	2,768	3,474
^{238}U mass per core (g)	692	11,141	11,141	14,109

In the criticality calculation, 10,000 particles per cycle, a total of 500 cycles (100 out of 600 skipped) were used to perform KCODE simulation, and a continuous energy neutron cross-section in the ENDF/B-VII.1 library was used at a temperature of 300 K. All the neutron population control rods in the core were completely withdrawn and the corresponding space was filled with moderator which is water, and the operation was performed in the initial stage of fresh fuel. The results of effective neutron multiplication factor, k_{eff} calculation to determine criticality and reactivity for each fuel type are listed in Table 2.

Table 2. k_{eff} of each type of fuel

Parameter	HEU (80 wt%)	LEU A (19.9 wt%)	LEU B (19.9 wt%)	HANARO (19.75 wt%)
k_{eff}	1.22315±0.00032	1.18092±0.00032	1.12561±0.00035	1.16303±0.00035
Excess reactivity (pcm-percent milli-k)	18,243	15,320	11,159	14,017

The k_{eff} value of HEU fuel shows the highest value and the remaining three LEU fuels show slightly inferior k_{eff} values, which can be attributed to the larger concentration of ^{238}U, because ^{238}U has a high neutron capture reaction (n, γ) cross section at neutron energy of less than 1 keV. In other words, if the enrichment is lowered but conserved the same amount of ^{235}U, which is the main purpose of this study, the probability that neutrons collide with ^{235}U decreases, and this gives the reactor a negative reactivity. The neutron flux of the core was calculated using F4 Tally (cell averaged neutron flux) in MCNP. F4 tally measured the average track length of neutron in the cell area designated by the user, and result was scaled up to neutron.cm^{-2}.s^{-1}. The neutron flux calculation was divided into three neutron energy ranges: thermal neutron (< 0.4 eV), epi-thermal (≥ 0.4 to < 1 MeV), and fast neutron (≥1 MeV to < 20 MeV). The calculated neutron flux values and the associated one-standard deviation (stochastic error due to MCNP's calculation methodology) are provided in Table 3.

Table 3. Average neutron fluxes of each type of fuel in 8MWth

Parameter	Neutron energy	HEU (80 wt%)	LEU A (19.9 wt%)	LEU B (19.9 wt%)	HANARO (19.75 wt%)
Core Neutron Flux (n.cm^{-2}.s^{-1})	Thermal	1.11E+14 ± 5.2E+10	1.06E+14 ±5.07E+10	1.01E+14 ± 5.06E+10	1.09E+14 ±5.22E+10
	Epi-thermal	1.19E+14 ± 3.8E+10	1.17E+14 ±3.75E+10	1.37E+14 ± 4.8E+10	1.21E+14 ±3.86E+10
	Fast	1.36E+14 ± 5.02E+10	1.35E+14 ±4.98E+10	1.55E+14 ± 5.74E+10	1.4E+14 ±5.05E+10
	Total	3.65E+14 ± 9.13E+10	3.57E+14 ±8.93E+10	3.93E+14 ± 1.02 E+11	3.7E+14 ±9.24E+10

To ensure successful core conversion, it is essential to maintain thermal neutron flux within the target range. As can be seen from table 3, the thermal neutron flux of all potential LEU fuels decreased to only up to 9% compared to conventional HEU fuels in the core area. Figure 3 shows the radial distribution of thermal neutrons in core. Thermal neutrons in the core showed a lower distribution in LEU fuel than in HEU. As mentioned above, this is because the neutron absorption effect of ^{238}U increased. In particular, in the case of Fuel LEU B, it can be seen that the number of thermal neutrons is relatively low due to the less amount of moderator in the core. Conversely the number of fast neutrons in the core shows the highest tendency for Fuel LEU B due to lower moderation effect. HANARO fuel showed a relatively high distribution of both thermal and fast neutrons.

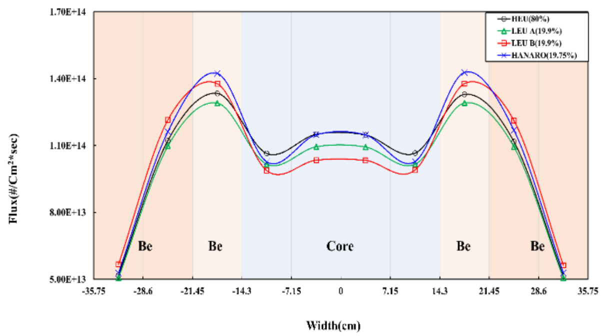


Figure 3. Radial thermal neutron flux distribution

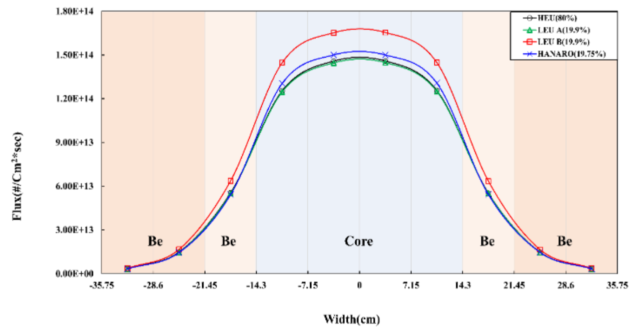


Figure 4. Radial Fast neutron flux distribution

Figure 5 illustrates the variation of k_{eff} over the reactor operation in days. The lifetime of HEU with full power is about 100 days, and it can be seen that the k_{eff} drops below 1.0 after that. In comparison, tubular LEU fuels showed relatively short effective full power days (EFPDs) of 85 and 50 days, respectively. Contrary to this, HANARO LEU fuel showed excellent performance with similar EFPD to HEU fuel despite being a LEU fuel. This is because the fuel contains a relatively high amount of ^{235}U, allowing it to burn longer under the same power.

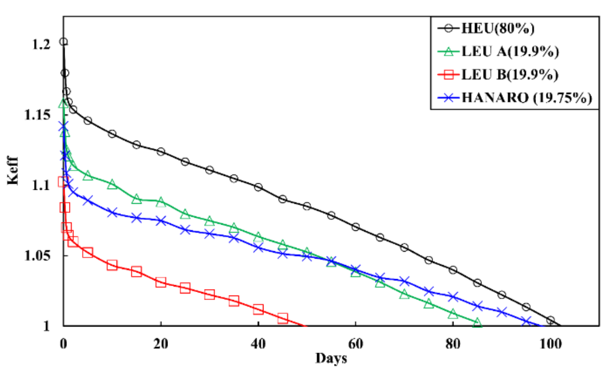


Figure 5. k_{eff} versus reaction operation days

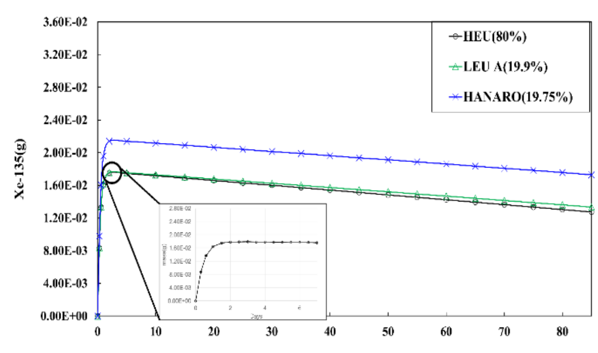


Figure 6. ^{135}Xe versus reactor operation days

In addition, all types of fuels tended to rapidly decrease in k_{eff} values after initial reactor start up due to the accumulation of fission product poisoning in the core during operation. A linear decrease in k_{eff} can be seen after this poisoning (mainly due to the buildup and saturation of the fission product ^{135}Xe) reaches equilibrium as shown in figure 6. As can be seen in figure 7, ^{137}Cs was accumulated in linear fashion as expected, which verified that there were no issues with the reactor core burnup simulation.

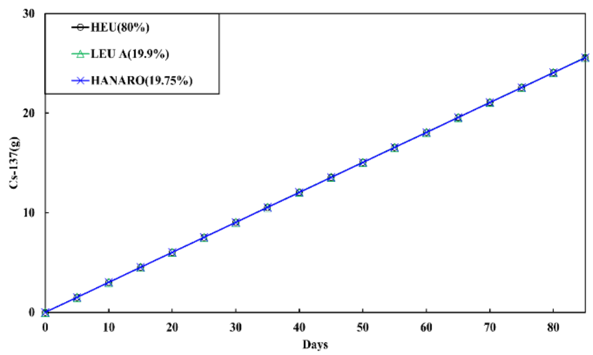


Figure 7. ^{137}Cs versus reactor operation days

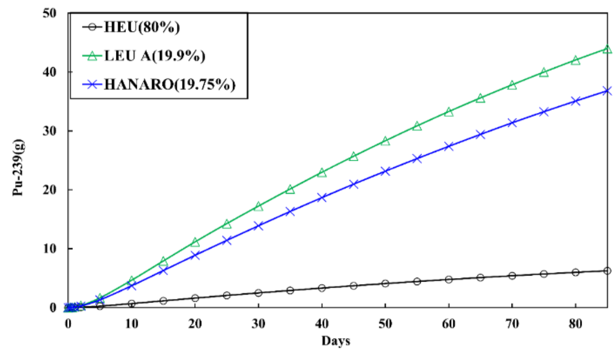


Figure 8. ^{239}Pu versus reactor operation days

Figure 8 shows the buildup of ^{239}Pu according to the reactor operation days. Fuel LEU A and HANARO fuel showed higher ^{239}Pu production compared to the 80% HEU fuel and this is mainly due to the presence of more ^{238}U in LEU fuels. As can be seen in Table 4, after fuel burnup for 85 days, which is the shortest EFPD among three fuels, 6.247 g of ^{239}Pu was produced in HEU, while 43.99g of ^{239}Pu was produced in Fuel LEU A and 36.82 g in HANARO fuel. This increased production of ^{239}Pu is due to the mass of ^{238}U that LEU fuel has about 16 times higher than HEU. Considering that an amount of plutonium equal to about 1% of total fuel is produced at a standard commercial light water reactor burnup of 45,000 MWd/tU, the plutonium production of these LEU fuels is rather low. However, it is still important to monitor and manage plutonium production as the DPRK has reprocessing facilities and has a history of extracting plutonium from IRT reactors.

Table 4. Production and consumption of U an Pu at 85th day with 8MWth

Fuels		HEU (80 wt%)	LEU A (19.9 wt%)	HANARO (19.75 wt%)
Burnup (MWd/tU)		197,000	48,900	38,700
Total amount of U (g)		3,460	13,909	17,583
Consumption (g)	^{235}U	843	873	833
	^{238}U	9.4	70	60
Production (g)	^{238}Pu	0.096	0.118	0.088
	^{239}Pu	6.247	43.99	36.82
	^{240}Pu	0.776	5.319	3.295
	^{241}Pu	0.235	1.585	1.048
^{239}Pu ratio to the total fuel		0.18%	0.32%	0.21%

Figures 9 through 11 show the uranium consumption and plutonium production of each fuel over operation time. It shows a higher gradient of ^{239}Pu accumulation when the amount of ^{238}U is higher. Also, as more ^{239}Pu is produced, more plutonium isotopes were produced. Results shows that all types of fuels showed a ^{239}Pu concentration of almost 90% when operated without stopping for about 85 days with a maximum power of 8MWth, which implies this weapons-grade plutonium should be considered and inspected by the International Atomic Energy Agency (IAEA) safeguards monitoring team after the reactor core conversion.

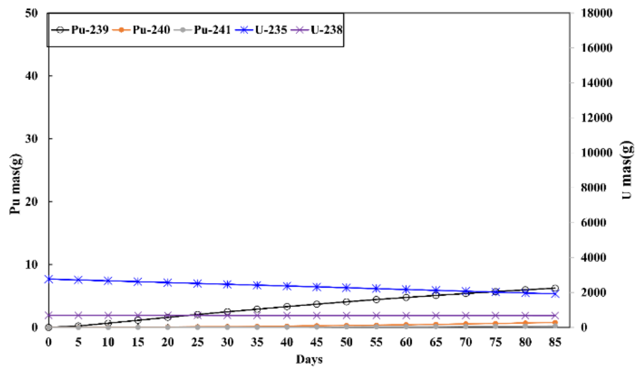


Figure 9. Buildup of Pu and consumption of U in 80wt% HEU fuel

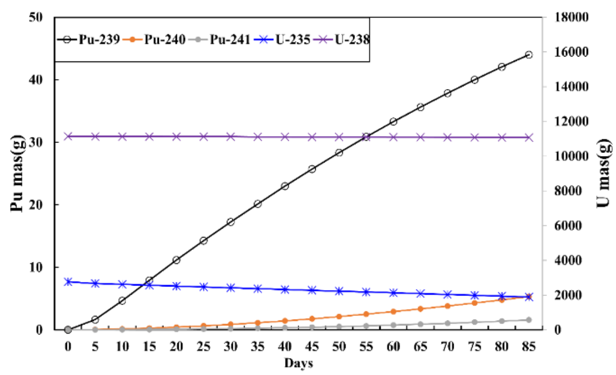


Figure 10. Buildup of Pu and consumption of U in 19.9wt% LEU A

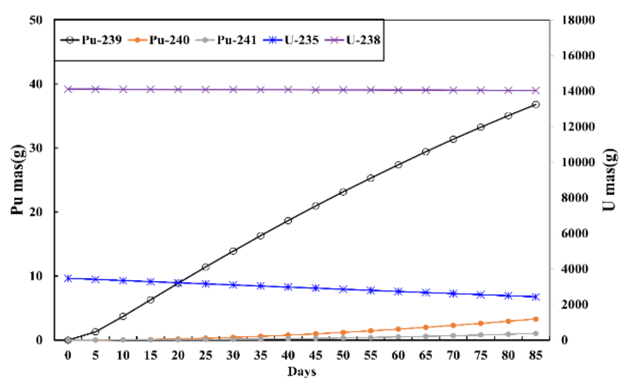


Figure 11. Buildup of Pu and consumption of U in 19.75wt% HANARO LEU fuel

6. CONCLUSION

The goal of this study was to design a potential fuel that can replace HEU with LEU in DPRK's IRT research reactor and to analyze the neutronics and non-proliferation performance changes. LEU fuels showed marginal inferior performance compared to HEU in common, but showed sufficient performance in terms of reactor operation and thermal neutron flux. The effective neutron multiplication factor and the corresponding excess reactivity decreased from 18,243 pcm (HEU 80 wt%) to 15,320 (LEU Fuel A) and 14,017 (HANARO LEU Fuel), respectively, while the thermal neutrons in the core were reduced only up to 5%, from 1.11E+14 $n.cm^{-2}.s^{-1}$ (HEU 80 wt%) to 1.06E+14 $n.cm^{-2}.s^{-1}$ (LEU Fuel A) 1.09E+14 $n.cm^{-2}.s^{-1}$ (HANARO LEU Fuel), respectively. The LEU fuel showed a relatively low fuel life compared to HEU, 100 days vs 85 days when fuel burnup simulations were performed before a subcritical state was achieved. But, the HANARO LEU fuel showed an excellent fuel life of 100days because it contained higher fissile content. The excellent performance of the HANARO fuel suggested the need to develop higher density fuels in the future for IRT-DPRK. Since the LEU fuel has a large amount of ^{238}U, it generates more ^{239}Pu, which is about six times higher than for the HEU fuel, from 6.247g (HEU 80 wt%) to 43.99g (LEU Fuel A) and 36.82g (HANARO LEU Fuel) at 85 days respectively, so attention is required with respect to nuclear proliferation due to higher plutonium production. This research represents an early attempt to address DPRK's research reactors from a non-proliferation standpoint. The study suggests that LEU fuel has the potential to perform equally or even better than HEU fuel, while also warning of the risk of nuclear proliferation caused by an increase in plutonium. This study highlights the feasibility and potential of converting HEU fuel to LEU fuel for IRT reactors and emphasizes the need for additional research on developing higher density fuels for IRT-DPRK.

7. FUTURE WORK

This initial feasibility study for the conversion of the IRT-DPRK research reactor fuel from HEU to LEU shows promise without substantial change in thermal neutron flux, which is the main characteristic needed for the research reactor to meet the radioisotope production objective. A detailed LEU fuel development research is required in the future. For this, research on fuel with a higher uranium density within the same dimensions as IRT fuel could be conducted in the future. In addition, if specific information on the DPRK's research reactor is available, research should be conducted on the thermal hydraulics and the corresponding safety performance of LEU fuel.

8. REFERENCES

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