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IGNITING BURNING WAVE IN A SMALL NUCLEAR REACTOR SUITABLE FOR REMOTE AREAS IN MONGOLIA

Tsendsuren Amarjargal[2], Munkhbat Byambajav[1,2*] and Odmaa Sambuu[1,2]

[1]School of Engineering and Applied Sciences, National University of Mongolia, Ikh surguulin gudamj-1, Sukhbaatar, Ulaanbaatar, Mongolia, 14201, 46A/22
[2]Nuclear Research Center, National University of Mongolia, Peace Avenue-122, Bayanzurkh District, Ulaanbaatar, Mongolia

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Corresponding author: munkhbat@seas.num.edu.mn

Abstract

In Mongolia, energy demand is increasing rapidly and installed capacity cannot keep up the demand due to a weak condition of both electricity access and grid structure. According to a survey, primary electricity demand by 2025 would be higher in the central region and tend to increase in other regions. Full coverage of the country by grid extension is difficult from technical as well as economic perspective because of high investment costs and high electrical loss over long distance, and low demand in the remote regions. Therefore, small power systems are suitable in remote regions and typical large size power systems are not a very good option. However, a small fast reactor system may be suitable, having unique characters, to reduce nuclear waste and effective use of nuclear fuel. In this study, preliminary design study on a small breed and burn type fast reactor was carried out using continuous energy Monte Carlo code MVP/GMVP II with the JENDL-3.3 data library. In the concept of breed and burn, igniting a burning wave is an important concern. This study concerns the igniting burning wave with enriched uranium for initiating the conversion process. As seen from the result, the proposed small reactor could operate more than seventy years under breed and burn mode.

1. Current energy demand in Mongolia

Total energy generation in Mongolia cannot supply the whole demand, around 20% of electricity is imported from Russia and China (Energy, G.o.M.M.o, 2018). Remaining 80% of electricity is generated from five independent electric power systems namely Central energy system, Western energy system, Eastern energy system, Altai-Uliastain energy system and Southern energy system as shown in Figure 1. Power generation in these systems comes mainly from coal, renewable sources, diesel generators and heat-only boilers or stove in off-grid areas. Even though there has been some improvements in recent years by increasing total installed capacity in thermal power plants and extending the national grid system and transmission lines, the country's energy supply system still remains in weak condition. There are several factors involved in this situation. First, almost all commercial energy generation plants are constructed in the capital resulting in the supply of electricity to remote areas with high losses of electricity over the long distance. Second, energy consumption varies significantly depending on the season of the year and time of the day. During peak demand in winter time, it is common to exceed the total capacity. Third, air pollution in the capital city exceeds the standard level and it is affecting an individual's health.

Fig.1. Energy systems in Mongolia

Electricity production in Mongolia has reached a volume of 6,624.8 GWh with an increase of 8.8% compared to the production in 2018. 93% of total electricity was produced by coal thermal power plants, 6% by solar and wind, 1% by hydro power sources, and 0.06% by diesel generators (Commission, 29th of April 2019). According to the project result conducted by "I-Jen and Mon-Energy LLC '' concerning the Sustainable Energy Development of Mongolia in 2013 (Munkhbat, 2019), there would be significant increase in the nation's electricity demand as compared to the current demand. For example, in the Central energy system including southern energy system, it is required to establish new power system with 1920 MWe and in other energy systems including western and eastern system and other remoted areas, it is expected that there should be more at least 100 MWe in each of the energy system by 2025 as shown in Figure 2.

Full coverage of the country by grid extension could be difficult from a technical as well as economic perspective because of high investment costs, high electrical losses to cover long distances and little demand in the countryside.

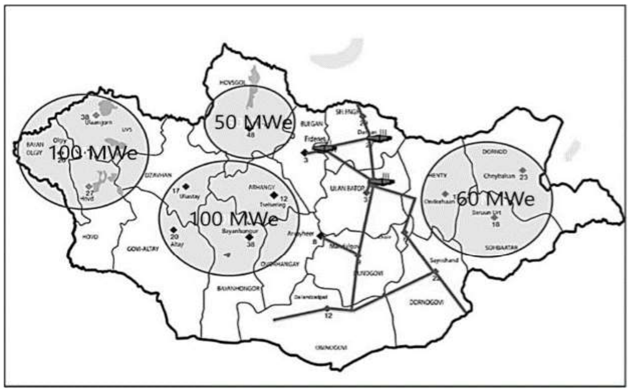

Fig.2. Energy demand in each energy system by 2025

Therefore, instead of producing all of primary energy in the central region and transmitting to remote areas, building a small power plant with long operation in remote regions might be a reliable and cost-efficient way of providing energy in rural areas.

According to Paris Agreement, countries should aim to reach global peaking of greenhouse gas (GHG) emissions as soon as possible and should aim for neutrality of the emissions in the second half of this century to keep the global average temperature increase to well below 2ºC and pursue efforts to limit it to 1.5ºC (M.Yan and H.Sekimoto, 2008). Therefore, de-carbonization needs to accelerate, which, in the power sector, means reducing electricity generated from coal and increasing the pace of investment in low carbon generation, including in nuclear power.

A type of nuclear reactor designed to be in smaller size than a traditional reactor is called small modular reactors (SMRs). They based on the same principle existed in larger reactors using nuclear fission to create heat, which can then be used to generate electricity. They are expected to be deployed with enhanced safety systems in the next 10-20 years (M.Yan and H. Sekimoto, 2008) and envisioned to provide a nuclear low carbon alternative to countries without large power grids, less developed infrastructures and limited financing capabilities.

This type of reactor can be more suitable in remote areas of Mongolia in terms of its construction and safety. Moreover, according to the 2016 'Red Book', Mongolia has 141,000 tU in reasonably assured resources which is accounted for almost 2% of world total uranium resources.

The objective of this study was to carry out preliminary design study on a small nuclear reactor suitable for remote areas which uses natural uranium as a fuel by using continuous energy Monte Carlo code.

2. Breed and burn concept

Fast reactors could sustain the nuclear chain reaction with natural uranium or depleted uranium fuel. This type of reactor, called Breed-and-Burn (B&B), is able to breed the fissile material and burn it in situ, without fuel reprocessing and enrichment. In this concept, fertile material, U-238, Th-232 is converted into fissile material, Pu-239, U-233 and burn in the region called "burning region". The region contains fertile material called breeding region. The movement of the burning region towards the breeding region is called burning wave. Depending on the direction of the burning wave, this type of reactor is divided into two main categories, including traveling wave and stationary wave. The reason for research and development of this concept is effective use of nuclear fuel, to reduce the amount of radioactive waste and long operation at time with initial fuel load. Therefore, many studies have been conducted on this concept. Following studies were selected as a reference design for the proposed reactor.

H.Sekimoto et al. (2008) investigated design study on small CANDLE reactor where shapes of neutron flux, nuclide densities and power density distributions remain constant but move to an axial direction. The research method used in this study was SRAC code system based on neutron diffusion and nuclide burnup-equations. Treatment of these equations was Galilean transformed variables in iteration scheme. From this study, it is obtained that CANDLE burnup with breed and burn mode can be established in a core with a radius of 1.0 m and a height of 2.0 m. Fuel burnup velocity would be 0.7 cm per year.

H.Sekimoto et al. (2008) investigated a design and safety features of small CANDLE fast reactor. The research method and core design parameters used in this study were the same as above. From this study, it is concluded that the burning moving velocity is less than 1.0 cm/year that enables a long life design easily. The core averaged discharged fuel burnup is about 40%. It means that if a light water reactor with a certain power output has been operated for 40 years, the CANDLE reactor can be operated for 2000 years with the same power output.

T.Obara et al. (2017) investigated feasibility of burning wave fast reactor concept with rotational fuel shuffling. The research method used in this study was continuous energy Monte Carlo code MVP2.0 and MVP-BURN with JENDL-4.0 nuclear data library and an original code to treat the fuel shuffling was developed. From this study, it was obtained that the reactor can achieve equilibrium condition and be critical with fuel shuffling.

3. Research Method

Core design parameters shown in Table.1 were chosen from (M.Yan and H. Sekimoto, 2008) and analyses conditions particularly number of assemblies in core and fuel assembly lattice shape is selected from (T.Obara et al, (2017). Fuel element of the core was chosen of "tube in the shell" – type, which allows increasing the volume of the fuel share in the active zone for the more effective use of neutrons (AtomicInfo.Ru.2005) shown in Figure 3.

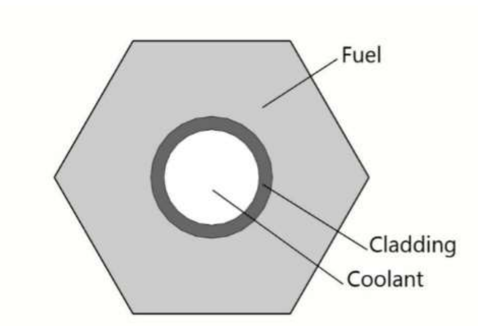

Fig.3. Tube-in-shell fuel element

Table 1. Design parameters for small breed and burn reactor

Design parameters	Values
Thermal power	350 MW_{th}
Core radius	100 cm
Core height	200 cm
Radial reflector thickness	50 cm
Number of fuel assembly	169 cm
Fuel material	UN, (N-15 enriched 100%)
Cladding material	HT-9
Coolant material	Pb-Bi (44.4-55.5%)
Cell type	Tube-in-shell
Coolant channel diameter	0.668 cm
Cladding thickness	0.035 cm
Fuel theoretical density	14.32 g/cm^3

As described in Light of CANDLE by H.Sekimoto, burning wave could be initiated by large number of external neutron sources, but this method could be too expensive (H.Sekimoto, 2010) and change drastically power density at startup. Another way to start the CANDLE reactor is to use enriched uranium or plutonium.

In this study, we used enriched uranium as an initiator for burning wave. By changing enriched uranium loading in the core, the fuel burnup analyses have been carried out. For each burnup analysis in each loading type, the effective multiplication factor (k-eff) and conversion ratio (CR) were calculated as a function of time in order to investigate whether the loading type can initiate burning wave in core.

Burnup analyses for enriched uranium loading have been carried out for following loading types, starting from homogeneous to heterogeneous, including radial and axial loading, and zone loading in which fuel assemblies in core were divided into sub-division.

Homogenous loading:

All fuel assemblies have the same enrichment in homogenous loading, as shown in Figure 4.

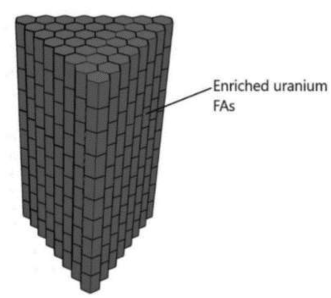

Fig.4. Homogenous fuel loading in 1/6 of core

Heterogeneous loading:

In heterogeneous loading, enriched uranium can be loaded in many different positions in one fuel pin or in one fuel assembly. Several possible loading positions have been studied with burnup calculation. Some of the heterogeneous loading are shown in Figure.5 and Figure.6.

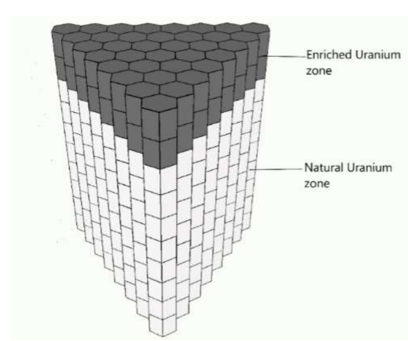

Fig.5. Heterogeneous fuel loading #1 in 1/6 of core

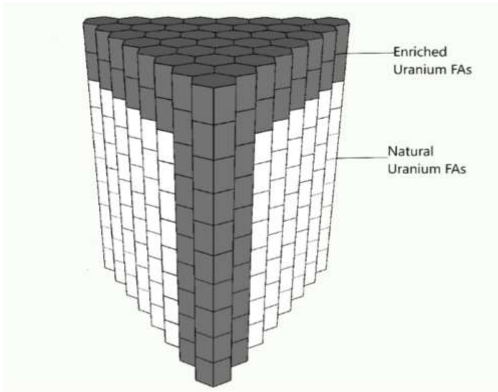

Fig.6. Heterogeneous fuel loading #2 in 1/6 of core

Zone loading:

In zone loading, core is divided into 8 zones, first zone (#1) has one fuel assemblies, second zone (#2) has 6 fuel assemblies, third zone (#3) has 12 fuel assemblies, fourth zone (#4) has 18 fuel assemblies, fifth zone (#5) has 24 fuel assemblies, sixth zone (#6) has 30 fuel assemblies, seventh zone (#7) has 36 fuel assemblies, and eight zone (#8) has 42 fuel assemblies. In this loading, if enrichment made in odd numbered zones (#1, #3, #5, #7), other zones (#2, #4, #6, #8) have natural uranium (breeding zone), as shown in Figure 7, in other words, breeding regions are in even numbered zones.

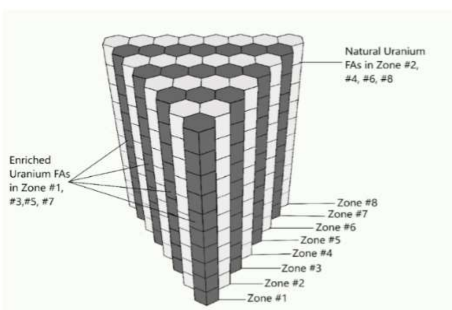

Fig.7. Zone fuel loading in 1/6 of core

The reactor power was set to 350 MWth (approximately 100 MWe) suitable for Western and Altai-Uliastain energy system. Active core radius is 100 cm and height is 200 cm.

The calculations were carried out using continuous energy Monte Carlo code MVP/GMVP II (Y.Nagaya et al. 2005) with the JENDL-3.3 (K.Shibata et al. 2002) data library. The burn-up calculation was also performed by its auxiliary code MVP-BURN (K.Okumura et al. 2000). MVP-BURN is a burn-up calculation code using continuous energy Monte Carlo code MVP.

4. Results and Discussions

Burnup calculations were carried out for the core with different loading cases. Burnup calculation results on following loadings are

(1) Homogenous loading;
(2) Heterogeneous loading;
(3) Zone loading.

In all these loading cases, we attempt to reach criticality by fuel enrichment. In typical thermal reactor calculation, fuel enrichment was chosen as the initial critical condition (k-eff) exceeds more than unity because there is no fuel breeding and the poisonous fission products accumulation happens. However, in this study, the initial critical condition was chosen as much as possible near to the one because if breed and burn happens in the core, initial critical condition may fluctuate near to the unity and keeps over the long time. Furthermore, one of the key parameters for fast reactor calculation is conversion ratio (CR) which is defined as the ratio of fissile material created to fissile material consumed either by fission and capture. If the CR is greater than one, it is often referred to as the breeding ratio, then the reactor is creating more fissile material than it is consuming. Therefore, we considered the above mentioned two parameters along with the burnup time for all the cases of loading.

4.1 Homogenous loading

In this case, we attempted to reach criticality with homogenous fuel loading by increasing fuel enrichment. Fuel enrichments were chosen from 9.1% up to 9.7% as considering the initial k-eff close to unity and longer core operation time. The results on k-eff and CR calculation were shown in Figure 8 and Figure 9.

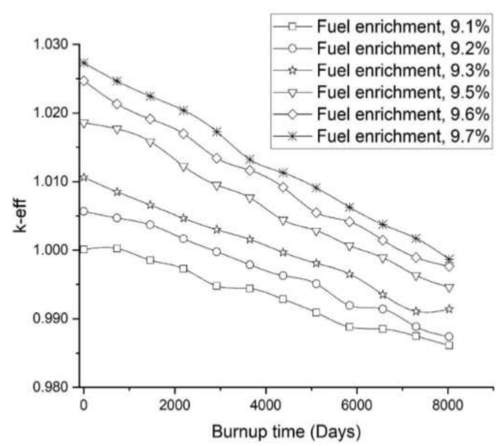

Fig.8. Change in effective multiplication factor along burnup

time in homogenous core

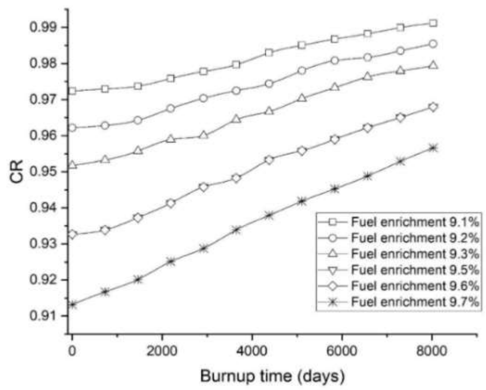

Fig.9. Change in conversion ratio along burnup time in homogenous core

From Figure 8 the initial k-eff for all the cases was limited by 1.030, over the period of 21 years of burnup time it has declined below unity. On the contrary, CR was kept on increasing towards the end of burnup but it kept on below unity which means fission material consumption was dominated over the operation time. In order to achieve breeding in the core (CR>1), longer operation time (with k-eff >1) is required.

4.2 Heterogeneous loading

From the previous case, it was analyzed that homogenous fuel loading cannot achieve breeding in the core. Therefore, we attempted to load enriched fuel heterogeneously to increase the rate of breeding process. In this case, two types of loading were investigated as shown in Figure 5 and Figure 6. The results obtained from heterogeneous loading one as shown in Figure 5 were illustrated in Figure 10 and Figure 11.

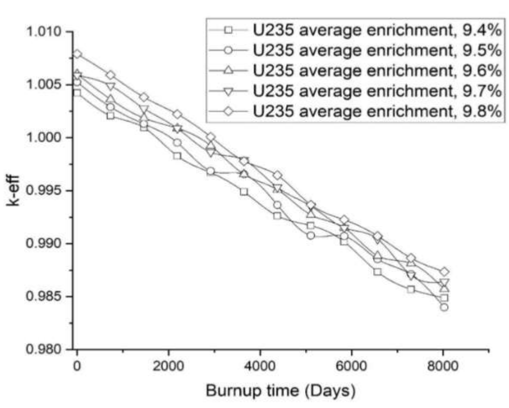

Fig.10. Change in effective multiplication factor along burnup time in heterogeneous core

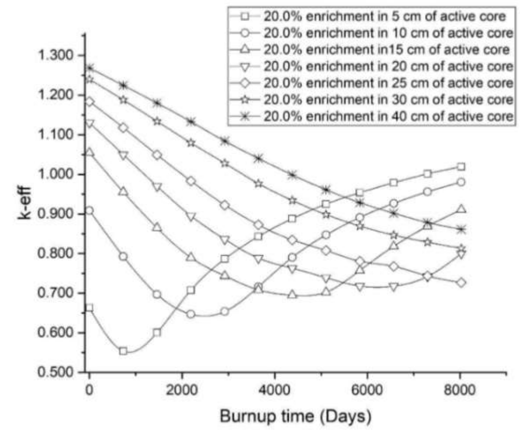

Fig.11. Change in conversion ration along burnup time in heterogeneous core

It can be seen from Figure 10 that the initial k-eff was under 1.010 for all cases. It started declining and became less than unity after 8 years. In contrast, CR kept on increasing till the end of burnup but it was less than unity which means fission material consumptions were dominated over the burnup time. Several possible heterogeneous loading cases were investigated but all the cases gave similar results as shown above.

Therefore, we moved on to loading case as shown in Figure 6. In this loading, the core was divided into two zones namely enriched uranium zone and natural uranium zone in axial direction. Burnup calculation was performed for 7 cases with different lengths of enriched uranium zone, starting from 5 cm to 40 cm from top of the core. Fuel enrichment in enriched uranium zone was fixed at 20.0% as LEU for all 7 cases. The results on k-eff and CR calculation were shown in Figure 12 and Figure 13.

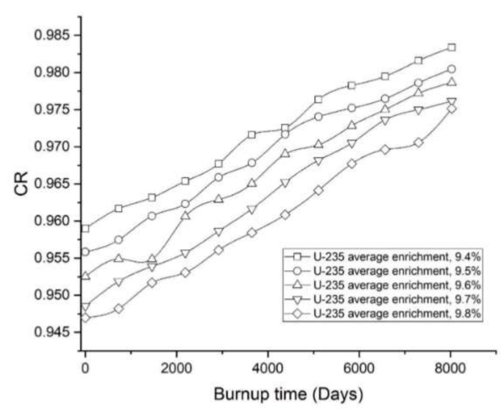

Fig.12. Change in effective multiplication factor along burnup time

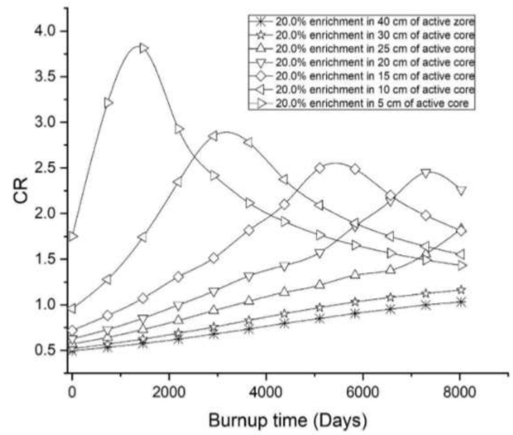

Fig.13. Change in conversion ration along burnup time in heterogeneous core

It can be analyzed from Figure 12 that initial k-eff was far higher than unity when enriched uranium zone was longer (40 cm, 30 cm, 25 cm), then it was kept on decreasing eventually and less than unity after 13 years, 10 years, 6 years respectively. Likewise, when enriched uranium zone was in 20 cm and 15 cm, burnup did not also take place longer. Finally, when enriched uranium zone was in 10 cm and 5 cm, the initial k-eff was far lower than unity and it was decreased during the initial burnup time and kept on increasing regularly to a steady value until the end of burnup.

The decrease in k-eff over the burnup time is mainly because of consumption of fissile material and accumulation of fission products in enriched uranium zone and the increase at the end of burnup indicates that breeding fissile material from natural uranium may take longer time.

4.3 Zone loading

From the previous two loading cases, it was analyzed that breeding fissile material from natural uranium zone may take longer burnup time in both homogeneous and heterogeneous loading. Therefore, we came up with a different approach, the core was divided into 8 zones radially and enriched fuel loaded in odd numbered zones (#1, #3, #5, #7). Fuel enrichment in odd numbered zones were 18.0%, 17.0% and 16.5% determined by initial k-eff value respectively. The results of k-eff calculation and CR calculation were shown in Figure 14 and Figure 15, respectively.

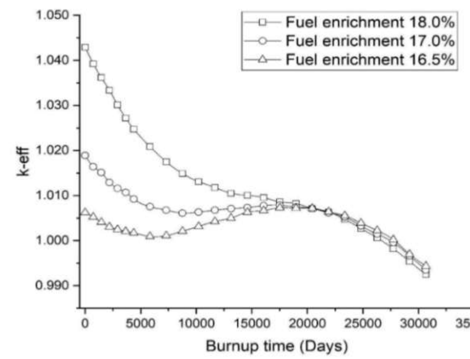

Fig.14. Change in effective multiplication factor along burnup time

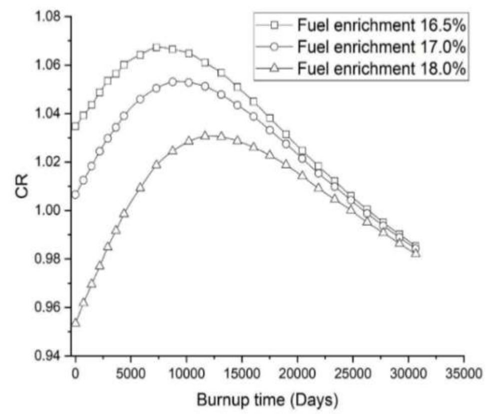

Fig.15. Change in conversion ration along burnup time in zone loading

It can be seen from Figure 14 that initial k-eff was under 1.050 for all three cases and burnup time continued for about 72 years which is far longer compared to 20 years in that of homogeneous and heterogeneous loading cases. In the first case, when fuel enrichment was at 18.0 %, initial k-eff at zero burnup was at 1.042 and it decreased significantly during the first 27 years burnup and then kept almost constant until 54 years. At the end of burnup, k-eff decreased slowly and became less than unity after 72 years of burnup. In the second case, we attempted to decrease initial k-eff by reducing fuel enrichment into 17.0 % and initial k-eff was found at 1.019 and then maintained almost constant until 54 year. At the end of burnup, it decreased slowly and became less than unity after 72 years.

In the last case, we also attempted to decrease initial k-eff by reducing fuel enrichment into 16.5%. In this case, initial k-eff was found at 1.006 which is near unity. Then it decreased into 1.0009 during the first 19 years of burnup. For the next 55 years it increased and reached at 1.009. After this point, it decreased again and became less than unity after 76 years.

CR result as depicted in Figure 15 illustrates a profile of an increasing value to a maximum initially and then slowly decreasing by the end of burnup time. All three cases show a profile of decreasing at the startup and then fluctuated and maintained near unity over long burnup time. Then the k-eff declined eventually and became less than unity at 72 to 76 years respectively. It can be analyzed from this result that the reactor with zone loading and initial k-eff close to unity could operate more than about 70 years with breed and burn mode.

4.4 DPA estimation

In order to operate the reactor over a long period of time, irradiation damage in the core must be estimated. Material irradiation damage estimated in unit of displacement per atom (DPA) for the core with 17.0% fuel enrichment in zone loading. Because of safety concern in cladding material, the irradiation damage limit is 650 dpa for 1.3×10^{24} neutrons fluence (Lemaignan, C, 2010). In this study, the dpa value was calculated using an approximation that $2.0*10^{23}$ n/cm^2 neutron fluence in neutron energy >100 keV corresponds to 100 dpa (K.Kuwagaki et al. 2019).

The result was shown in Figure 16. An expression of the displacement damage rate (R_d) defined as the number of displacements per unit volume (cm^3) per second. R_d is basically proportional to the number of target atoms per cm^3, N, and the displacement cross section for neutrons with energy E_n, and the neutron flux, and can generally be written as

$$R_d = N \cdot \sigma_d(E_n) \cdot \phi(E_n) \quad (1)$$

From the Eq.1 DPA can be defined as

$$dpa = \frac{R_d t}{N} \approx t\int_0^{\infty} \sigma_d(E_n) \cdot \phi(E_n) dE_n \quad (2)$$

In this calculation, we used approximation formula as above.

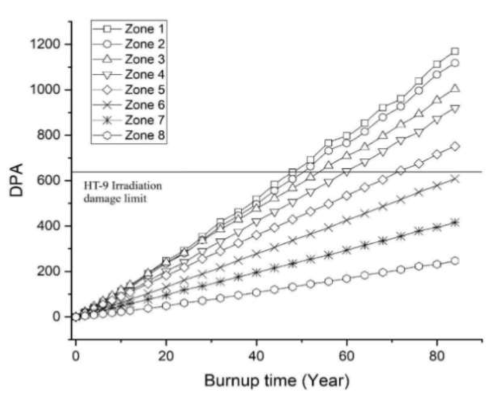

Fig.16. Irradiation damage estimate in fuel cladding (HT9)

Figure.16 shows the estimated result on DPA versus burnup time. DPA was calculated in the core with zone loading where assemblies were tallied into eight zones. It can be seen that cladding DPA value exceeded its limiting value of 650 dpa at 48 years in Zone 1 and Zone 2.

5. Conclusion

In this study, a small breed and burn reactor concept was proposed for remote regions in Mongolia. It was analyzed when fuel enrichment 17.0% in zone loading, initial k-eff was near to unity and it maintained almost constant over the long burnup time without any drastic change in k-eff. The reactor can be critical over 70 years. It means that reactor can be operated over 70 years without adding new fuel. However, this period will be limited by irradiation damage in cladding material. From DPA estimation, 48 years is maximum value for cladding, which in turn limits reactor operation period.

Future work

The following studies needs to be carried out:

(1) Determining burning wave direction
(2) Power peaking factor
(3) Thermal hydraulic analyses

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Author contribution

All calculation on design study and neutronic analyses have been carried by Tsedndsuren Amarjargal with the guidance of Munkhbat Byambajav. Results have been discussed with Odmaa Sambuu.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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