Study on Erbium Loading Method to Improve Reactivity Coefficients for Low Radiotoxic Spent Fuel HTGR

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Abstract

Erbium loading methods are investigated to improve reactivity coefficients of Low Radiotoxic Spent Fuel High Temperature Gas-cooled Reactor (LRSF-HTGR). Highly enriched uranium is used for fuel to reduce the generation of toxicity from uranium-238. The power coefficients are positive without the use of any additive. Then, the erbium is loaded into the core to obtain negative reactivity coefficients owing to the large resonance the peak of neutron capture reaction of erbium-167. The loading methods are attempted to find the suitable method for LRSF-HTGR. The erbium is mixed in a CPF fuel kernel, loaded by binary packing with fuel particles and erbium particles, and embedded into the graphite shaft deployed in the center of the fuel compact.

It is found that erbium loading causes negative reactivity as moderator temperature reactivity, and from the viewpoint of heat transfer, it should be loaded into fuel pin elements for pin-in-block type fuel. Moreover, the erbium should be incinerated slowly to obtain negative reactivity coefficients even at the End Of Cycle (EOC). A loading method that effectively causes self-shielding should be selected to avoid incineration with burn-up. The incineration mechanism is elucidated using the Bondarenko approach.

As a result, it is concluded that erbium embedded into graphite shaft is preferable for LRSF-HTGR to ensure that the reactivity coefficients remain negative at EOC.

KEYWORDS: erbium, HTGR, LRSF-HTGR, highly enriched fuel, reactivity coefficient

1. Introduction

Low Radiotoxic Spent Fuel High Temperature Gas-cooled Reactor (LRSF-HTGR) has been proposed and researched by the nuclear hydrogen and heat application research center of Japan Atomic Energy Agency (JAEA) (Fukaya et al. 2015). The objective of the concept is to reduce potential toxicity in the spent fuel of LRSF-HTGR. LRSF-HTGR employs Highly Enriched Uranium (HEU), as described in Section 2.

The subject of LRSF-HTGR is to ensure that the power coefficients remain negative under all operation conditions. Negative reactivity feedback of the Doppler effect is reduced by removing uranium-238. In HTGR, there is also a factor for the moderator of graphite to make the power coefficient of reactivity positive. The positive reactivity is caused by the neutron spectrum shift effect of the Maxwellian peak in the thermal energy range when the moderator temperature increases. The spectrum shift reduces neutron capture reaction by nuclides with 1/v characteristics such as xenon. To achieve the neutronic safety feature of self-regulation, the characteristics should be improved by any suitable means. In general, erbium is employed for the purpose (Kodochibov, et al. 2003 and Akie 2007) because the giant resonance neutron capture cross section peak of erbium-167 at 0.3 eV counterbalances the 1/v characteristics across the energy range of the Maxwellian peak.

In the present study, the loading method of erbium for LRSF-HTGR is investigated, and a new loading method is proposed to obtain negative isothermal temperature coefficient, which corresponds to the power coefficient, in all operation ranges with effective erbium loading method because the erbium has been employed for other fuel types (Kodochibov, et al. 2003 and Akie 2007) of reactor as described in Section 3.

In Section 2, the concept underlying the LRSF-HTGR is described. In Section 3, the erbium loading method and its characteristics are described. In Section 4, suitable erbium loading methods for LRSF-HTGR are investigated. Finally, concluding remarks are given in Section 5.

2. Reactor concept and calculation model

Fig.1

Figure 1 shows the change in potential toxicity of Spent Fuel (SF) of uranium fueled Light Water Reactor (LWR) (Oigawa, 2012). The toxicity is normalized by that of the natural uranium required to fabricate the fuel. The toxicity decays because of the cooling time from fuel discharge. If the SF and/or High Level radioactive Waste (HLW) from the SF are disposed after the decay of toxicity to a level under that of natural uranium, the total amount of toxicity in environment does not increase compared with that before the nuclear reactor operation. The characteristics are almost common for low enriched uranium fuel reactors. The toxicity of uranium and neptunium are not problematic because they are lower than that of natural uranium. The toxicity of plutonium is significant, and a long cooling time of approximately 100,000 years is necessary for it to decay to a level below that of natural uranium. The toxicity of americium is significant as well, although less than that of plutonium, and it takes approximately 3,000 years to decay to a level below that of natural uranium. Furthermore, curium shows toxicity higher than that of natural uranium, but the magnitude and cooling time are less than those of Fission Products (FPs). The toxicities of plutonium, americium, and curium are generated from uranium-238. Americium and curium are well known as Minor Actinoids (MAs). Furthermore, uranium-235 generates neptunium, another MA. However, its toxicity is negligible compared with that of natural uranium, as described above. If uranium-238 is removed from the fuel, the SF has low toxicity, mainly composed of the toxicity of FPs, and the cooling time to decay the toxicity to a level below that of natural uranium level might be drastically reduced to approximately 300 years. Therefore, the SF can be disposed with low environmental burden, even for direct disposal into geological repositories after realistic cooling time.

In this context, LRSF-HTGR with highly enriched fuel has been proposed and researched. The core is designed on the basis of GTHTR300 (Yan et al. 2003), a commercial HTGR design with 600 MW thermal power and an annular-type core with 14 wt% enriched uranium fuel. The major specifications of LRSF-HTGR are listed in Table 1. LRSF-HTGR

employs HEU enriched to 93 wt%, which can be realistically achieved. To prevent proliferation and maintain fuel integrity, HEU is diluted with Yttria-Stabilized Zirconia (YSZ) in a fuel kernel of Coated Fuel Particles (CFPs) to reserve the uranium-235 inventory of the original design of GTHTR300 per particle of CFP. YSZ is composed of 88 mol% of ZrO_2 and 12 mol% of Y_2O_3 (Shiratori et al. 1999). The uranium inventory of the original GTHTR300 design is approximately 7.69 tons for the entire core. The uranium inventory of LRSF-HTGR is set to be 1.16 tons to reserve the uranium-235 inventory with uranium enriched to 93 wt%. Furthermore, the YSZ matrix is preferable from the viewpoint of nuclear proliferation resistance because the matrix cannot be dissolved in the nitric acid (Akie, et al. 1994) used by reprocessing. To dissolve the YSZ kernel, hydrogen fluoride must be added (Shirasu, et al. 2001). Hydrogen fluoride is difficult to treat because it corrodes the dissolver via the formation of very strong acids. Moreover, the graphite matrix of the fuel compact and coating layers should be removed before dissolution. Therefore, it is found that the LRSF-HTGR fuel has high “proliferation technical difficulty,” “proliferation cost,” and “proliferation time,” which are considered as the essence of proliferation resistance in the Generation IV International Forum (GIF) (The Proliferation Resistance and Physical Protection Evaluation Methodology Expert Group of the Generation IV International Forum, 2006) compared with other types of reactors. Moreover, by maintaining the uranium-235 inventory, core specifications relevant to fuel integrity such as FP generation, excess oxygen generation, palladium generation, and fuel material irradiation, can be restricted around the original design.

Figs.2 and 3

The core configuration is same as that of GTHTR300, as shown in Fig. 2. The fuel columns comprise eight fuel block layers in the axial direction. The height of the fuel blocks is 1 m and the core height is 8 m. As described above, the HTGR core comprise eight parts in the axial direction. Therefore, fuel reloading is assumed in the axial direction. The GTHTR300 design employed a purpose-built loading pattern called sandwich loading (Yan et al. 2003). In this pattern, the core is divided into two batches, in particular, irradiated fuel

batch and fresh fuel batch. The irradiated fuel blocks are sandwiched between fresh fuel blocks. The LRSF-HTGR inherits this loading pattern. The loading pattern is shown in Fig. 3. Furtuermore, the fuel blocks are divided into three groups along the radial direction to distinguish burn-up compositions as shown in Fig.2.

In this study, neutronic feasibility, which includes criticality and negative power coefficients, is assessed by core burn-up calculation using the Monte Carlo neutron transport code MVP (Nagaya, et al. 2006) with evaluated nuclear data of JENDL-4.0 (Shibata, et al. 2011). Moreover, a statistical geometry model (Murata, et al. 1997) is employed to treat double heterogeneity for CFP directly. A two-fuel-layers model is developed to simulate the core with infinite height with sandwich shuffling. Each fuel layer is modeled for half height with a reflective boundary condition to simulate sandwich shuffling of two batches as shown in Figs. 2 and 3. For the radial direction, this model considers 1/6 part of the core. The approximation with infinite core height is suitable because the neutron leakage effect in the axial direction contributes only slightly to the criticality (approximately 0.5 %⊿k/kk') because of the very high core height of approximately 8 m, and negligibly, in particular, in a study on reactivity coefficient characteristics such as the present study. This model was also employed in a feasibility study of LRSF-HTGR (Fukaya et al. 2015). To confirm the negative power coefficient, the isothermal temperature coefficients, which include the effects of both the Doppler coefficient and the moderator temperature coefficient as same as power coefficient, are evaluated for all temperature ranges from Cold Zero Power (CZP) to Hot Full Power (HFP) in the present study. In the evaluation, the xenon concentration is assumed to be in equilibrium for full power operation even in low temperature range because xenon has a large capture cross section with 1/v characteristics in thermal energy and yield a conservative value on the positive side.

3. Loading method of erbium and its characteristics

3.1 Loading method of erbium in previous study

Erbium loading to improve reactivity coefficient has been performed in various ways. In GT-MHR (Kodochibov, et al. 2003), which is a weapon-grade plutonium burner reactor based on prismatic-type HTGR, erbium is loaded as a Burnable Poison (BP) compact at the corners of the fuel block independently of the fuel material. In general, the reactivity feedback of fuel temperature works without lag time because the sources of heat and negative reactivity are at the same position. In contrast, that of moderator temperature works with lag time because of heat transfer. However, the GT-MHR design achieves safety even in a Reactivity Insertion Accident (RIA) by control rod withdrawal. The GT-MHR employs a multi-hole-type fuel block (Tak, et al. 2008), in which the fuel compact is directly embedded into a fuel block. Moreover, heat is transferred from the fuel compact to the fuel block directly. The fuel block is cooled by coolant gas through coolant holes in the fuel block. In this type of fuel, the fuel block works as the heat medium. Furthermore, the erbium compact is directly embedded into a fuel block. Heat is transferred directly to the erbium compact. However, the LRSF-HTGR based on the GTHTR300 described in the previous section employs pin-in-block-type fuel (Yan et al. 2003). The fuel pin is inserted in the coolant hole in the fuel block. The coolant flows through the gap between the fuel block and the fuel pin. Heat is not transferred directly to the fuel block, except for that transferred via radiation. The fuel pin temperature increases independently of the fuel block in a transient event. It is likely that the neutronic characteristics in the peripheral region of the fuel pin would be different from that in the fuel pin. In the case of the loading erbium independently onto the pin-in-block-type fuel, reactivity feedback would be delayed. In terms of Doppler reactivity of erbium, it occurs after heat transfer to the block. The reactivity feedback is directly delayed because of the lag time. In terms of moderator reactivity of erbium, only the graphite in the fuel block instantly contributes to the spectrum shift in the erbium loaded region. The magnitude of this reactivity is small. After heat transfer to the block, reactivity of a larger is seen because of the spectrum

shift caused by temperature increase in the block. The reactivity feedback is delayed because of the lag time. Therefore, independent erbium loading of the fuel pin is not suitable for pin-in-block-type fuel.

Furthermore, there is a case in which erbium is mixed into the fuel kernel on a pebble bed reactor (Akie 2007). However, unlike block-type fuel, the neutronic characteristics do not change during operation, and fresh fuel always exists because of continuous online fuel loading. Therefore, the feasibility of this loading method for block-type fuel should be confirmed.

Figs.4 and 5

Table 2, Figs.6 and 7

3.2 Characteristics of reactivity coefficient with erbium loading

The isothermal temperature coefficients of LRSF-HTGR with and without erbium loading are shown in Fig. 4. Erbium is loaded into the fuel kernel as a mixture. This loading method is only one candidate for LRSF-HTGR at this stage, as described in the previous section. In this study, the erbium composition is set to naturally abundant. The chemical form is assumed an oxide or its solid solution. The amount is set to be the half atomic number of uranium-235 nuclides. The isothermal temperature coefficient without erbium loading shows positive values for almost all temperature ranges at the Beginning Of Cycle (BOC) and EOC. With erbium loading, the reactivity coefficients are negative for all temperature ranges at BOC. However, the reactivity coefficients show positive values from 500 K to 1000 K at EOC. To realize negative reactivity coefficients at EOC, the amount of erbium loaded should be increased. However, this is difficult from the viewpoint of criticality, as shown in Fig. 5. The multiplication factor without erbium loading decreases linearly with the number of days of operation. In contrast, the multiplication factor with erbium loading shows a small value at BOC.

Figure 6 shows the change in the neutron capture reaction rate of erbium nuclides because of an increase in temperature from 700 K to 800 K at BOC. The reactivity coefficients at temperatures around 700 K tend to become positive in the LRSF-HTGR design,

and they improve at BOC with erbium loading as a mixture into the fuel kernel. The reaction rate is normalized to develop the neutron production unity for an entire core. The increase in the capture reaction corresponds to negative reactivity worth according to the exact perturbation theory for reactivity expression. Almost all the negative reactivity worth is contributed by erbium-167 around 0.3 eV. The reactivity worth is caused by the resonance peak of the neutron capture cross section at 0.3 eV, as shown in Fig. 7. The positive reactivity coefficient and improvement in erbium loading have been elucidated as follows (Kodochibov, et al. 2003). The positive reactivity is generated by the spectrum shift of the Maxwellian peak in terms of thermal energy and cross sections with 1/v characteristics. Xenon-135 is a representative nuclide with a large capture cross section with 1/v characteristics, and it is generated with burn-up in the fuel region. The neutron fluxes in the fuel region are shown in Fig. 7. These fluxes are normalized by the neutron generation rate across the core. The peak energy shifts from 0.1 to 0.3 eV, which is also the peak energy of the resonance cross section of erbium-167, along with an increase in temperature from 400 to 1600 K. In the presence of nuclides with 1/v characteristics cross sections, the positive reactivity is caused by the spectrum shift. However, the positive reactivity can be counterbalanced with the existence of erbium, and the reactivity coefficient can be turned negative. To confirm this assertion numerically, reactivity coefficients—Doppler coefficient, moderator temperature coefficient, and isothermal temperature coefficient—are evaluated at 700 K at BOC for the reactors with and without erbium loading, as summarized in Table 2. To evaluate the Doppler coefficients, the fuel kernel temperature was increased by 100 K. The temperature of the graphite moderator region, which is composed of not only a graphite block but also of graphite structures in the fuel pin is increased by 100 K to evaluate the moderator temperature coefficient. The Doppler coefficient shows a negative value of -8.95×10^{-7} $\Delta k/kk'/K$ even for the reactor without erbium loading because of the capture reaction of uranium-236 generated by a burn-up reaction with a fraction of approximately 20 % of the neutron absorption reactions of uranium-235. Furthermore, the Doppler coefficient is improved by erbium

loading from -8.95×10^{-7} to -4.40×10^{-6} $\Delta k/kk'/K$. The moderator temperature coefficient is drastically improved from the large positive value of 2.26×10^{-5} $\Delta k/kk'/K$ to a large negative value of -1.10×10^{-4} $\Delta k/kk'/K$. The isothermal temperature coefficient, which includes the effects of both the Doppler and the moderator temperature coefficients, is also drastically improved by erbium loading. It is found that the major contribution toward the improvement of the isothermal coefficient is the effect of the spectrum shift due to an increase in moderator temperature.

Figure 8 shows the change in neutron flux for the fuel pin and the BP hole under the Dowell pin deployed at the corner of the fuel block when only the temperature in the fuel pin region increases from 700 K to 800 K. The flux change in the BP hole, the characteristics of which correspond to that of independent loading, is smaller by 16 % compared with that in fuel pin. The reactivity would be smaller as well. Therefore, erbium loading in the fuel pin region is preferable for pin-in-block-type fuel.

Fig.9

Figure 9 shows the change in the erbium-167 inventory with the number of days of operation. The inventory is normalized by the amount of loading. The LRSF-HTGR core comprises two batches. Almost all the loaded erbium-167 is incinerated within one cycle, and approximately one percent of the erbium-167 remains and is reloaded to the next cycle as a second batch. The amount of erbium-167 in the second batch is almost constant because of erbium-166 to erbium-167. This rapid incineration of erbium-167 turns the reactivity coefficient positive at EOC, and the resonance reaction at 0.3 eV strongly contributes to the incineration.

Fig.8

In contrast, the pebble bed reactor can retain negative reactivity coefficients even with erbium loading as a mixture. This is because of its constant neutronic characteristics during operation. The core includes all fuels with a history of burn-up, and it is considered to have characteristics similar to that of prismatic fuel core at the Middle Of Cycle (MOC), which is characterized by average burn-up. At MOC, approximately 15 % of loaded erbium remains in the first batch. If more erbium should be loaded, the criticality would be

sufficiently high at MOC.

To realize negative reactivity coefficients even at EOC with the prismatic fuel core, the erbium-167 consumption should be reduced. The giant neutron capture resonance peak at 0.3 eV strongly contributes to the consumption and it can be effectively reduced using self-shielding effect. The key technology is an erbium loading method to enhance the self-shielding effect.

4 Investigation of suitable erbium loading method for LRSF-HTGR

4.1 Characteristics of self-shielding effect and its decomposition method

A neutron transport calculation code based on the Monte Carlo method with continuous energy treatment is very convenient if its huge calculation cost is acceptable, and it is employed for core design in this study because it can accurately evaluate core characteristics with accuracy without less approximation. For each neutron, transportation is simulated until the particle varnishes. The reaction is determined by probability sampling using flight pass length and cross sections. The cross sections are continuously prepared for the entire energy region. Furthermore, Doppler effect can be considered by preparing the cross sections using the Doppler broadening technique for arbitrary temperatures. The Monte Carlo code can directly evaluate physical phenomena. However, it is difficult to find a factor that causes the phenomena, unlike deterministic methods. The deterministic methods have been developed with models to simulate each of the effect which composes the phenomena. In particular, considerable effort has been devoted to treating resonance cross sections with accuracy. Bondarenko established the group constant generation method (Bondarenko 1964) to treat the self-shielding effect. In this study, the Bondarenko approach is employed to elucidate the mechanism of the self-shielding effect.

In an infinite medium with narrow resonance approximation, neutron flux can be expressed as follows:

$$\phi(\mathrm{E}) \propto \frac{W(E)}{\Sigma_t(E)}\,, \qquad (1)$$

where:

ϕ: neutron flux ($cm^{-2}s^{-1}$),

W: weighting function (-),

Σ_t: macroscopic total cross section (cm^{-1}),

E: neutron energy (eV).

The weighting function is a smooth function that expresses the representative neutron spectrum for a target system. In the present study, a neutron spectrum without erbium loading is employed. Here, the macroscopic total cross section is divided into two parts as follows:

$$\Sigma_t(E) = \mathrm{N}_{iso}\left(\sigma_{t,iso}(\mathrm{E}) + \sigma_0\right), \qquad (2)$$

where:

N_{iso}: number density of nuclide under consideration (cm^{-3}),

$\sigma_{t,iso}$: microscopic total cross section of nuclide under consideration (cm^2),

σ_0: microscopic background cross section (cm^2).

Bondarenko introduced the background cross section to consider the effect on self-shielding by other nuclides. Using Eq.(2), Eq.(1) can be rewritten as follows,

$$\phi(\mathrm{E}) \propto \frac{W(E)}{\sigma_{t,iso}(\mathrm{E}) + \sigma_0}\,. \qquad (3)$$

From Eq.(3), the characteristics of the self-shielding factor are found. If the cross section increases rapidly, similar to a resonance peak, the neutron flux decreases. This is the energy self-shielding effect. The self-shielding effect diminishes as the background cross section increases. If the background cross section is adequately large to ensure that the resonance cross section of the nuclide under consideration can be neglected, the self-shielding effect is not caused and the effective cross section is called an infinite dilution cross section. Bondarenko proposed a group constant condensed by the flux described in Eq. (3) and arranged cross sections based on the infinite dilution cross sections as follows:

$$\sigma_{eff,g} = \mathrm{f}_g(\mathrm{T}, \sigma_0)\sigma_{\infty,g}(T), \qquad (4)$$

where:

$\sigma_{eff,g}$: effective cross section of g-th energy group (cm^2),

f_g: self-shielding factor of g-th energy group (-),

$\sigma_{\infty,g}$: infinite dilution cross section of g-th energy group (cm^2).

This type of group constant set is called the Bondarenko type group constant.

Here, the background cross section in an infinite medium is described as follows:

$$\sigma_{0,n} = \frac{1}{\mathrm{N}_n}\sum_{m\neq n}\mathrm{N}_n\sigma_{t,m}\ . \qquad (5)$$

This theory was extended to heterogeneous system by considering neutron escape from fuel lump as follows:

$$\sigma_{0,n} = \frac{1}{\mathrm{N}_n}\sum_{m\neq n}\mathrm{N}_m\sigma_{t,m} + \frac{(1-C)\Sigma_e}{\mathrm{N}_n}\,, \qquad (6)$$

where:

Σ_e: escape cross section (cm^{-1}),

C: Dancoff correction factor (-).

Wigner introduced the escape cross section (Wigner et al. 1955), which is defined as the inverse of the mean chord length, to consider the effect of neutron escape from the fuel lump. Carlvik applied the Dancoff correction factor to the escape cross section (Carlvik 1966) to consider the effect of neutron re-entry into the fuel lump without collision in the moderator region. The first term of the right-hand side of Eq. (6) is called volume term, and the second term is called surface term.

In this study, the background cross section is inversely determined by the method described above using the NJOY code (MacFarlane, et al. 2010), which is used for processing nuclide data, to realize the effective cross section evaluated by the MVP code. The volume term is evaluated using the number density and the cross sections determined with the MVP code. The surface term of the background cross section is evaluated as difference between the

total background cross section and the volume term.

Furthermore, the spatial shielding effect can be determined as the ratio of the flux level in a target region to the spatially averaged flux level (Yamashita, et al. 1994). In this study, the ratio is evaluated to the averaged flux in fuel blocks.

Fig.10

4.2 Erbium loading method with self-shielding effect

As described above, the self-shielding effect of erbium loading should be enhanced. To that end, the background cross section must be reduced. To decrease the volume term, the density of erbium should be increased. To decrease the surface term, the size of the erbium lump should be increased. Both these treatments also enhance the spatial self-shielding effect.

In this study, erbium loading by mixing in a fuel kernel as a mixture has already been attempted. To increase the density of erbium, it should be concentrated locally. We attempt two alternative candidates. The first one is binary packing of ordinary CFP and coated erbia (Er_2O_3) particles. The coated erbia particles are packed in a ratio of 1:14 CFPs. Such binary packing stands for the packing of two different types of particles in one medium. This loading method is shown in Fig. 10. The binary packing technology aims to achieve a higher packing fraction, and it has been demonstrated and established (El-Genk et al. 2004). In this case, particles of different size is used. However, the particle size of erbium is provisionally assumed same as the fuel particle size in the present study. This type of packing is easier to achieve from the fabrication viewpoint. The second method involves embedding an erbia compact into the center of the graphite shaft in the fuel rods. The graphite shaft is deployed at the center of an annular fuel compact to support the fuel rod structure. The temperature change is closely related to the fuel compact. The reactivity feedback of the Doppler coefficient works without lag time, even for the third candidate. Moreover, erbium is loaded into 18 fuel rods per fuel block, which includes 57 fuel rods, as shown in Fig.10. The 18 fuel rods are dispersed in the fuel block to avoid power peaking generation with strong self-shielding effect. The radius of the erbium compact is set

to 1.2 mm. The graphite shaft assumes an annular structure, and its thickness is 3.3 mm. This fuel structure is strong enough to be feasible because Korea Atomic Energy Research Institute (KAERI) developed a similar double-side from the viewpoint of heat removal (Tak, et al. 2008). The thickness of the graphite support layer inside the fuel compact was set to approximately 1 mm. This thickness is approximately 1/3 of that in our proposal.

4.3. Confirmation of isothermal temperature coefficient and its self-shielding effect for proposed loading method

The results of the isothermal temperature coefficients are shown in Fig. 11. The isothermal temperature coefficients at BOC are successfully improved in all cases. However, at EOC, the coefficients for erbium loading as a mixture and as binary packing are positive at 500–1000 K. Only in the case with the erbium loading into the graphite shaft are the values negative even at EOC. Figure 12 shows the erbium-167 inventory during the operation. For the cases of erbium loading as mixture and binary packing, almost all of the loaded erbium is incinerated in the first batch until EOC. In contrast, in the case of erbium loading into the graphite shaft, approximately 10 % of the initially loaded erbium remained at EOC in the first batch, and an equal amount remained in the second batch during operation. This is the reason for realize negative reactivity coefficients for the case of erbium loading into the graphite shaft. However, the number of days of operation is reduced by approximately 50 because of reactivity defect of the remaining erbium, as shown in Fig. 13. To elucidate the mechanism of improvement in the incineration characteristics, the neutron capture reaction of erbium-167 in the first batch is investigated as follows. The temperature of 1400 K is selected by assuming the full power condition. The reaction rate and the cross sections at BOC are listed in Table 3. The reaction rate is normalized by the neutron production for an entire core. The fractions in the resonance peak at 0.3 eV to total reaction rate are from 74.0 % of the fuel center to 81.4 % of the mixture. The major part of the neutron reaction is occupied only by the reaction at the resonance peak. The total capture reaction rate by erbium loading in the graphite shaft has the

least value of 8.30×10^{-2} s^{-1}. The reaction rate is 40 % and 51 % of the reaction rates for erbium loading as a mixture and as binary packing, respectively. The self-shielding factor of the resonance peak for erbium loading in the graphite shaft has the least value of 0.386. The self-shielding factor value is 54 % and 65 % of the shielding factor for erbium loading as a mixture and as binary packing, respectively. The low shielding factor can be ascribed to the low background cross section. The background cross section of erbium loading in the graphite shaft is the least value of 3.72×10^{2} barn. The background cross section is 7 % and 17 % of the background cross sections for erbium loading as a mixture and as binary packing, respectively. The background cross sections of the volume term for erbium loading in graphite shaft and by binary packing are almost same. Those are 7.25×10^{-1} and 6.79×10^{-1} barn. This is because the erbium lump comprises pure erbium oxide for both erbium-loading methods. The background cross section of the volume term for erbium loading as a mixture has the highest value of 2.56×10^{3} barn because the erbium is mixed into the uranium fuel nuclides, which are actinoid nuclides and have large total cross sections. The background cross section of surface term for erbium loading in the graphite shaft is approximately ten times lower than that of erbium loading as a mixture and as binary packing. This is because of the larger erbium lump size, which corresponds to a smaller escape cross section compared with the CFP kernel even when considering the lower probability of neutron re-entry into the erbium lump, which corresponds to the Dancoff correction factor. The concentration of erbium independent of fuel nuclides results in smaller background cross sections for both volume and surface terms. Furthermore, the spatial shielding factor shows the least value for erbium loading in the graphite shaft. The value of 0.483 is 55 % and 63 % of those for erbium loading as a mixture and as binary packing. Moreover, the erbium concentration causes a spatial shielding effect.

Table3, Figs.11,12 and 13

5. Conclusions

To obtain negative isothermal temperature coefficients for LRSF-HTGR under all operation conditions, erbium-loading methods were investigated. From the viewpoint of heat transfer, erbium should be loaded into the fuel pin element because LRSF-HTGR employs pin-in-block-type fuel. Erbium loading into the fuel kernel as a mixture was a candidate for erbium loading into the fuel pin element. The above erbium-loading method was attempted in LRSF-HTGR. The amount of erbium loaded was limited by the criticality at BOC. The amount is approximately the half number of uranium-235 nuclides. Even with that amount of erbium, negative isothermal temperature coefficients could not be obtained at EOC because almost all the loaded erbium-167 was incinerated at EOC. An erbium-loading method that has a strong shielding effect is desired to ensure retention of erbium-167 even at EOC.

Therefore, in this study, two candidate methods were attempted and investigated. Moreover, the self-shielding effect factor was decomposed following the Bondarenko approach to elucidate the mechanism. The first candidate is erbium loading using another type of coated particle as binary packing. The second candidate is erbium loading in the graphite shaft at the center of the fuel element. The first candidate cannot achieve negative isothermal coefficient at EOC. The second candidate successfully obtains negative isothermal coefficients under all operation conditions. For erbium loading in the graphite shaft, the self-shielding factor of the resonance peak of erbium-167 at 0.3 eV has the least value compared with the other two cases because of the small background cross section obtained by the highest density of erbium as purely erbium oxide for the volume term and larger erbium lump size for the surface term. Moreover, the erbium concentration causes the largest spatial shielding effect.

Therefore, we concluded that erbium loading in the graphite shaft at the center of the fuel compact is preferable for LRSF-HTGR. This conclusion contributes toward establishment of the LRSF-HTGR concept.

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Figure captions

Table 1 Major specifications of LRSF-HTGR

Table 2 Individual reactivity coefficients at 700K at BOC (Δ k/kk'/K)

Table 3 Characteristics of neutron capture reaction of ^{167}Er for first batch of fuel at 1400K at BOC

Fig. 1 Potential toxicity of each nuclide in spent fuel of uranium fueled LWR

Fig. 2 Core geometry of GTHTR300 and its calculation model

Fig. 3 Loading pattern and its calculation model

Fig. 4 Reactivity coefficient of LRSF-HTGR without erbium loading and with erbium mixed into fuel kernel

Fig. 5 Criticality of LRSF-HTGR without erbium loading and with erbium mixed into fuel kernel

Fig. 6 Difference in capture reaction rates at temperature of 800K and 700K

Fig. 7 Capture cross sections with 1/v characteristics and neutron fluxes at each temperature

Fig. 8 Flux changes because of temperature increase of 100 K in each region

Fig. 9 Change in erbium-167 inventory with number of operation days

Fig. 10 Erbium-loading method

Fig. 11 Reactivity coefficient of each candidate erbium-loading method

Fig. 12 Change in erbium-167 inventory with number of operation days for each candidate method

Fig. 13 Change oin erbium-167 inventory with number of operation days for each candidate method

Table 1 Major specifications of LRSF-HTGR

Item	Value
Thermal power (MWt)	600
Electric generation (MWe)	
Gross:	280
Net:	274
Inlet coolant temperature (K)	860
Outlet coolant temperature (K)	1123
Coolant pressure (MPa)	7.0
Uranium inventory (ton)	1.16
Uranium-235 enrichment(wt%)	93.0
Fuel particle	SiC coated particle
Particle packing fraction (%)	33.0
Cycle length (days)	550
Number of batches	2
Discharge burn-up (GWd/t)	577

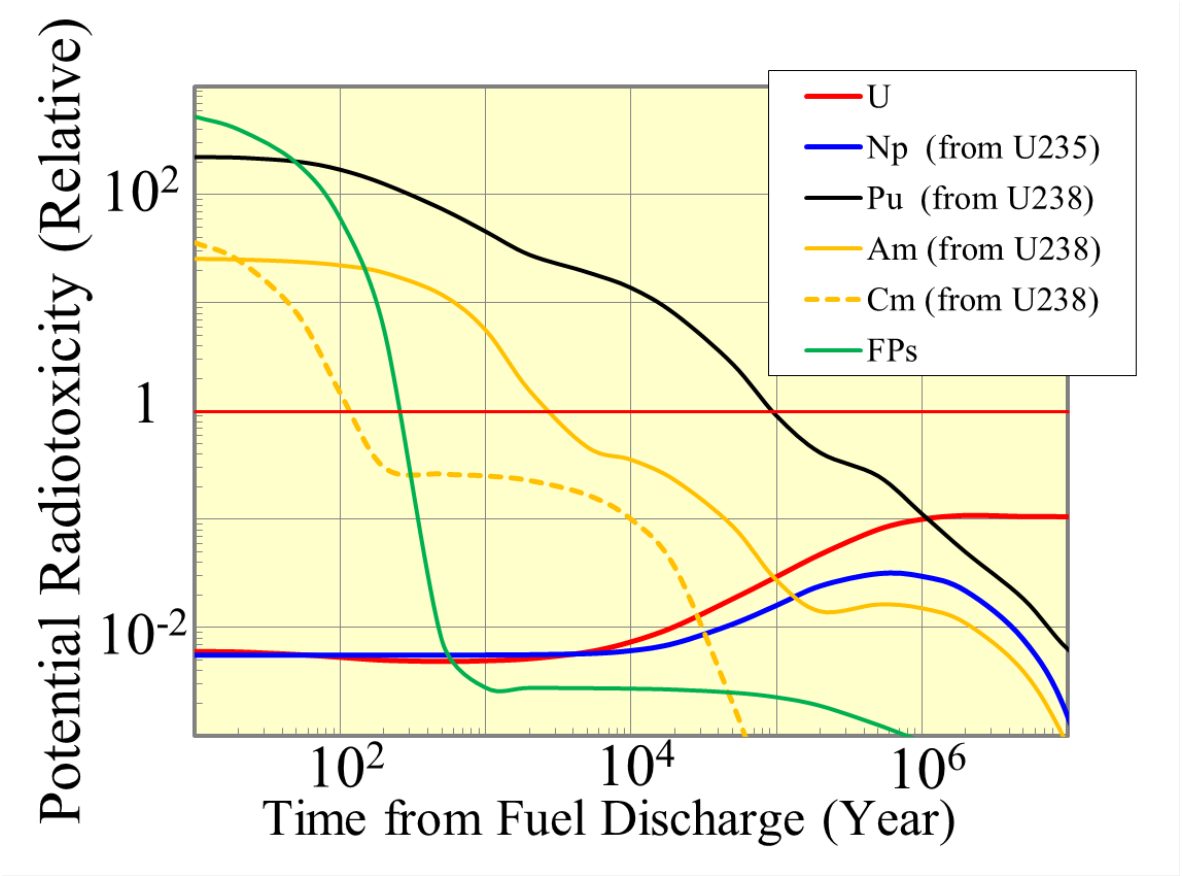
Table 2 Individual reactivity coefficients at with 700K at BOC (Δ k/kk'/K)

	Without Er	Mixture
Doppler coeff.	-8.95×10^{-7}	-4.40×10^{-6}
	(53.4 %)	(15.3 %)
Moderator coeff.	2.26×10^{-5}	-1.10×10^{-4}
	(1.94%)	(0.63 %)
Isothermal coeff.	2.23×10^{-5}	-1.16×10^{-4}
	(2.12 %)	(0.60 %)

* Values in parentheses correspond to a statistical error of 1 σ .

Table 3 Characteristics of neutron capture reaction of ^{167}Er for first batch of fuel at 1400K at BOC

	Mixture	Binary	Graphite shaft
Reaction rate (s^{-1})	2.06×10^{-1}	1.64×10^{-1}	8.30×10^{-2}
Reaction rate at resonance peak (s^{-1})	1.68×10^{-1}	1.32×10^{-1}	6.14×10^{-2}
Fraction of reaction at resonance peak (%)	81.4	80.6	74.0
Infinite dilution cross section (barn)	2.62×10^{3}	2.62×10^{3}	2.62×10^{3}
Effective cross section (barn)	1.88×10^{3}	1.55×10^{3}	1.01×10^{3}
Resonance shielding factor (-)	0.718	0.592	0.386
Background cross section (barn)			
Total	5.03×10^{3}	2.20×10^{3}	3.72×10^{2}
Volume term	2.56×10^{3}	6.79×10^{1}	7.25×10^{1}
Surface term	2.47×10^{3}	2.14×10^{3}	2.99×10^{2}
Spatial shielding factor (-)	0.875	0.761	0.483



*This figure was redrawn by referring to Oigawa, H.

Fig. 1 Potential toxicity of each nuclide in spent fuel of uranium fueled LWR

Y. Fukaya:

Study on Erbium Loading Method to Improve Reactivity Coefficients for Low Radiotoxic Spent Fuel HTGR

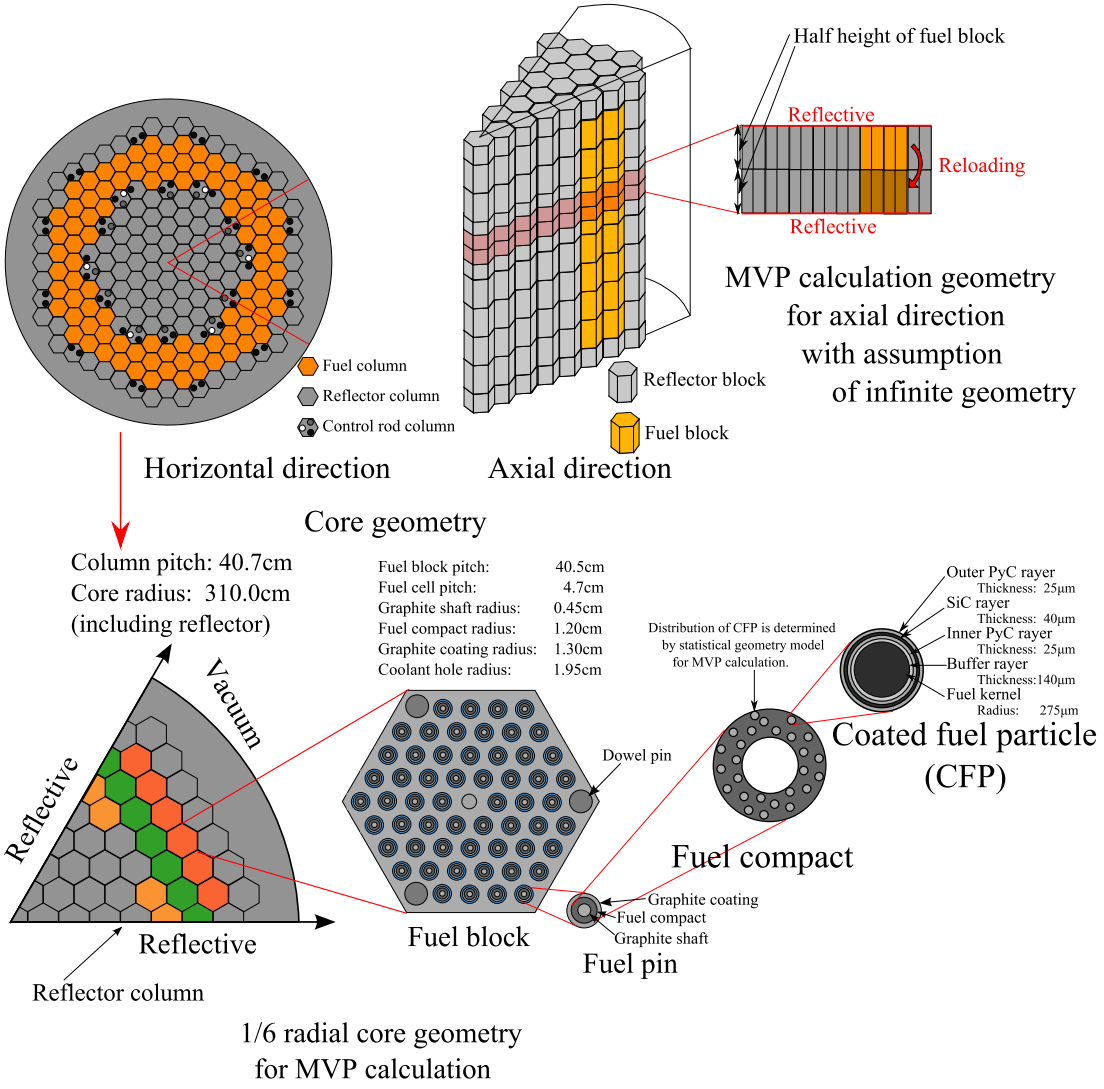


Fig. 2 Core geometry of GTHTR300 and its calculation model

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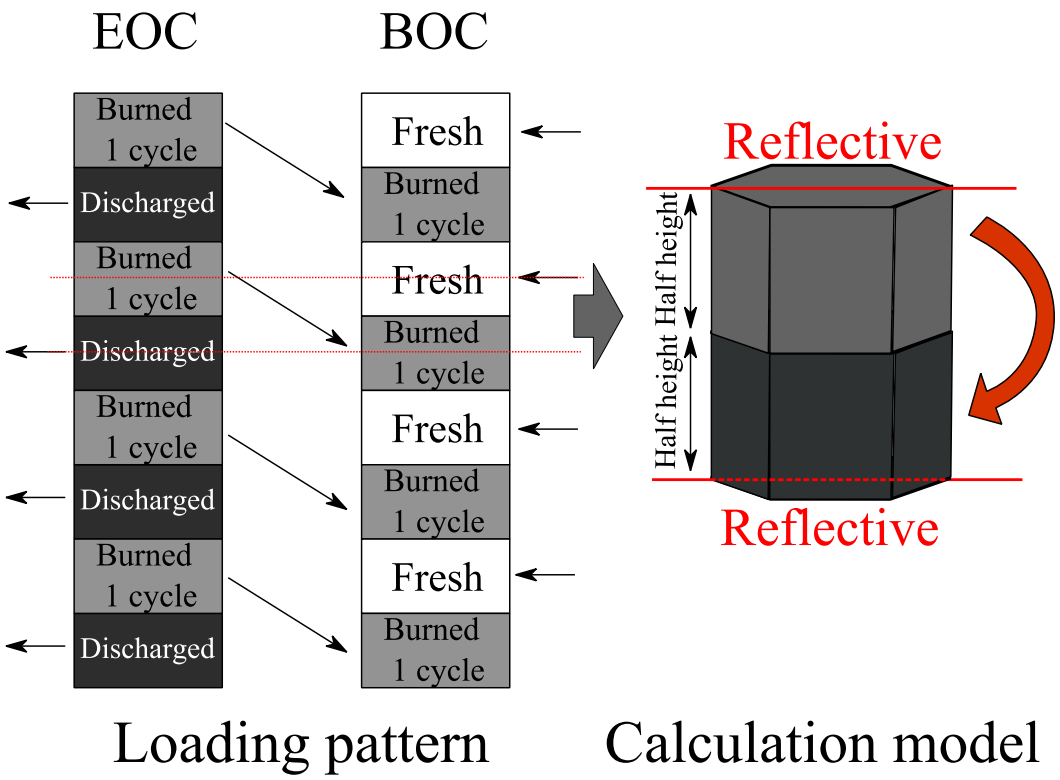

Fig. 3 Loading pattern and its calculation model

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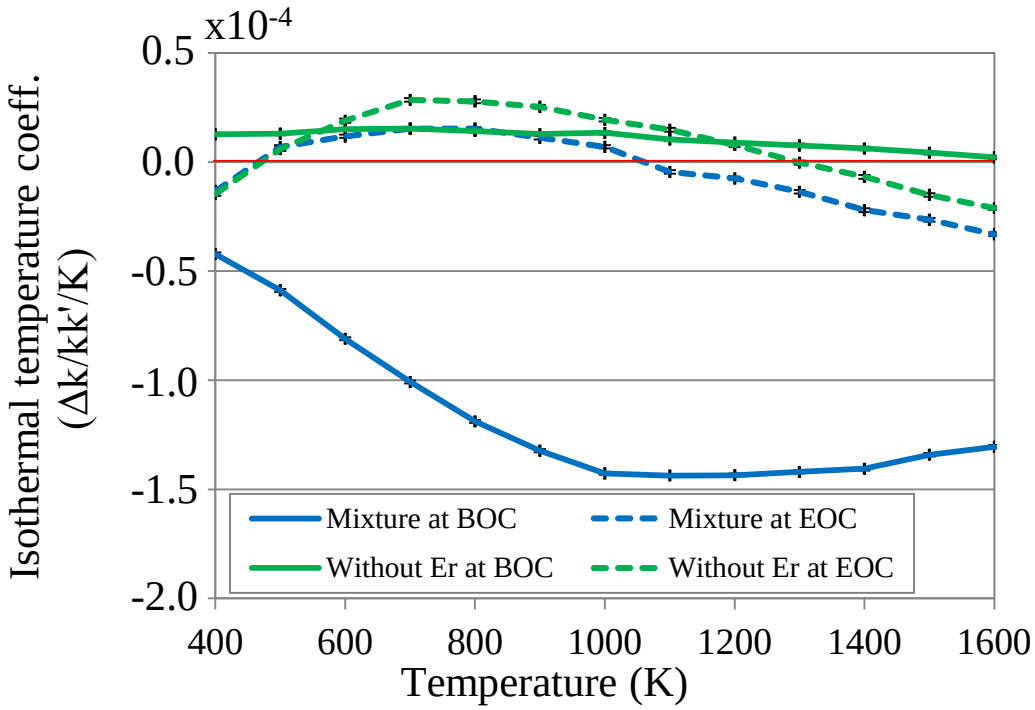
Study on Erbium Loading Method to Improve Reactivity Coefficients for Low Radiotoxic Spent Fuel HTGR



* The error bar corresponds to 1 σ .

Fig. 4 Reactivity coefficients of LRSF-HTGR without erbium loading and with erbium mixed into fuel kernel

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Study on Erbium Loading Method to Improve Reactivity Coefficients for Low Radiotoxic Spent Fuel HTGR

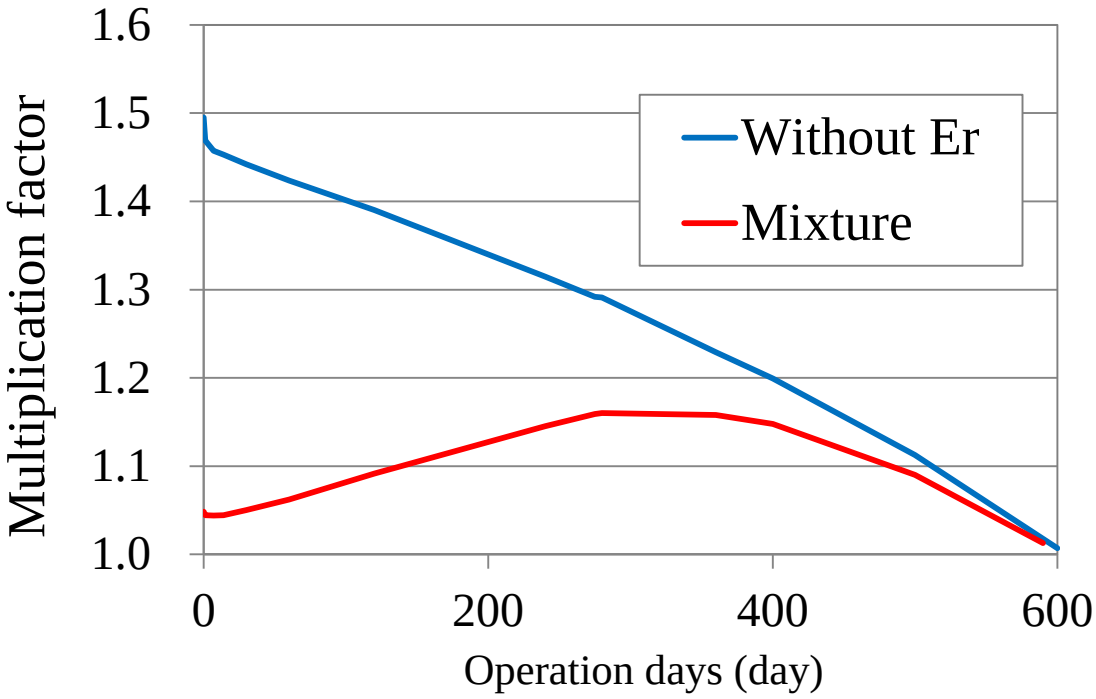

Fig. 5 Criticality of LRSF-HTGR without erbium loading and with erbium mixed into fuel kernel

Y. Fukaya:

Study on Erbium Loading Method to Improve Reactivity Coefficients for Low Radiotoxic Spent Fuel HTGR

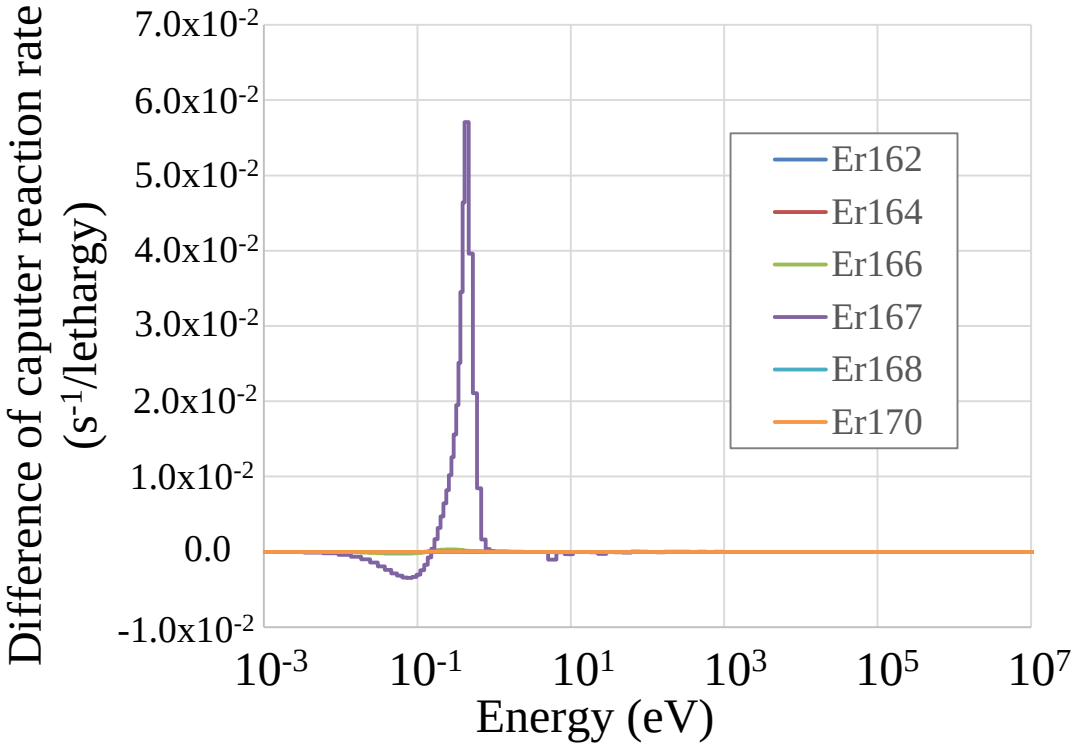

Fig. 6 Difference in neutron capture reaction rate of erbium nuclides at 800K and 700K

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Study on Erbium Loading Method to Improve Reactivity Coefficients for Low Radiotoxic Spent Fuel HTGR

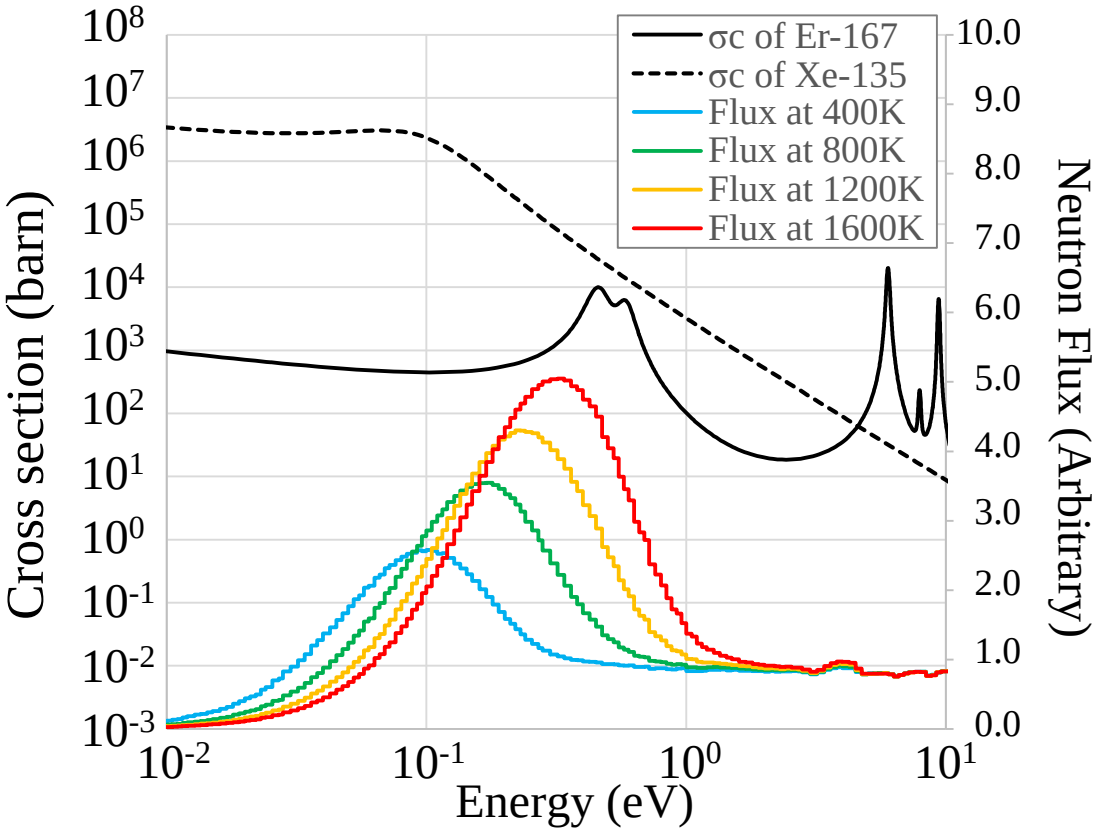

Fig. 7 Capture cross sections with 1/v characteristics and neutron fluxes at each temperature

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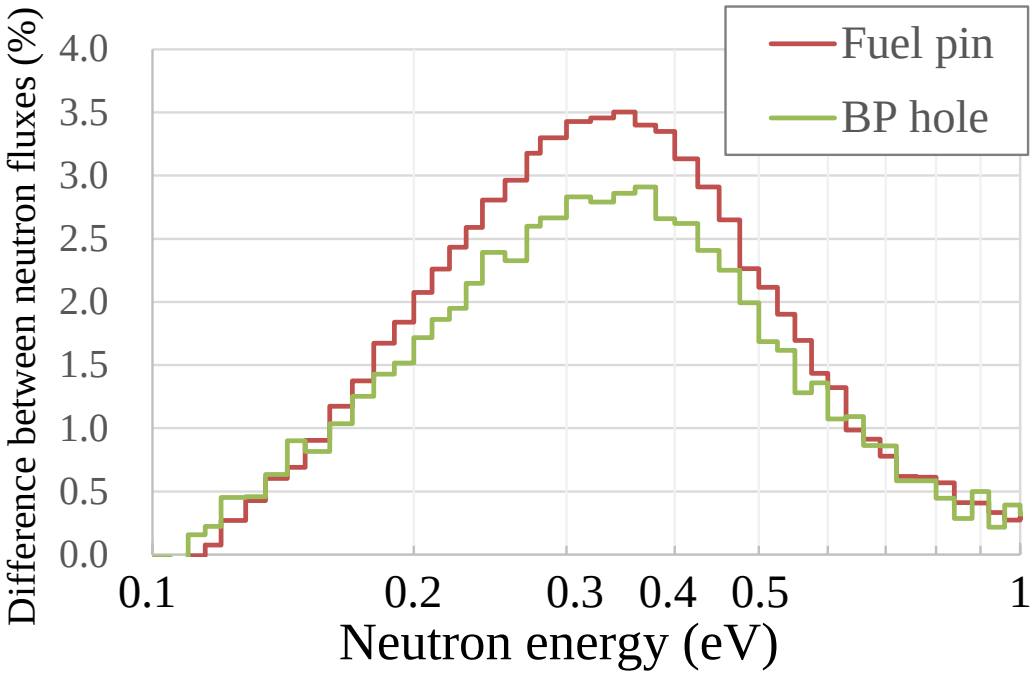

Fig. 8 Flux changes because of temperature increase of 100 K in each region

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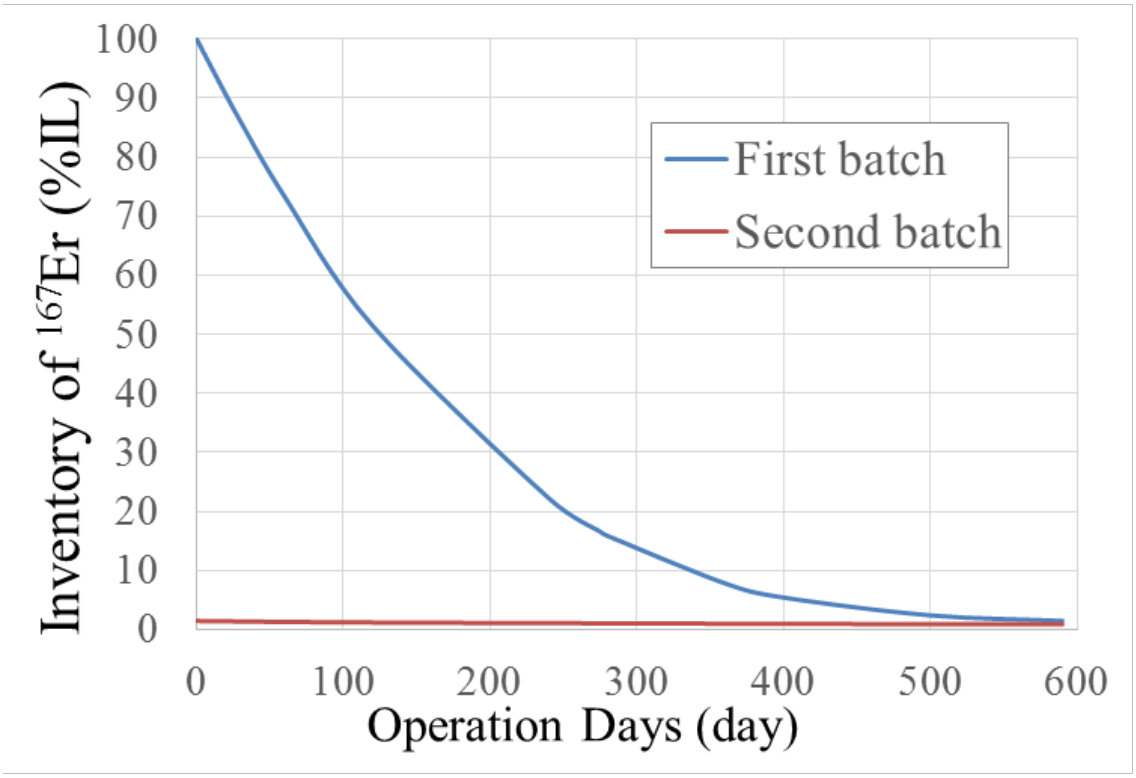

*IL stands for initial loading.

Fig. 9 Change in erbium-167 inventory with number of operation days

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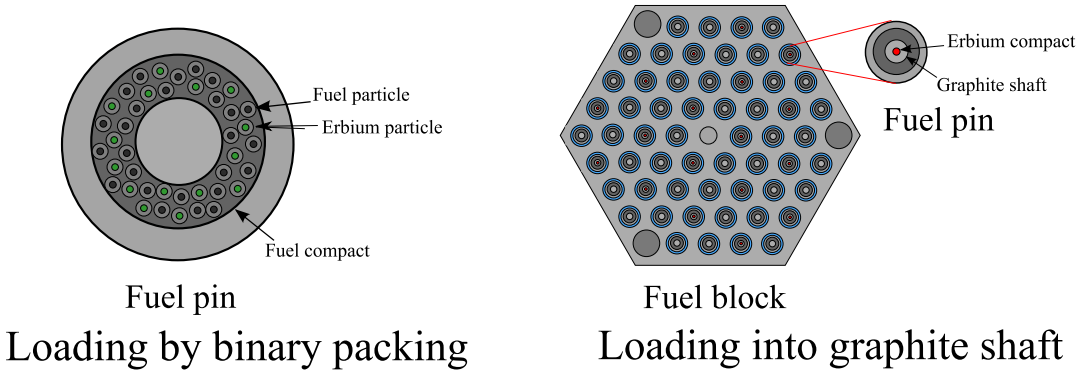

Fig. 10 Erbium-loading method

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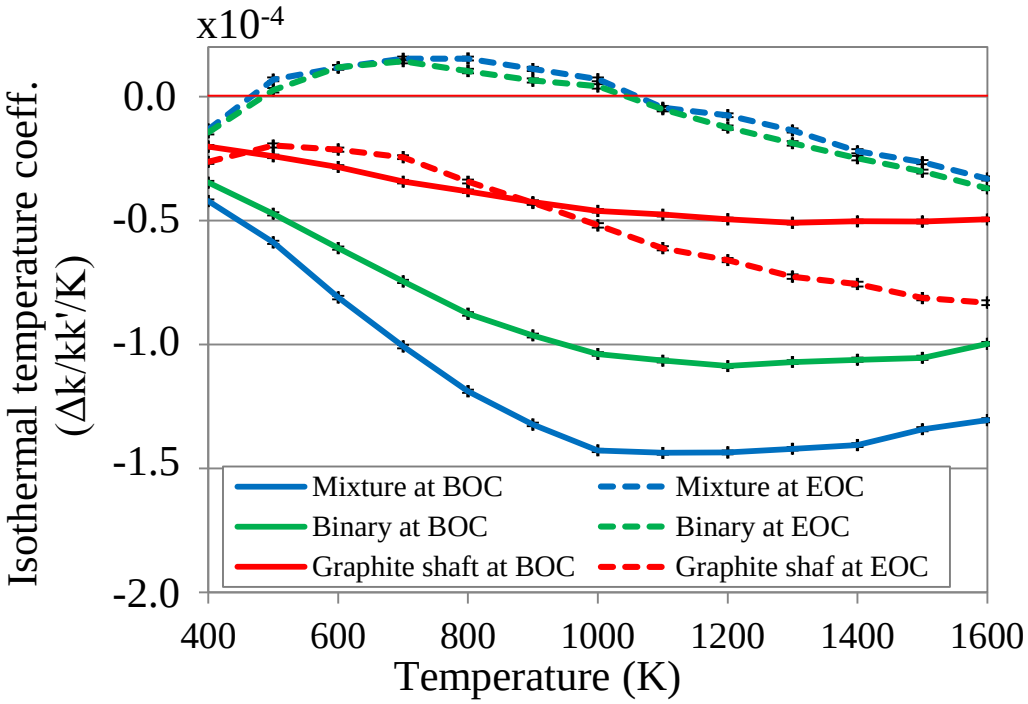
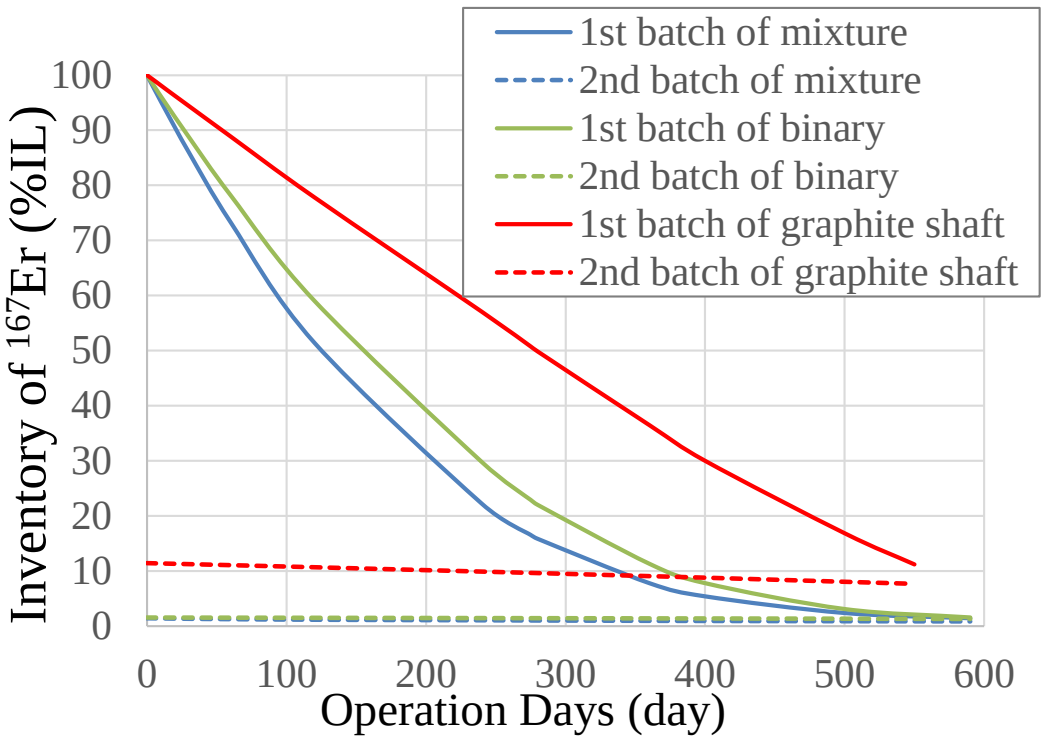


* The error bar corresponds to 1 σ .

Fig. 11 Reactivity coefficient for each candidate of erbium-loading method



*IL stands for initial loading.

Fig. 12 Change in erbium-167 inventory with number of operation days for each candidate method

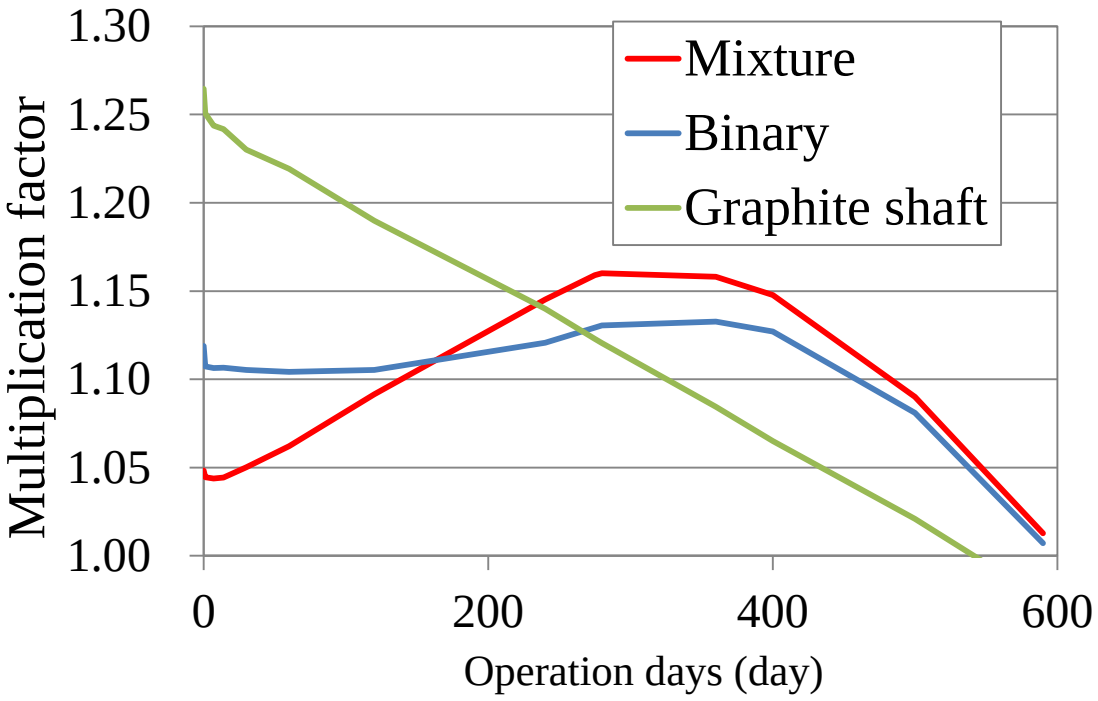


Fig. 13 Change on erbium-167 inventory with number of operation days for each candidate method