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Loading method of Li rods for tritium production using High-Temperature Gas-Cooled reactor for fusion reactors

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A B S T R A C T

An initial tritium inventory is required to start fusion DEMOnstration Power Station (DEMO) reactors. However, a method to supply adequate tritium has not been determined yet. Tritium production via ^{6}Li(n,α)T reaction by loading Li rods into the burnable poison (BP) holes of a high-temperature gas-cooled reactor (HTGR) has been proposed to address this problem (Matsuura et al., Nucl. Eng. Des. 243 (2012) 95 – 101). In previous preliminary studies, Li rods loaded in all BP holes were assumed to have the same design. This study evaluated whether the performance of Li rods can be improved for future optimization by adjusting the Li rod arrangement and the amount of Li compounds in them. The amount of tritium produced for gas turbine high-temperature reactor 300 (GTHTR300) was evaluated, while the total amount of Li compounds was maintained and the amount of loaded Li compounds changed depending on the layers and fuel regions. The maximum amount of tritium produced did not increase during the evaluations when reactor feasibility was satisfied. This implies that it is possible to reduce the number of Li rods while maintaining the amount of tritium produced for optimization, thereby reducing the costs of manufacturing Li rods and tritium recovery. GTHTR300 can produce 800 g of tritium in 360 days of operation using 2160Li rods. The results showed that the same amount of tritium could be produced by loading 720Li rods with the same number of fuel blocks. In addition, the effective multiplication factor, burn up, and power density of GTHTR300 were not significantly influenced during the operation.

1. Introduction

A method for supplying tritium using an external source is required to precisely plan an engineering test of tritium circulation and to prepare initial tritium in the DEMOnstration Power Station (DEMO) (Botter et al., 1986). Tritium for the International Thermonuclear Experimental Reactor was produced in the Canadian Deuterium Uranium (CANDU) reactor via the D(n,γ)T reaction (Gierszewski, 1989). However, uncertainty regarding the tritium supply for DEMO reactors is increasing. Tritium production using high-temperature gas-cooled reactors (HTGRs) has been proposed as a method for supplying tritium (Goto et al., 2018). Tritium production analyses were conducted assuming that Li compounds were loaded in the HTGR as burnable poisons (BPs) instead of boron compounds (B4C). HTGRs have several advantages for tritium production. First, the cross-section of ^{6}Li(n,α)T used for the HTGRs is almost six orders of magnitude larger across the thermal neutron energy range compared to the D(n,γ)T reaction used for the CANDU reactors. Second, the HTGR structure consists of graphite, which is chemically stable and does not react with Li compounds. Third, although the large reactor size of the HTGR is not attractive from the perspective of economy, there is sufficient space to place sufficient Li compounds and tritium barrier without ^{6}Li enrichment. B_4C (genuine BP) in the standard design is loaded in the solid state separately from the fuel components. Therefore, Li compounds can be loaded into the

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reactor core without significantly changing the original structural design. The nuclear characteristics and fuel temperature conditions were analyzed to confirm the thermal and nuclear stability of Li-loaded HTGRs (Hollenberg, 1986); which confirmed that the safety requirements of the design were satisfied. Currently, an HTGR is being researched that produces tritium with a power generation performance similar to that of the standard specification (when B_4C was loaded as BP). A schematic of the Li rod structure of the HTGRs is shown in Fig. 1. The Li rods have Ni-coated Zr and $LiAlO_2$ in sealed cylinder-shaped high-density Al_2O_3 to decrease the leakage of tritium during high-temperature operation (approximately 900 ℃).

The amount of tritium produced from 2160Li rods loaded in gas turbine high-temperature reactor 300 (GTHTR300) (Katayama et al., 2015) was simulated to be 500–800 g over 360 days of operation (Kawamura et al., 1992). In previous studies, it has been assumed that Li rods loaded in all BP holes have the same design for preliminary evaluations. Additionally, the characteristics of the effective multiplication factor (keff) were different from those of the standard specifications (Katayama et al., 2015). It has been considered that the amount of tritium produced in the GTHTR300 is 500–600 g/year by loading same design Li rods with natural abundance ^{6}Li into whole of the reactor on the real operation, and k_{eff} was analyzed to be about 1.05 after 360 days of operation. We have been focused on 800 g/year tritium production on our studies to challenge furthermore performance. The purpose of this study is to evaluate whether the performance of Li rods and the reactor characteristics of GTHTR300 can be improved for future optimization by the Li rod arrangement and the amount of Li compounds in them.

2. Calculation model

2.1. HTGR design and Li rod structures

A schematic of the GTHTR300 core is shown in Fig. 2. The GTHTR300 is an HTGR design with a thermal output of 600 MWt (300 MWe), created by the Japan Atomic Energy Agency. The GTHTR300 core had a ring-shaped structure consisting of 90 fuel columns, 30 control rod guide columns, and 46 replaceable reflector columns. The core was surrounded by permanent reflector columns both inside and outside. There were eight core layers between the two reflector layers vertically. The core has a height of 8 m and diameter of approximately 5.6 m. The height and width across the flats of the hexagonal block were 1,000 and 405 mm, respectively. The fuel blocks contained 57 fuel rods and three BP holes. The enrichment of ^{235}U was 14 wt% in all the fuel rods. The fuel columns in the core are divided into three fuel regions horizontally, as shown in Fig. 2. Each fuel region was given an identification number: 1–1 to 8–3. 1–2 implies the fuel regions 2 in layer 1 for example.

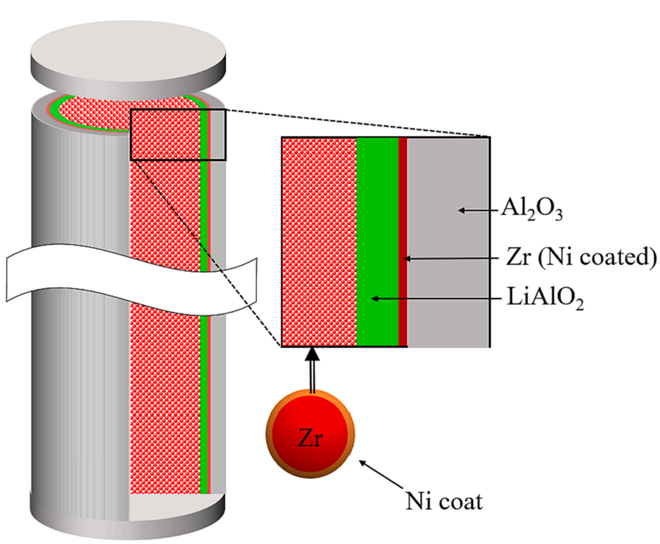

Fig. 1. Schematic of Li rod structure.

The design of proposed Li rod for GTHTR300 is shown in Fig. 3(a) (Koga, 2022). These Li rods were 1000 mm in height and 44 mm in diameter. They consisted of a hollow portion, Li compound (LiAlO2) with 85 % theoretical density (Kunitomi et al., 2004), Zr layer/particles, and an Al_2O_3 layer. The concentration of ^{6}Li in $LiAlO_2$ is naturally abundant. The inserted Zr particles occupied 60 % of the hollow portion excluding Zr layer and $LiAlO_2$ volume. This Li rod design is referred to as a layer type Li rod to distinguish from following one. There is a limit to the amount of ^{6}Li that can be loaded into the Li rod if the intent is to increase the amount of $LiAlO_2$. This was due to the natural abundance of ^{6}Li in the Li rods. Therefore, a Li rod model with high enrichment ^{6}Li was utilized. The Li rod model for the GTHTR300 used in this study is shown in Fig. 3(b). The enrichment of ^{6}Li was 90 at%, and $LiAlO_2$ was particle shaped. It was assumed that Li with an enrichment of ^{6}Li lower than 90 at% would not be manufactured for fusion reactors. The amount of loaded Zr was increased by decreasing the $LiAlO_2$ volume with increasing ^{6}Li concentration. This Li rod model is referred to as a particle type Li rod.

2.2. Nuclear calculation

Nuclear calculations from the continuous-energy Monte Carlo transport code MVP-BURN (Matsuura, 2017; Matsuura, 2021) using the Japanese Evaluated Nuclear Data Library-4.0 (JENDL-4.0) (Matsuura et al., 2012) were utilized to evaluate the amount of tritium produced in the Li rods and the effective multiplication factor k_{eff}. It was assumed that the GTHTR300 core system had Li rods loaded into all BP holes, and the operation period was 360 days. In addition, the amount of loaded $LiAlO_2$ can be changed in each fuel region. The average moderator temperature of the Li rods for GTHTR300 was set to 1170 K. It was assumed that all control rods were pulled up during the simulations. The k_{eff} on day 360 must be greater than 1.02, because this is the minimum amount of k_{eff} required for the actual reactor operation. The time steps for the burn-up simulation were set to 0, 1, 5, 30, 60, 120, 180, and 360 days. The thermal output of the GTHTR300 throughout the operation was set to 600 MW. Additionally, 6 000 000 neutron particles were generated at each time step such that the statistical error was guaranteed to be less than 0.1 % for the k_{eff} and reaction rates of nuclides to be burned or transmuted.

2.3. Tritium absorption model for Zr

Diffusion calculations using the diffusion equation and Sieverts' law were conducted to evaluate the tritium absorption rate of Zr. The Zr particles and Zr layer were converted into a Zr cylinder with the same surface area for simpler evaluation. The diffusion equation used to calculate the tritium concentration distribution in Zr for a cylindrical coordinate system is expressed as follows:

$$\frac{\partial C_{Zr}(r_{Zt},t)}{\partial t} = \frac{D_{Zr}}{r_{Zr}}\frac{\partial}{\partial r_{Zt}}\left(r_{Zr}\frac{\partial C_{Zr}(r_{Zt},t)}{\partial r_{Zr}}\right) \quad (1)$$

where C_{Zr}, t, D_{Zr}, and r_{Zt} are the tritium concentration in Zr (mol/m^3), elapsed time (s), diffusion coefficient of Zr (m^2/s), and distance in the radial direction (m), respectively. Sieverts' law was used as the boundary condition for the Zr cylinder surface and is expressed as

$$C_{Zr0} = S_{Zr}\sqrt{P} \quad (2)$$

where C_{Zr0}, S_{Zr}, and P are the tritium concentration in the Zr cylinder surface (mol/m^3), the solubility coefficient of Zr (mol/m^3/Pa$^{1/2}$), and the tritium partial pressure (Pa), respectively. Subsequently, C_{Zr} was integrated into the Zr volume and differentiated in time to evaluate the amount of tritium absorbed in Zr using the following equation:

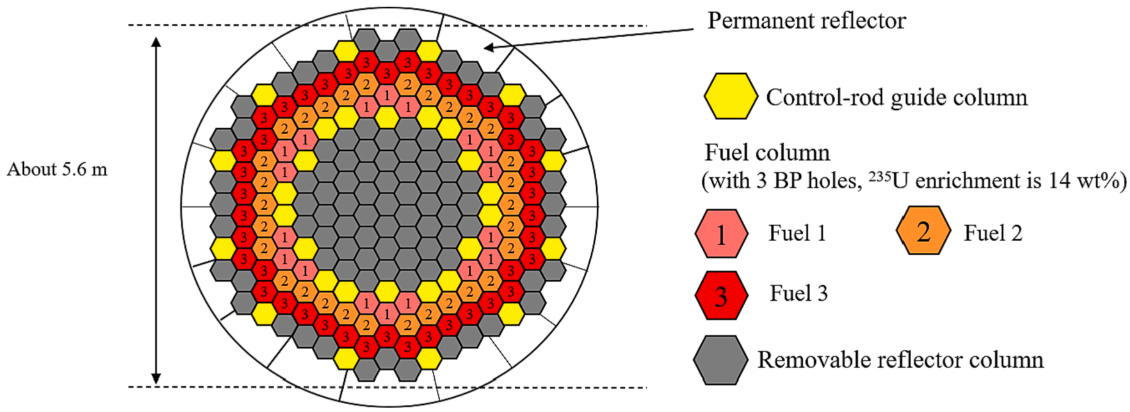

Fig. 2. Schematic of the GTHTR300 core. The GTHTR300 consists of eight core layers. The fuel columns in the core were divided into three fuel regions in this study.

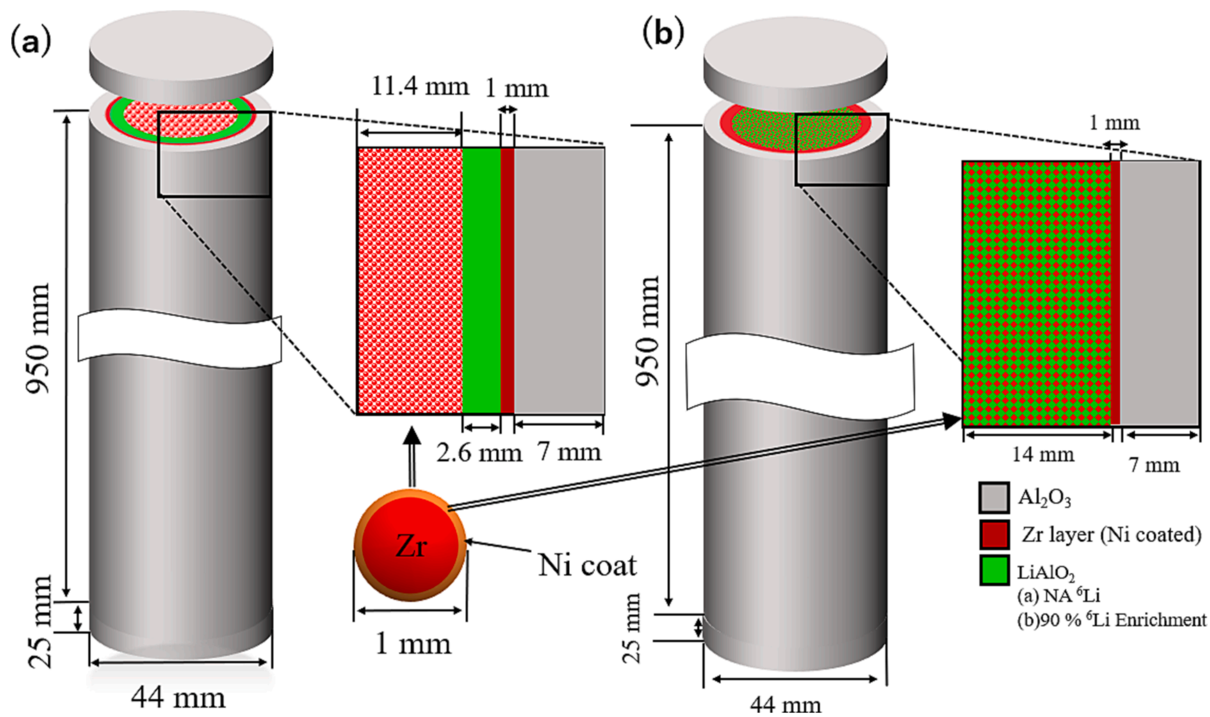

Fig. 3. Schematics of proposed Li rod designs for the GTHTR300. Layer type Li rod (b) Particle type Li rod.

$$J_{Zr} = -\frac{\partial}{\partial t}\int_{V_{Zr}} C_{Zr}(t,r)d^3r \tag{3}$$

where J_{Zr} and V_{Zr} are the tritium flux from the Zr surface (mol/s) and the volume of the assumed Zr cylinder (m^3), respectively. Matsuura et al. obtained the D_{Zr} and S_{Zr} values at 1170 K (Matsuura et al., 2019). Furthermore, D_{Zr} was reduced by 1/2000 to consider the reported influence of Ni coating and LiAlO2 (Nagaya, 2017). The temperature effect of this reduction was small on the four temperature conditions in the experiment, and it was neglected for this study.

2.4. Tritium leakage model for Al_2O_3 layer

To evaluate the tritium leak rate, a tritium diffusion equation in cylindrical coordinates was used, which is expressed as

$$\frac{\partial C_{Al}(r_{Al},t)}{\partial t} = \frac{D_{Al}}{r_{Al}}\frac{\partial}{\partial r_{Al}}\left(r_{Al}\frac{\partial C_{Al}(r_{Al},t)}{\partial r_{Al}}\right) \tag{4}$$

where C_{Al}, t, D_{Al}, and r_{Al} are the tritium concentration in the Al_2O_3 layer (mol/m^3), elapsed time (s), diffusion coefficient of the Al_2O_3 layer (m^2/s), and distance in the radial direction (m), respectively. Sieverts' law was used as the boundary condition, similar to the Zr tritium absorption model, and is expressed as

$$C_{Al0} = S_{Al}\sqrt{P} \tag{5}$$

where C_{Al0}, S_{Al}, and P are the tritium concentrations in the inner surface of the Al_2O_3 layer (mol/m^3), solubility coefficient of the Al_2O_3 layer ($mol/m^3/Pa^{1/2}$), and tritium partial pressure in the hollow portion (Pa), respectively. The D_{Al} and S_{Al} values were obtained by Katayama et al. (Nakata, 2002). Fick's law was used to calculate the amount of permeated tritium in the inner and outer surfaces of the Al_2O_3 layer, which is expressed as

$$J_{in,out} = -A_{in,out}D_{Al}\left.\frac{\partial C_{Al}}{\partial r_{Al}}\right|_{in,out} \tag{6}$$

where J_{in}andJ_{out} are the tritium fluxes from the inner surface of the Al_2O_3 layer and inside the Al_2O_3 layer to inside the Al_2O_3 layer and outer surfaces of the Al_2O_3 layer (mol/s), respectively. A_{in} and A_{out} are the inner and outer surface areas of the Al_2O_3 layer (m^2), respectively. J_{in} represents the tritium leakage rate. The tritium in the outer surface of the Al_2O_3 layer was assumed to immediately leak into the He coolant; therefore, the tritium concentration in the outer surface was set at 0. Finally, **Eqs.** (3)–(6) were combined with the tritium balance equation to evaluate tritium absorption and leakage:

$$\frac{dP}{dt} = \frac{GRT}{V_{hp+Li(15)}} + \frac{J_{Zr}RT}{V_{hp+Li(15)}} + \frac{J_{in}RT}{V_{hp+Li(15)}} \tag{7}$$

where G, R, and $V_{hp+Li(15)}$ are the tritium molecule generation speed at the tritium production rate (mol/s), gas constant (J/K mol), and volume of the hollow portion and void of the $LiAlO_2$ layer in the Li rod (m^3), respectively. The anti-permeation property of Zr, which prevents tritium from permeating into the Al_2O_3 layer, was ignored for conservative evaluation. This tritium leakage calculation is sufficiently accurate compared to a highly accurate evaluation (Matsuura et al., 2019).

3. Results and discussion

3.1. Performance evaluation of particle type Li rod

In this study, the amount of tritium produced, and reactor characteristics were evaluated by changing the amount of $LiAlO_2$ in the particle type Li rods depending on the layers and fuel regions. There is a possibility that the amount of tritium produced and reactor characteristics for the GTHTR300 is affected by replacing the layer type Li rods (Fig. 3(a)) to the particle type Li rod (Fig. 3(b)) because the self-shielding effect is weakened by uniformly loading particle $LiAlO_2$ into Li rods. First of all, the influences on produced/leaked tritium, k_{eff}, fuel burnup, and power densities for the GTHTR300 while using particle type Li rod were evaluated in this section. The cumulative amounts of tritium produced and k_{eff} throughout 360 days of operation for the GTHTR300 when the layer type or particle type Li rods were loaded are shown in Fig. 4. The total amount of loaded ^{6}Li for the layer type and particle type Li rods in the entire reactor were 6554 and 6249 g, respectively, which produced approximately 800 g of tritium after 360 days of operation. k_{eff} decreased sharply at the beginning of the operation by generation of Xe. The negative reactivity for Li rods decreases with the amount of ^{6}Li by tritium production. However, the reactivity less decreased than that for ^{10}B contained in B_4C BPs with operation time and k_{eff} decreased straightly. The transmutation performance of the particle type Li rod was better than that of the layer type because particle $LiAlO_2$ was loaded more uniformly with Zr particles: effective ^{6}Li density for neutrons reduced and self-shielding effect was weaken. Therefore, the amount of loaded $LiAlO_2$ was reduced in the particle type Li rod. The k_{eff} was almost same in each step for the two cases. The cumulative amounts of leaked tritium throughout the 360 days of operation for the two cases are shown in Fig. 5. The amount of leaked tritium decreased by 27 % because more particle Zr was loaded into the particle type Li rods. Next, the fuel burnup and power density were compared to those when B_4C BPs were loaded. It was important to confirm the reactor feasibility for operation, as in the research conducted by Goto et al. (Hollenberg, 1986), because the loading method of the Li rods was changed. The fuel burnups in each fuel region when the B_4C BPs or Li rods are loaded are shown in Fig. 6. The numbers on the horizonal axis denote layer and fuel region, respectively. For example, 1–2 implies the fuel regions 2 in layer 1. There was no significant difference in fuel burnup with changes in BP. The burnup for the particle type Li rods was almost the same as the results for the layer type; therefore, they were omitted. The power densities in each fuel region when the B_4C BPs are loaded are shown in Fig. 7. The numbers on the horizonal axis denote the same as those in Fig. 6. The maximum power density was approximately 9 W/cm^3, which did not exceed the design data of GTHTR300 (Nishikawa et al., 2012). The power density distributions were different because the control rods were inserted into the reactor in the calculations of the design data. Therefore, the distributions of the fuel burnup and power density when B_4C BPs are used should be similar to those when Li rods are used. To guarantee reactor feasibility, the fuel burnup and power density in each fuel region must not exceed 42 GWd/t and 9 W/cm^3, respectively. The power densities in each fuel region when the layer type Li rods were loaded are shown in Fig. 8. The power densities for the particle type Li rods were similar to the results for burnup, and hence they were omitted. The power density values and distributions were similar to those of the B_4C BPs. The feasibility of the reactor was confirmed when the particle type Li rods were uniformly loaded. The particle type Li rod was used for subsequent evaluations.

3.2. Evaluations of the effect on tritium production performance by changing $LiAlO_2$ distribution

The amount of tritium produced and reactor characteristics can be influenced by changing $LiAlO_2$ distribution on in the vertical (layers) and radial direction (three fuel regions). These influences were evaluated when the loaded $LiAlO_2$ distribution was changed on fuel regions of the GTHTR300 while maintaining the total amount of $LiAlO_2$ loaded into the entire reactor constant in this section. At first, the influences were evaluated when the loaded $LiAlO_2$ distribution was changed in vertical direction. The loading ratios of $LiAlO_2$ (%) on the layers of the GTHTR300 for each calculation case are listed in Table 1. The

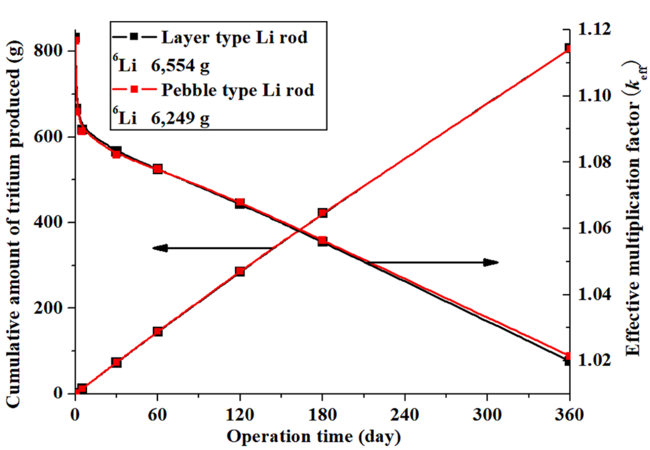

Fig. 4. The cumulative amount of produced tritium and the k_{eff} value throughout the 360 days of operation for the GTHTR300 with Li rods shown in Fig. 3.

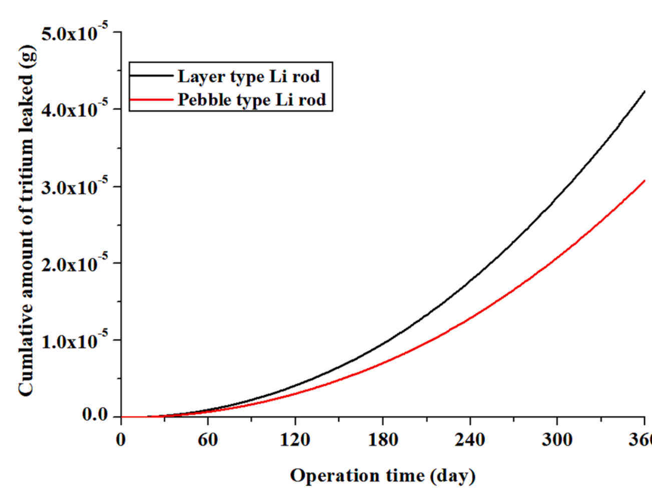

Fig. 5. The cumulative amounts of leaked tritium throughout the 360 days of operation for the Li rods shown in Fig. 3 in the operation of Fig. 4.

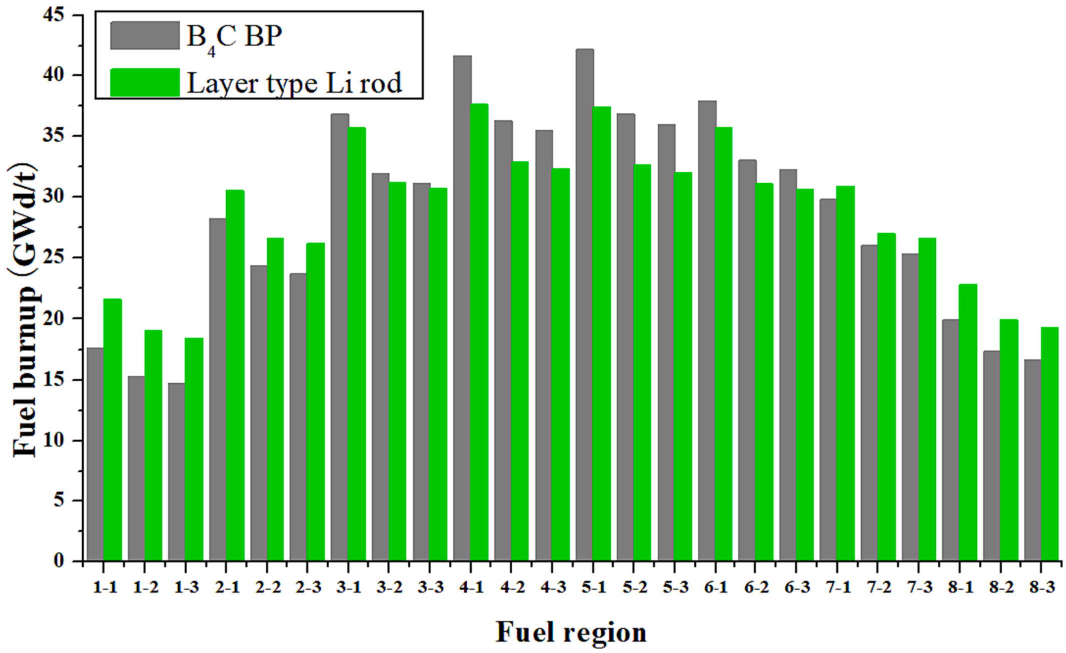

Fig. 6. The fuel burnups in each fuel region for the GTHTR300 when the B_4C BPs or layer type Li rods were loaded. The numbers on the horizonal axis denote layer and fuel region, respectively. 1–2 implies the fuel regions 2 in layer 1, and so on. The results for the particle type Li rods were almost identical to those shown in green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

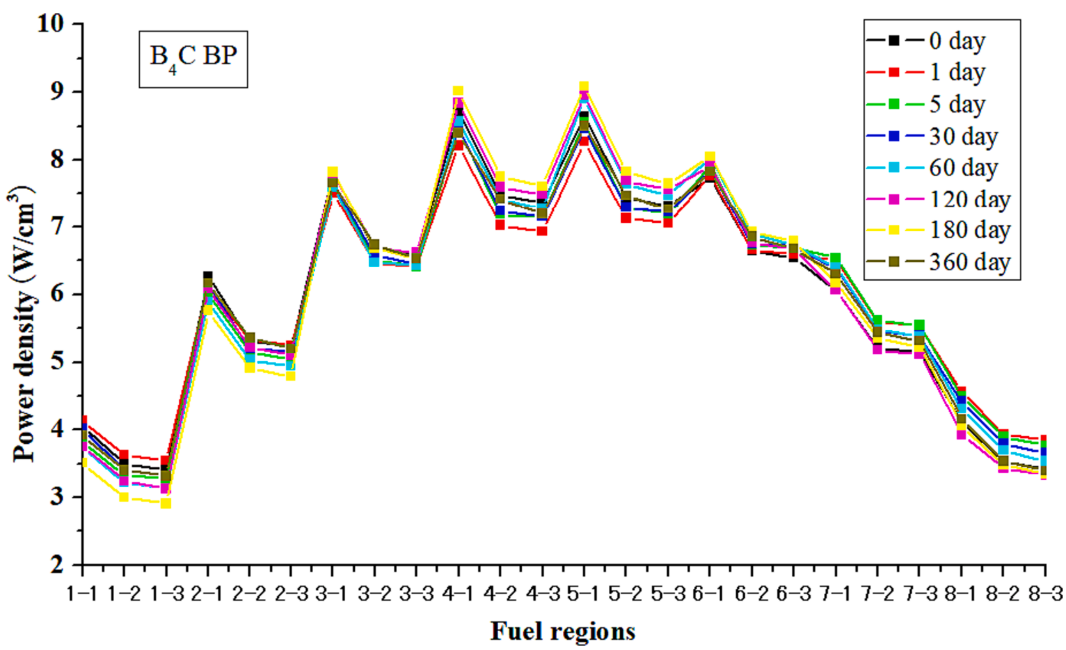

Fig. 7. The power densities in each fuel region for the GTHTR300 when the B_4C BPs were loaded. The numbers on the horizonal axis denote the same as those in Fig. 6.

percentage of loading ratios was set to be 100 % when the amount of $LiAlO_2$ was the same as that the $LiAlO_2$ distribution was uniformly. Therefore, Case 6 is the same condition as that of section 3.1. The loaded $LiAlO_2$ was biased towards the center or outside of the layers, because the neutron flux was higher in the center layers. The amount of tritium produced and k_{eff} after 360 days of operation in Cases 1–11 are shown in Fig. 9. With the increase in $LiAlO_2$ loading in the center layers, the amount of tritium increases and k_{eff} decreases. However, it can be observed that the amount of tritium that was produced decreased slightly from Case 10, and k_{eff} was the minimum in Case 9. This is because the increase in transmutation rate of ^6Li in the center layers due to the addition of $LiAlO_2$ was less than the decrease in transmutation rate in the outer layers due to the reduction of $LiAlO_2$. Therefore, k_{eff} started increasing from Case 9 owing to the decrease in the amount of tritium produced.

Next, the influence of the loaded $LiAlO_2$ distribution in the radial direction was evaluated. The loading ratios of $LiAlO_2$ (%) in the radial direction of the GTHTR300 for each calculation case are listed in Table 2. The loaded $LiAlO_2$ was biased towards the center (1) or outside (2, 3) of the fuel regions. Cases 17 was the same conditions to Case 6.

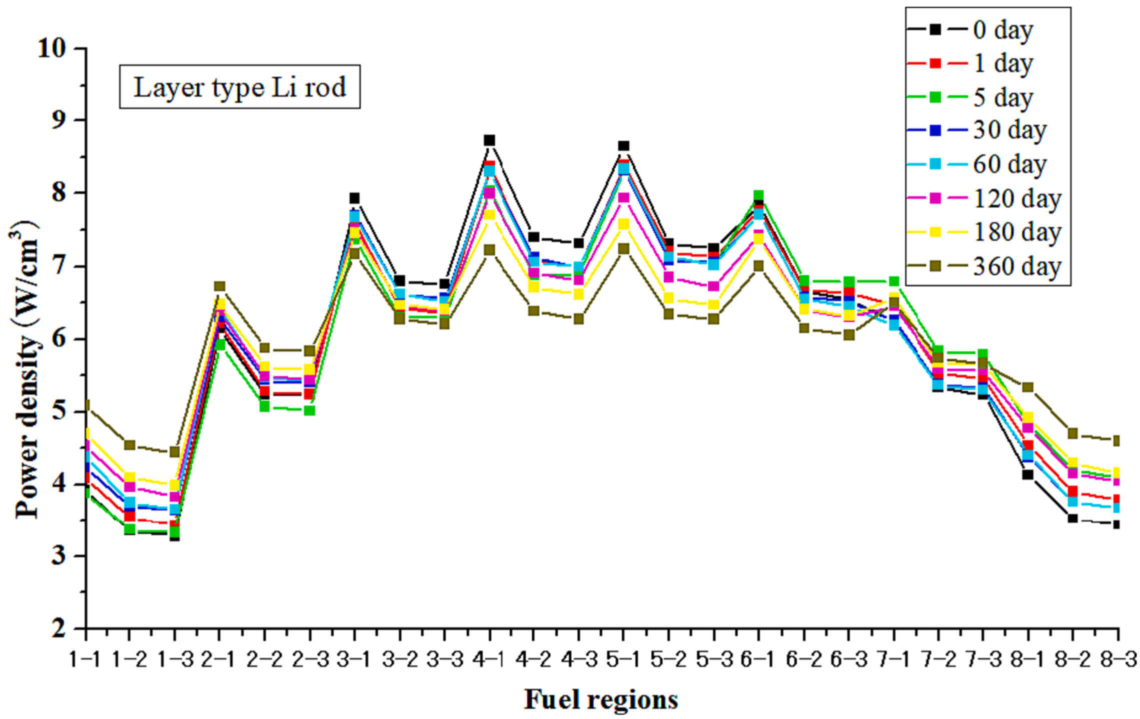

Fig. 8. The power densities in each fuel region for the GTHTR300 when layer type Li rods. The horizontal axis denotes layer and fuel region, respectively. The results for the particle type Li rods were almost identical to these.

Table 1
The loading ratios of $LiAlO_2$ (%) on the layers of GTHTR300 for each calculation case.

		Calculation case										
		1	2	3	4	5	6	7	8	9	10	11
Layer	1, 8	115	112	109	106	103	100	97	94	91	88	85
	2, 7	105	104	103	102	101	100	99	98	97	96	95
	3, 6	95	96	97	98	99	100	101	102	103	104	105
	4, 5	85	88	91	94	97	100	103	106	109	112	115

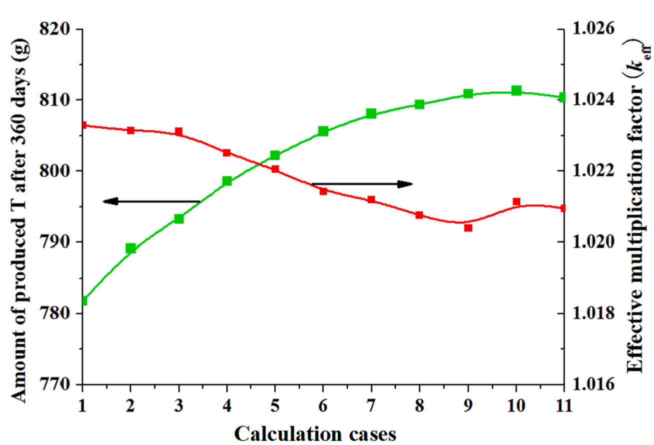

Fig. 9. The amount of produced tritum and k_{eff} values after 360 days of operation when the $LiAlO_2$ distribution was changed in layers of the GTHTR300.

The amount of tritium produced and k_{eff} after 360 days of operation in Cases 12 – 22 are shown in Fig. 10. The amount of tritium produced increased with increasing loading of $LiAlO_2$ outside and decreased after the peak in Case 16. However, k_{eff} was at a minimum in Case 16, which was inversely proportional to the produced tritium. This is because the increase in transmutation rate of ^{6}Li in the fuel regions due to the addition of $LiAlO_2$ was less than the decrease in transmutation rate in the other regions due to the reduction of $LiAlO_2$. Therefore, k_{eff} started increasing from Case 16.

Overall, the maximum amount of tritium produced was approximately 800 g when the amount of $LiAlO_2$ changed, depending on the layers and fuel regions, while maintaining the total amount of Li. In addition, the amount of tritium produced reached approximately 800 g in all cases if the operation time was adjusted until k_{eff} decreased to 1.02. This demonstrates that effective optimization can occur while maintaining the amount of tritium produced.

3.3. Evaluations of the effect on tritium production performance by reducing the number of loaded Li rods

3.3.1. Reducing the number of Li rods in all fuel regions uniformly

Reducing the number of Li rods while maintaining the amount of tritium produced was considered for one of the optimizations. The amount of loaded ^{6}Li to produce 800 g/y tritium by a smaller number of Li rods and reactor characteristic were evaluated. It is clear that the distributions of burnup and power density were extremely distorted, and reactor feasibility was not assured for operation if there were fuel regions without Li rods. Therefore, it is noted that the amounts of loaded $LiAlO_2$ were uniform in all Li rods and at least one Li rod was placed in the fuel block during the subsequent examination. The amount of tritium produced and k_{eff} throughout the 360 days of operation based on

Table 2
The loading ratios of $LiAlO_2$ (%) in the radial direction of the GTHTR300 for each calculation case.

		Calculation case										
		12	13	14	15	16	17	18	19	20	21	22
Fuel region	1	179.2	133.3	147.5	137.7	115.8	100	84.2	68.3	52.5	36.7	20.8
	2	87.5	90	92.5	95	97.5	100	102.5	105	107.5	110	112.5
	3	75	80	85	90	95	100	105	110	115	120	125

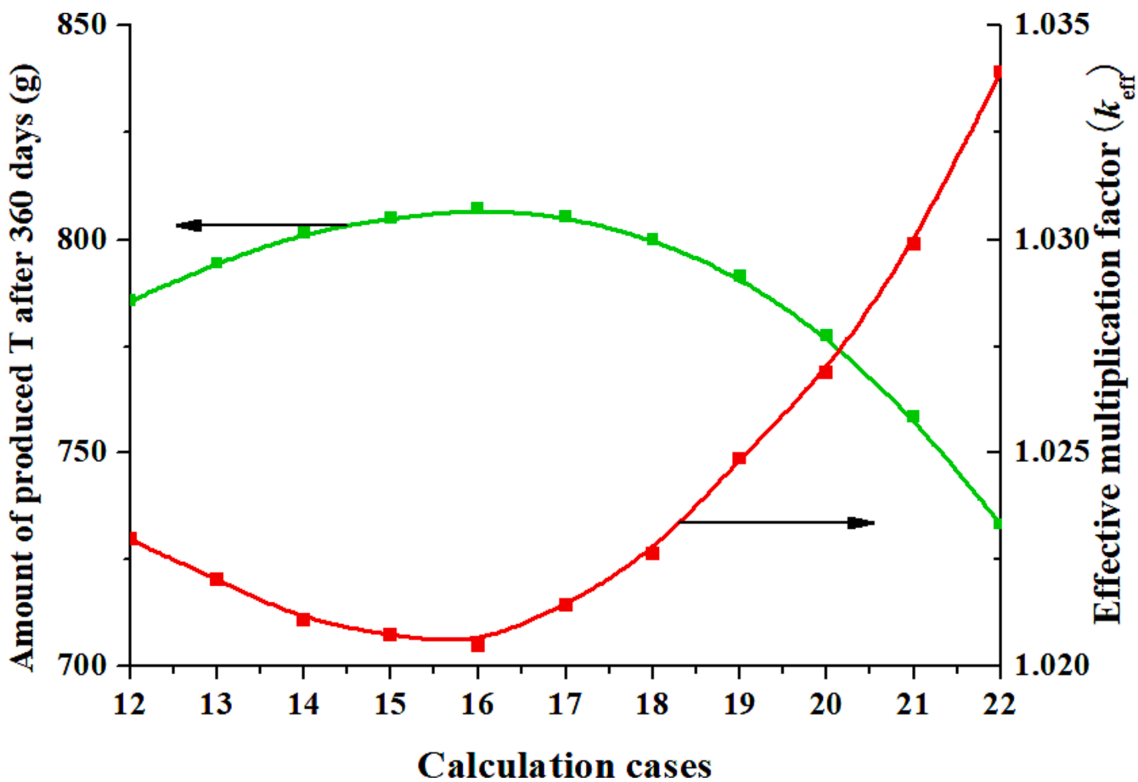

Fig. 10. The amount of tritium produced and k_{eff} values after 360 days of operation when the $LiAlO_2$ distribution was changed in the radial direction of the GTHTR300.

the amount of loaded ^6Li when two Li rods were loaded in each fuel block (1440 loaded Li rods) were evaluated as shown in Fig. 11. The amount of $LiAlO_2$ loaded in one of 1440Li rods is as 1.5 times as that of 2160Li rods when the total amount of $LiAlO_2$ loaded is same. In addition, the amount of particle Zr loaded decreased by the adjustment. The amount tritium produced tritium and that of ^6Li loaded were proportional but k_{eff} and ^6Li were inverse proportional as past research showed. The maximum amount of tritium produced was 800 g when 8187 g of ^6Li was loaded into the reactor. The amount of loaded ^6Li to produce 800 g of tritium increased when two Li rods were loaded in each fuel block. This is because the total transmutation performance of the Li rods decreased by reducing the number of Li rods, and more ^6Li was required to produce 800 g of tritium during 360 days of operation. The amount of tritium produced and k_{eff} throughout the 360 days of operation according to the amount of loaded ^6Li when one Li rod was loaded in each fuel block (720 loaded Li rods) were shown in Fig. 12. The amount of $LiAlO_2$ loaded in one of 720Li rods is as 3 times as that of 2160Li rods when the total amount of $LiAlO_2$ loaded is same. The transition of the produced tritium and k_{eff} was more unclear than Fig. 11 despite enough statistic errors. Because the increase of ^6Li loaded was much smaller for the total amount of it for the evaluation condition. The maximum amount of tritium produced was 801 g when 39 059 g of ^6Li was loaded into the entire reactor. The total transmutation performance of the Li rods was significantly decreased by reducing two Li rods in each fuel block, which required a much larger amount of ^6Li to produce 800 g of tritium.

The cumulative amount of tritium produced and k_{eff} throughout the 360 days of operation, when two Li rods (one Li rod) were loaded and the total amount of loaded ^6Li was 8187 g (39 059 g), are shown in Fig. 13 **of** red lines (blue lines). The k_{eff} for one Li rod exceeded that for two Li rods because the transmutation performance was inferior in early time of operation by self-shielding effect: Significant operation of control rods is required to suppress reactivity when the number of Li rods is reduced. The fuel burnups and power densities for both cases were similar to those when three Li rods were loaded (Figs. 6 and 8), which satisfied reactor feasibility. Their transitions were similar to those observed when the three Li rods were loaded. The reactor feasibility was also satisfied when one Li rod was loaded into each fuel block. The amounts of tritium leaked when one, two, and three Li rods were loaded in each fuel block are shown in Fig. 14. The amount of Zr decreased with an increase in the amount of $LiAlO_2$ (^6Li) to maintain the amount of tritium produced to be 800 g when the number of Li rods was reduced. Compared with the result when three Li rods were loaded, the amount of leaked tritium increased by 441 % and 58 % when one and two Li rods were loaded in each fuel block, respectively. This is because reducing the amount of Zr caused tritium to leak more from Al_2O_3 layer by tritium leakage-absorption balance.

3.3.2. Reducing the number of Li rods in specific fuel regions

There is a possibility that tritium production and containment per-

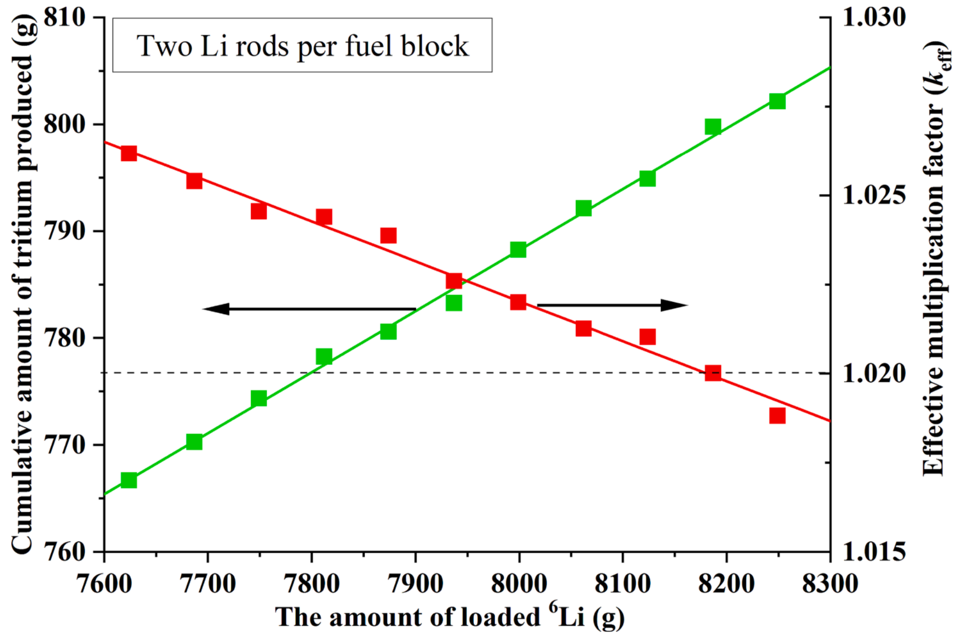

Fig. 11. The amount of tritium produced and k_{eff} values after 360 days of operation based on the amount of loaded ^{6}Li when two Li rods were loaded in each fuel block of the GTHTR300.

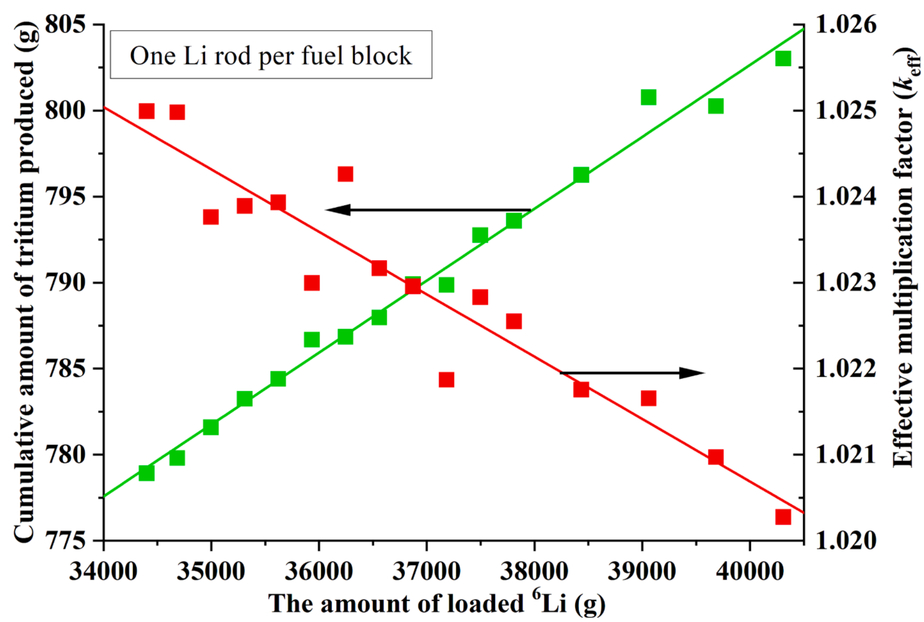

Fig. 12. The amount of tritium produced and k_{eff} values after 360 days of operation based on the amount of loaded ^{6}Li when one Li rod was loaded in each fuel block of the GTHTR300.

formance are improved by reducing the number of Li rods in specific fuel regions. The amount of tritium produced and reactor characteristics were evaluated by reducing the number of Li rods in specific fuel regions. GTHTR300 has a vertical temperature distribution direction, and the lower layers have a higher temperature (Katayama et al., 2015). The influence of reducing Li rods in the upper layers was evaluated based on our research, which suggested that the tritium absorption performance of Zr was better at higher temperatures (Okumura et al., 2000), and the tritium containment performance of Li rods was superior at higher temperatures. The number of Li rods in each layer when the Li rods were reduced in the upper (lower temperature) layers is shown in Table 3. At least one Li rod was loaded into each fuel block in layers 1 − 4 to ensure that the fuel burnup and power density were not distorted. The amount of tritium produced and k_{eff} throughout the 360 days of operation, based on the amount of loaded ^{6}Li under the conditions listed in Table 3, were evaluated using the method on section 3.3.1. The amounts of loaded $LiAlO_2$ were uniform in all Li rods for each evaluation. The maximum amount of tritium produced was 570 g when the amount of loaded ^{6}Li was 10 624 g and k_{eff} was over 1.02. Under these conditions, 800 g of tritium could not be maintained. The cumulative amount of tritium produced and k_{eff} throughout 360 days of operation for 10 624 g of loaded ^{6}Li are shown in Fig. 15 (red lines).Their tendencies with respect to the operation time were similar to those when the Li rods were uniformly loaded (Fig. 4, for example), except the k_{eff} significantly decreased throughout the time because the transmutation performance of the Li rods worsened. However, the fuel burnups and power densities

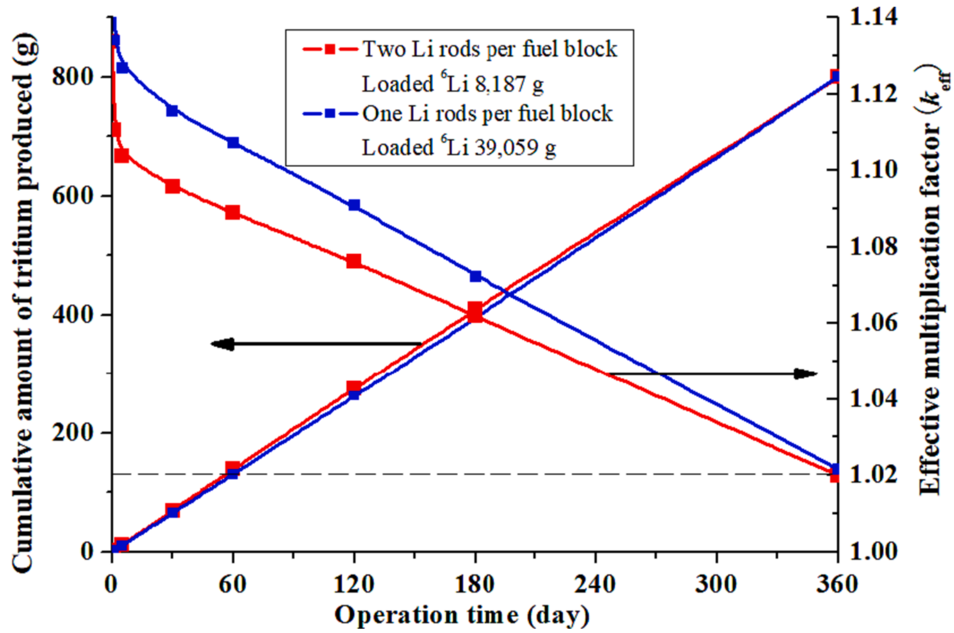

Fig. 13. The cumulative amount of tritium produced and the k_{eff} value throughout the 360 days of operation for the GTHTR300 when two (one) Li rods were loaded in each fuel block and the total amount of loaded ^{6}Li was 8187 g (39 059 g).

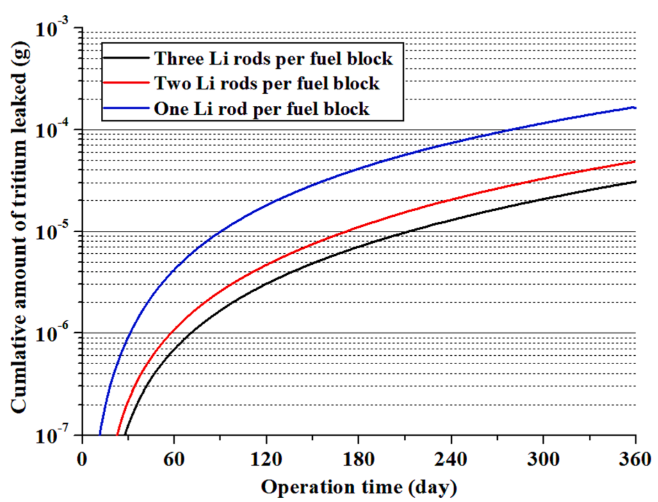

Fig. 14. The cumulative amounts of leaked tritium throughout the 360 days of operation when one, two, and three Li rods were loaded in each fuel block and approximately 800 g of tritium was produced.

Table 3
The number of loaded Li rods in each layer when the number of Li rods were reduced in the lower temperature layers.

Layer	The number of Li rods per fuel block	The number of Li rods in layer
1	1	90
2	1	90
3	1	90
4	1	90
5	2	180
6	2	180
7	3	270
8	3	270

are completely different from those when Li rods were uniformly reduced. Even when one Li rod was loaded in each fuel block of the upper layers, both the results significantly increased and exceeded the expected limit in the upper layers, and these distributions were distorted in the upper layers. Therefore, this loading method does not achieve adequate feasibility and tritium production.

Considering that the neutron flux is generally higher in the center layers and more tritium is produced there, the influence of reducing the Li rods in the outer layers was also evaluated. The number of Li rods in each layer when the Li rods were reduced in the outer (lower neutron flux) layers is listed in Table 4. The amount of tritium produced and k_{eff} throughout the 360 days of operation for loaded ^{6}Li under the conditions listed in Table 4 were also evaluated using the method described above. The amounts of loaded $LiAlO_2$ were also uniform in all Li rods. The maximum produced tritium was 902 g when loaded ^{6}Li was 29 372 g and k_{eff} was over 1.02. This loading method increased the amount of tritium produced at 100 g. The cumulative amount of tritium produced and k_{eff} for 29 372 g of loaded ^{6}Li throughout the 360 days of operation are shown in Fig. 15 (blue lines). The tendencies of these transitions were similar to those of uniformly loaded Li rods, except that k_{eff} decreased more after 120 days than before 120 days. The fuel burnups and power densities exceeded the expected limit in the upper and lower layers, and these distributions were distorted in the upper and lower layers. Therefore, this loading method increased the amount of tritium produced from 800 g/year; however, the reactor feasibility could not be satisfied.

4. Concluding remarks

This study evaluated whether the performance of Li rods and the reactor characteristics of the GTHTR300 can be improved for future optimization by adjusting the Li rod arrangement and the amount of Li compounds in them. The maximum amount of tritium produced did not increase from 800 g/year in the evaluations when the amount of loaded Li compounds changed, depending on the layers and fuel regions, while maintaining the total amount of Li compounds. Next, the effect of reducing the number of loaded Li rods was evaluated as an example of optimization. By uniformly reducing the number of Li rods, the maximum amount of produced tritium was maintained at 800 g. However, the amount of loaded Zr decreased and the amount of leaked tritium increased about 5 times and 1.6 times when one and two Li rods were loaded in each fuel block, respectively, compared to three loaded Li

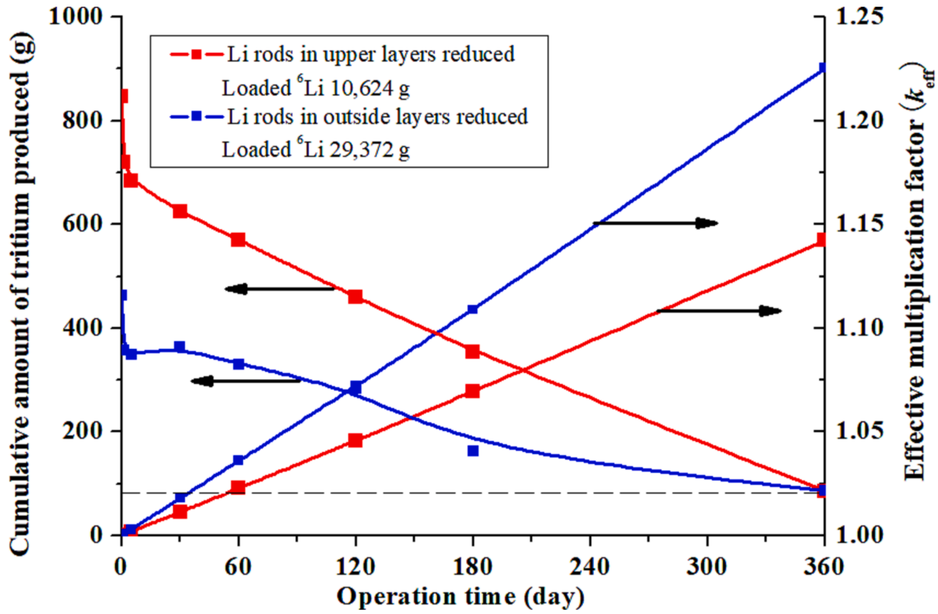

Fig. 15. The cumulative amount of tritium produced and the k_{eff} value throughout the 360 days of operation for the GTHTR300 when the number of Li rods was reduced in the lower temperature layers (the outer layers) and the total amount of loaded ^{6}Li was 10 624 g (29 372 g).

Table 4
The number of loaded Li rods in each layer when Li rods were reduced in outer (lower neutron flux) layers.

Layer	The number of Li rods per fuel block	The number of Li rods in layer
1	1	90
2	1	90
3	2	180
4	3	270
5	3	270
6	2	180
7	1	90
8	1	90

rods, because more ^{6}Li was required on reducing the Li rods. However, the ratio of T/Zr increased to 1.99 at% from 0.54 at% (layer type Li rod) at maximum and tritium partial pressure was evaluated to be a few pascals. Therefore, The Zr + T phase was in β regime in the any evaluations. He partial pressure caused by ^{6}Li(n,α)T reaction was evaluated MPa but its magnitude balanced with He coolant pressure for the HTGR. The GTHTR300 reactor characteristics were not significantly influenced during operation; therefore, the feasibility of the reactor was satisfactory. Additionally, investigations were conducted to ascertain whether reducing the number of Li rods at specific loading positions can improve the tritium production and containment performance. The amount of tritium produced was increased using this approach, but the reactor feasibility could not be satisfied. Therefore, uniformly reducing the number of Li rods from 1440 to 720 is an effective optimization method for tritium production by GTHTR300.

It is concerned whether Li rods can keep feasibility with effected by phenomena such as swelling in thermonuclear environments. We assumed the amount of Zr loaded conservatively for that. The swelling for $LiAlO_2$ was reported to be very small (Otsuka, 2020; Shibata, 2011). The Li rod feasibility will be confirmed by an irradiation examination by an HTGR.

The k_{eff} characteristic of HTGRs with Li rods is expected to be close to the standard specifications to avoid changing the operation method when Li rods are loaded. The simultaneous use of B_4C BPs and Li rods is considered to make the k_{eff} characteristic closer to the standard specifications for further optimization. The characteristic and amount of tritium produced, when B_4C BPs are loaded into the BP holes from which the Li rods are removed, should be evaluated.

Measures are required to reduce the number of Li rods while preventing tritium leakage, which increases the amount of loaded Zr. Increasing the radius of Li rods and making the Al_2O_3 layer thinner while maintaining the Al_2O_3 layer tritium containment performance and physical strength can be one of the measures. This can also increase the transmutation performance by weakening the self-shielding effect and decreasing the required amount of ^{6}Li. The amount of tritium produced could not be significantly increased while satisfying the reactor feasibility in this study. However, research on optimization should continue to develop a method to increase the amount of tritium produced by burning the fuel uniformly.

CRediT authorship contribution statement

Yuki Koga: Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing. **Hideaki Matsuura:** Conceptualization, Supervision, Project administration, Funding acquisition, Validation, Writing – review & editing. **Kazunari Katayama:** Validation, Writing – review & editing. **Teppei Otsuka:** Validation, Writing – review & editing. **Minoru Goto:** Validation, Writing – review & editing. **Shimpei Hamamoto:** Validation, Writing – review & editing. **Etsuo Ishitsuka:** Validation, Writing – review & editing. **Shigeaki Nakagawa:** Validation, Writing – review & editing. **Kenji Tobita:** Validation, Writing – review & editing. **Youji Someya:** . **Yoshiteru Sakamoto:** .

Declaration of Competing 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.

Data availability

The authors do not have permission to share data.

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