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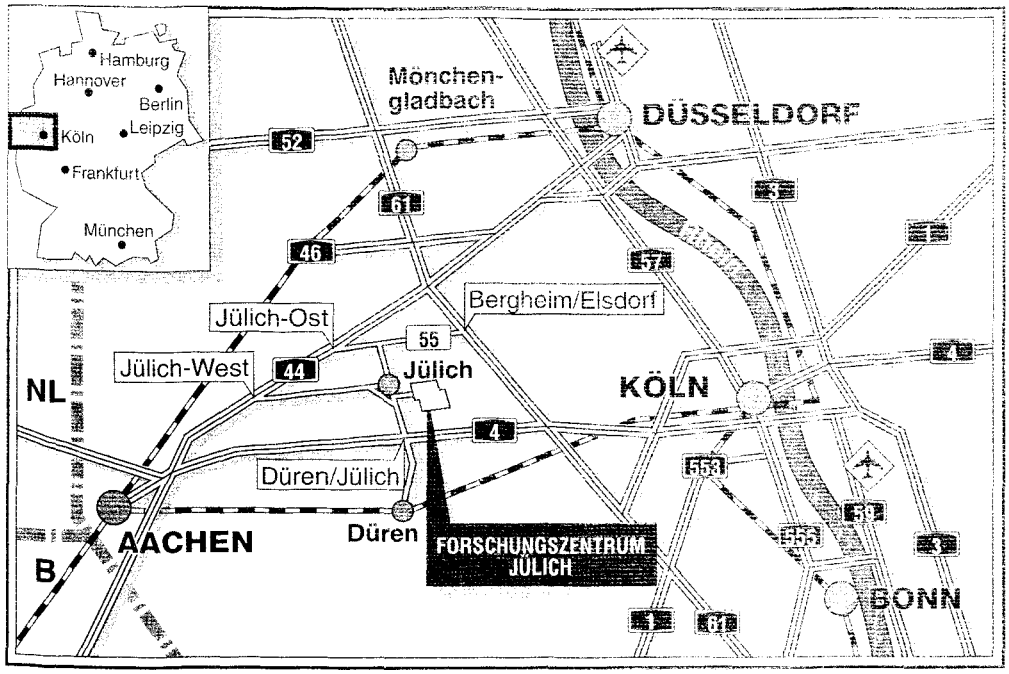

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Study on Temperature Coefficients of Actinide Burning HTGRs

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ABSTRACT

HTGRs have the potential to achieve a high transmutation ratio, burning transuranium isotopes. The main reason is the large burnup, which is achieved by the fuel in the form of coated particles. In view of inherent safety features temperature coefficients have been studied for HTGR-fuel containing Pu and Minor Actinides in various fuel specifications in each case aiming at a high Pu burning ratio.

The performed cell burnup calculations indicate, that HTGRs have the potential to achieve a high transmutation potential. In view of the temperature coefficients U^{238} as breed material has an advantage compared to Th^{232}, maintaining a negative temperature coefficient even at a very high fuel burnup.

In order to maximize the yearly depletion rate of Pu, small amounts should be loaded to the fuel elements without U. For utilizing Pu effectively, i.e. to achieve a long burnup cycle and a high burnup of the Pu loaded to the fuel elements, a high heavy metal loading including U as breed material is adequate.

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Contents

List of Tables

List of Figures

1. Introduction

Minor actinides (MA) transmutation is one of the superior ways to reduce the amount of high level wastes from fuel reprocessing. Many ways have been proposed for MA transmutation[1]. It is reported that the MA transmutation by High Temperature Gas-cooled Reactors (HTGRs) with reprocessed Pu fuel has the possibility to achieve a high MA transmutation ratio[2,3]. HTGRs can achieve high fuel burnup with their coated fuel particles (CFP). Moreover, HTGRs with reprocessed Pu fuel produce less MA than U-fueled HTGRs. Therefore, the MA transmutation by Pu-fueled HTGRs have a possibility to achieve a transmutation ratio of up to 70 % [2,3].

In Pu-fueled reactors, however, there is a concern that the temperature coefficients might become positive. The temperature coefficients of any reactor should be negative to maintain the inherent safety features. It is also necessary to achieve negative temperature coefficients in MA transmutation HTGRs.

To clear the basic characteristics of temperature coefficients of MA transmutation HTGRs, isothermal temperature coefficients of MA+Pu fuels are calculated by cell calculation in different fuel specifications and utilizing resonance materials.

Moreover, isothermal temperature coefficients and Pu burning performance of Pu burning HTGRs which aim at a high burnup and at a high Pu burning ratio have also been studied. To improve the burning performance, U is utilized as a resonance material.

The MA transmutation HTGRs are Pu-fueled HTGRs which have reprocessed Pu fuel. A study on the temperature coefficients of reprocessed Pu-fueled HTGRs would give important information to the study on the temperature coefficients of the MA transmutation reactors.

Also, reprocessed Pu-fueled HTGRs have a possibility as Pu burning HTGRs. Now, a reduction of Pu stockpiles gets a major concern because of the increase in Pu stockpiles due to the discontinuation of military programs, as well as an increase in irradiated reactor fuel. It is reported that pebble bed type Pu burning HTGRs for weapon grade Pu could achieve a high Pu burning ratio[4]. Therefore, it is expected that the pebble bed type HTGRs would also achieve a high Pu burning ratio for reactor grade Pu, which is obtained from reprocessed light water reactor (LWR) fuels. For Pu

burning reactors, a higher burnup is expected to achieve a high burning ratio of Pu. High burnup is also expected to the MA transmutation HTGRs to achieve a high MA transmutation ratio. Therefore, the study will give information not only for Pu burning HTGRs but also for MA transmutation HTGRs.

2. Calculation Model and Method

The aim of the study is to show a possibility to achieve negative power coefficients with high fuel burnup of MA transmutation HTGRs. Therefore, the characteristics of the reactor have been calculated by cell burnup calculations using the VSOP code[5].

The code is a system of codes linked together for the simulation of reactor life histories and temporary in-depth research. In comprises neutron cross section libraries, repeated neutron spectrum evaluation, 2-D diffusion calculation with depletion and shut-down features, in-core and out-of-pile fuel management, fuel cycle cost analysis and thermal-hydraulics.

The code system has extensively been used for comparison studies of reactors, their fuel cycles, simulation of safety features, developmental research and reactor assessments. Besides its use in research and development work for HTGRs, the code has successfully been applied to LWRs, heavy water reactors and hybrid systems with different moderators.

MA transmutation HTGRs are pebble bed type HTGRs which are able to continuous refueling. The Pu is reprocessed Pu which contains 70% of fissile Pu. MA and Pu are contained in the kernel of CFP. Fuel balls which contain CFP are loaded into the core randomly. Table 2.1 shows the specification of CFP, fuel ball and core. Isotope compositions of Pu and MA are based on the composition obtained by reprocessed LWR fuel. The specification of CFP is based on the Pu coated particles which have been irradiated up to high burnup[6]. The specification of the core are based on the previous works[2,3].

In the calculation, the infinitive multiplication factor (k_{inf}), isothermal temperature coefficients and Pu burning performance for the Pu burning HTGRs have been calculated. To clear the specification of fuel which can achieve a criticality, the

k_{inf} with different heavy metal loading to the fuel ball and the ratio of fissile Pu to total heavy metal (Pu+MA) have been calculated. Based on the results, isothermal temperature coefficients have been calculated under different burnup. The isothermal temperature coefficient is a temperature coefficient of equal temperatures of fuel and moderator. It is considered that temperature coefficients and power coefficients are negative when the isothermal temperature coefficients are negative. In the case of fuels which have no ^{238}U or ^{232}Th, no resonance calculation has been done. In the case of fuels with ^{238}U or ^{232}Th, effective cross section of these materials have been calculated by resonance calculation.

Table 2.1 Specification of CFP, fuel ball and core

Coated fuel particle :

Material	Pu oxide and MA oxide			
Isotope composition (wt%)	Pu		MA	
	^{239}Pu	60	^{237}Np	50
	^{240}Pu	25	^{241}Am	35
	^{241}Pu	10	^{243}Am	10
	^{242}Pu	5	^{244}Cm	5
Density (g/cc)	1.585		10.0	
Radius (cm)	0.0275			

Coating layers :

No.	Material	Thickness (cm)	Density (g/cc)
1 st	Low density PyC	0.0021	1.1
2 nd	High density PyC	0.0045	1.7
3 rd	SiC	0.0041	3.18
4 th	High density PyC	0.0062	2.0

Fuel ball :

Outer radius	3.0 cm
Radius of matrix region	2.5 cm
Density of matrix graphite	1.7 g/cc
Density of shell	1.7 g/cc

Core :

Thermal power	200 MW
Power density	3 W/cc
Number of fuel balls in the core	360,000

3. Temperature coefficients of MA transmutation reactors

3.1 Temperature coefficients of MA+Pu fuel

MA transmutation in HTGRs with a fuel of MA+Pu has been reported in earlier publications [2,3]. To clear the characteristics of isothermal temperature coefficients of the reactor, k_{inf} and isothermal temperature coefficients are evaluated.

(1) Infinitive multiplication factor

Figure 3.1.1 shows the relation of k_{inf} of MA+Pu fuels to Pu loading in a fuel ball under different MA loading to the fuel. A ratio of fissile Pu to total heavy metal (Pu+MA) is a parameter of MA loading. The Pu contains 70% of fissile Pu. Therefore, the lower ratio of fissile Pu to total heavy metal means a large MA content. In the calculation, no resonance material such as Th or ^{238}U is considered.

The k_{inf} have peaks at about 0.1 g to 0.2 g of Pu loading in a fuel ball. The k_{inf} is decreased with increase in MA loading to the fuel. It is because of the larger neutron absorption cross section of MAs. At more than the Pu loading of 3g Pu/ball, the k_{inf} increases. It is considered that fast fission becomes dominant in the Pu loading.

It is expected that the k_{inf} above 1.1 would achieve criticality considering the leakage of neutron. To achieve a high burnup, reactors should have a higher initial k_{inf}. Also to transmute much MA, reactors should contain much MA. Therefore, it is considered that the ratio of fissile Pu to total heavy metal should be between 70% to 50%, and the Pu loading per fuel ball should be between 0.2 g and 0.8 g per fuel ball to have a high initial k_{inf} and to achieve much MA transmutation. To keep the basic characteristics of HTGRs as thermal reactors, Pu contents above 3 g Pu/ball is not considered.

(2) Temperature coefficients of Pu fuel

To clear the basic characteristics of Pu-fueled HTGRs, isothermal temperature coefficients of Pu fuel have been calculated. Figure 3.1.2 shows the isothermal temperature coefficients of Pu fuel of 0.3 g Pu/ball with no MA.

At 0 GWD/T, the isothermal temperature coefficients are positive below 500°C and negative above 500°C. It is considered that ^{135}Xe has an important contribution to the isothermal temperature coefficients. The cross section of ^{135}Xe is about $3x10^7$

barns below 0.08 eV. Above 0.08 eV, the cross section decreases rapidly. With increase in temperature, the peak of thermal neutron spectrum shifts to the high energy side. It means a decrease in the neutron absorption by ^{135}Xe which brings a positive effect on the reactivity. This is why the isothermal temperature coefficients are positive in the low temperature region.

With increase in burnup, isothermal temperature coefficients increase in the low temperature region. In the high temperature region, isothermal temperature coefficients decrease with increase in burnup. In the calculation, the power density is kept constant through burnup. With increase in burnup, therefore, the neutron flux increases due to decrease in fissile material in a fuel ball. Higher neutron flux enhances the effect of ^{135}Xe on the isothermal temperature coefficients mentioned above.

It is reported that much heavy metal loading into a fuel ball is effective to keep the isothermal temperature coefficients negative[4,7]. Figure 3.1.3 shows the isothermal temperature coefficients with the fuel of 0.5 g Pu/ball. The isothermal temperature coefficients at 0 GWD/T are negative through the whole temperature range. Compared to the case of 0.3g Pu/ball, the isothermal temperature coefficients are improved. In this case, the neutron flux is expected to be lower than that of the case of 0.3 g Pu/ball. The power density is the same as in the case of 0.3g Pu/ball. Therefore, the neutron flux is lower because of a high Pu content per ball. The lower neutron flux brings a smaller effect of ^{135}Xe. It makes the isothermal temperature coefficients small.

With increase in burnup, isothermal temperature coefficients also increase in the low temperature region. The increasing neutron flux brings more positive isothermal temperature coefficients. However, the change in neutron flux is small due to the high heavy metal loading. The change in the isothermal temperature is less than that of the case of 0.3g Pu/ball as shown in Fig. 3.1.2.

It is considered that much heavy metal in a fuel ball would achieve a higher fuel burnup with negative temperature coefficients.

(3) Temperature coefficients of MA transmutation reactor

To clear the effect of MA on temperature coefficients, isothermal temperature coefficients of MA+Pu fuel which contents 50% of fissile Pu to total heavy metal and 0.3 g Pu/ball are calculated. The isothermal temperature coefficients in different

burnup are shown in Fig. 3.1.4. The fuel contains 0.3 g Pu and 0.12 g of MA per fuel ball.

AT 0 GWD/T, isothermal temperature coefficients are positive below 400°C. Compared to the results of Pu-fueled HTGRs as shown in Fig. 3.1.2, the temperature region in which the isothermal temperature coefficients are negative becomes wider. However, the change in the isothermal temperature coefficients with increase in temperature becomes larger than that of Pu fuel which has the same Pu content per ball as shown in Fig. 3.1.2. Also the maximum value is larger than that of the case without MA.

With the increase in burnup, the isothermal temperature coefficient becomes larger below 800°C. The tendency is the same as the results of Pu fuel as shown in Fig. 3.1.2. However, the changes are larger. It is concluded that the addition of MA into Pu fuel brings larger isothermal temperature coefficients in the low temperature region. MA such as ^{241}Am, have a larger neutron absorption cross section than Pu in the thermal region. The absorption cross section changes according to the 1/v law in the thermal region. With increase in temperature, the neutron absorption by MAs decreases, which brings a positive effect on the reactivity. The large neutron absorption cross section in the thermal region and the change of the neutron absorption are expected to bring larger isothermal temperature coefficients and a larger change with burnup in the low temperature region.

It has already been shown that much heavy metal loading in a fuel ball brings smaller isothermal temperature coefficients. Therefore, it is expected that the higher heavy metal content brings smaller isothermal temperature coefficients in a MA transmutation reactor. Figure 3.1.5 shows the isothermal temperature coefficients with the fuel of 0.5 g Pu/ball and 50% of fissile Pu to total heavy metal. The fuel contains 0.5g Pu and 0.2g MA per fuel ball.

At 0 GWD/T, the isothermal temperature coefficients are negative in the whole temperature region. With increase in burnup, the isothermal temperature coefficients increase in the low temperature region. However, the change of the isothermal temperature coefficients is smaller than the results of the case of 0.3g Pu per fuel ball.

It is concluded that the high heavy metal loading per fuel ball also brings the smaller isothermal temperature coefficients in a MA transmutation reactor. This is the

same as for Pu fuel. However, it may be difficult to attain high burnup with negative temperature coefficients because the value of k_{inf} is low as shown in Fig. 3.1.1. However, it is concluded that the high heavy metal loading is one possible way to achieve negative isothermal temperature coefficients.

(4) Effect of MA kernel density

In the above calculation, the Pu kernel density is 1.585 g/cc and the MA kernel density is 10 g/cc. It is considered that a lower MA kernel density brings more neutron absorption by MA. It is expected to bring smaller temperature coefficients because it may reduce the effect of the giant fission resonance peak of ^{239}Pu.

Figure 3.1.6 shows the isothermal temperature coefficients of 0.3g Pu/ball and 50% of fissile Pu to total heavy metal, the kernel density being 4 g/cc. The specification of the Pu kernel is the same as above.

(5) Effect of Pu kernel density

In the above calculations, the density of the Pu kernel is 1.585 g/cc which is based on Ref. 6 keeping the amount of Pu per CFP. This design aims at a higher burnup by reducing the Pu content in a CFP. Low density of Pu kernels would bring a higher neutron absorption by Pu because of a small selfshielding factor. MA such as ^{241}Am have a peak of the absorption cross section around 0.3 eV. An increase in the density of the Pu kernel brings less neutron absorption by Pu. Therefore, it would increase neutron the absorption by MA which would be expected to reduce the temperature coefficients.

The k_{inf} with different Pu kernel density but the same dimensions of CFP are shown in Fig. 3.1.7. Increasing the density of the Pu kernel reduces the number of CFP in a fuel ball and brings a higher heterogeneity in a fuel cell. Therefore, the peak of k_{inf} is shifted to the higher Pu loading side with increase in Pu kernel density. The peak of k_{inf} shifts to 0.4 g Pu/ball at 8 g/cc of Pu kernel density. The k_{inf} value at the peak is not changed.

Isothermal temperature coefficients with a Pu kernel density of 5 g/cc and 8 g/cc are shown in Fig. 3.1.8 and Fig. 3.1.9, respectively. Compared to the results as shown in Fig. 3.1.5, isothermal temperature coefficients increase with an increase in

the Pu kernel density. The change of isothermal temperature coefficients during burnup increases with an increase in the Pu kernel density, too.

The higher Pu kernel density means less coated particles in a fuel ball. This means a higher heterogeneity. The higher heterogeneity brings a higher neutron flux to obtain 3 W/cc of power density. Higher neutron flux enhances the effect of ^{135}Xe as mentioned.

Therefore, 8 g/cc of Pu kernel brings larger isothermal temperature coefficients.

(6) Effect of the size of the fuel kernel

There are two kinds of particle design in Ref. 6. One is a diluted kernel which is a low density kernel applied in the above calculations. Another one is a concentrated kernel which has a smaller diameter and a high density. Both kernels have similar Pu contents per CFP.

To clear the difference of these concepts, k_{inf} of these fuels are calculated. A comparison of k_{inf} of each fuel particle design is already shown in Fig. 3.1.7. The specifications of the concentrated kernel are shown in Table 3.1.1. The isotopic compositions of Pu and MA and the specification of the fuel ball are the same as those of the diluted kernel as shown in Table 2.1.

The k_{inf} of the concentrated kernel is similar to the k_{inf} of diluted kernel of 1.585 g/cc Pu kernel density. The Pu content per CFP of both kernels is about $1.2 10^{-4}$ g. Therefore, it is concluded that the k_{inf} is dominated by the Pu content per CFP. It is also expected that the isothermal temperature coefficients would be similar to the result for the diluted kernel which 1.585 g/cc of Pu density.

Figure 3.1.10 shows the results of isothermal temperature coefficients with concentrated kernels. The results are very similar to the results as shown in Fig. 3.1.4. It is also concluded that the same Pu content per CFP brings similar results of isothermal temperature coefficients. The differences in the kernel diameter, the kernel density, etc. do not bring a significant difference of the isothermal temperature coefficients.

In order to improve the temperature coefficients of MA transmutation HTGRs, k_{inf} and isothermal temperature coefficients under different fuel specifications have

been calculated. As a result, the possible heavy metal contents which will attain criticality are cleared.

Moreover, isothermal temperature coefficients with different specification of fuel have been calculated. As a results, negative temperature coefficients in the whole temperature range will be achieved with suitable heavy metal loading into the fuel ball. However, it is expected that it is difficult to achieve a higher MA transmutation ratio because of the short burnup period with negative temperature coefficients. The difference in the dimensions of the kernel diameter, the kernel density, etc., do not bring a significant difference of the isothermal temperature coefficients.

It is concluded that it may be necessary to utilize resonance materials to achieve a negative temperature coefficients in order to obtain a higher MA transmutation ratio.

Table 3.1.1 Specification of concentrated kernel

Kernel :

Radius (cm)	0.0125
Density (g/cc)	8.0 (for Pu kernel) 10.0 (for MA kernel)

Coating layer :

No.	Material	Thickness (cm)	Density (g/cc)
1 st	Low density PyC	0.0019	1.1
2 nd	High density PyC	0.0029	1.6
3 rd	SiC	0.0032	3.18
4 st	High density PyC	0.0050	2.0

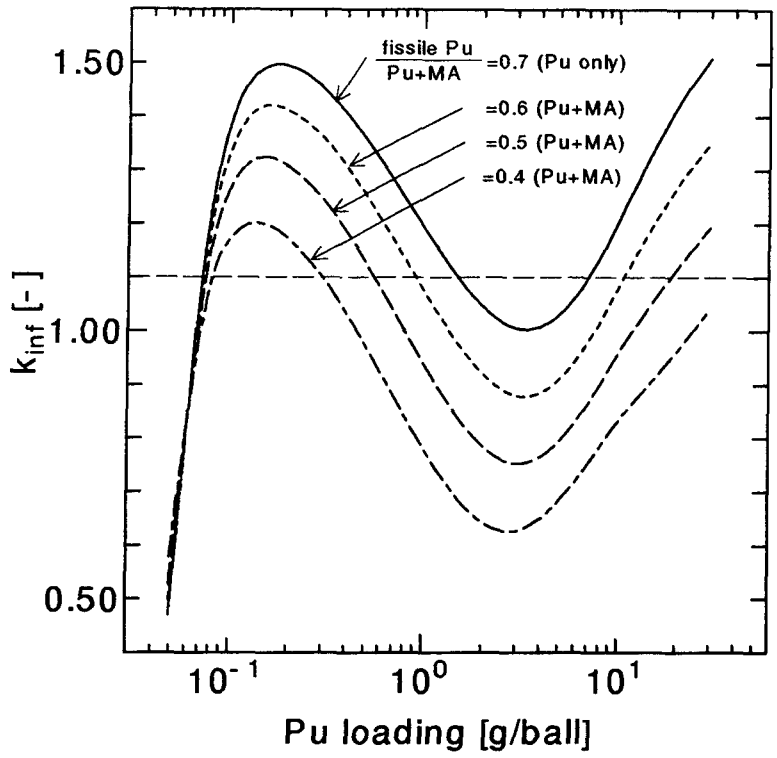

Fig. 3.1.1 Infinitive multiplication factors of MA+Pu fuel in different heavy metal loading

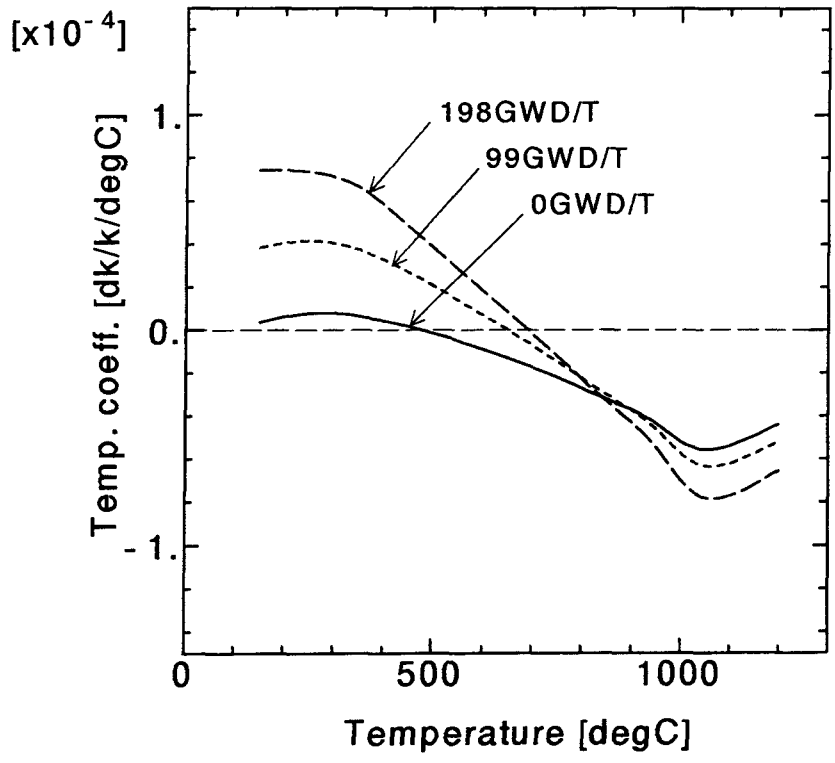

Fig. 3.1.2 Isothermal temperature coefficients of Pu fuel of 0.3g Pu/ball without MA

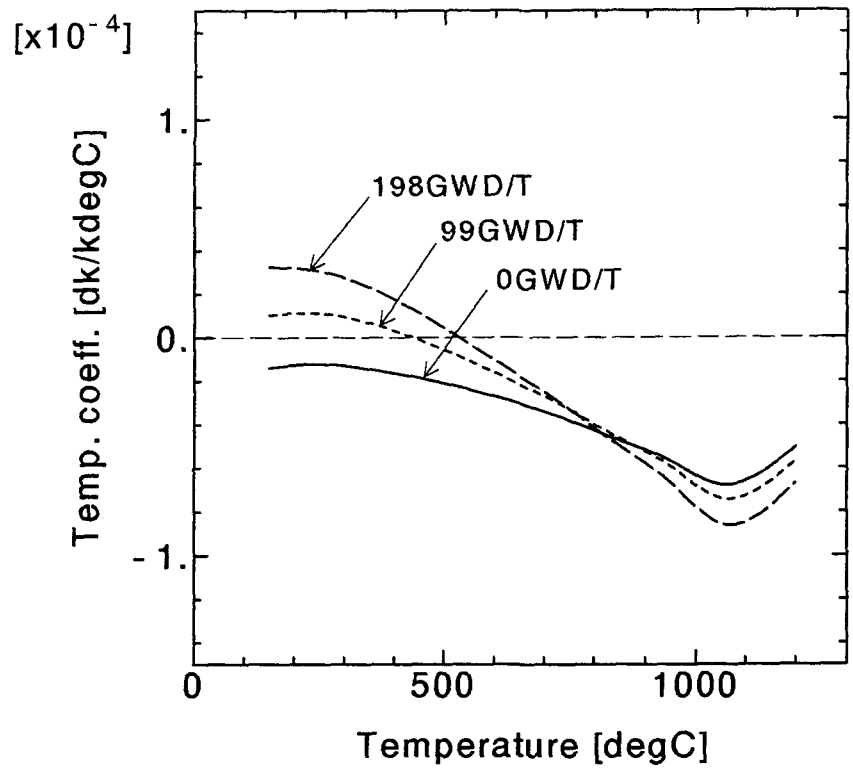

Fig. 3.1.3 Isothermal temperature coefficients of Pu fuel of 0.5g Pu/ball without MA

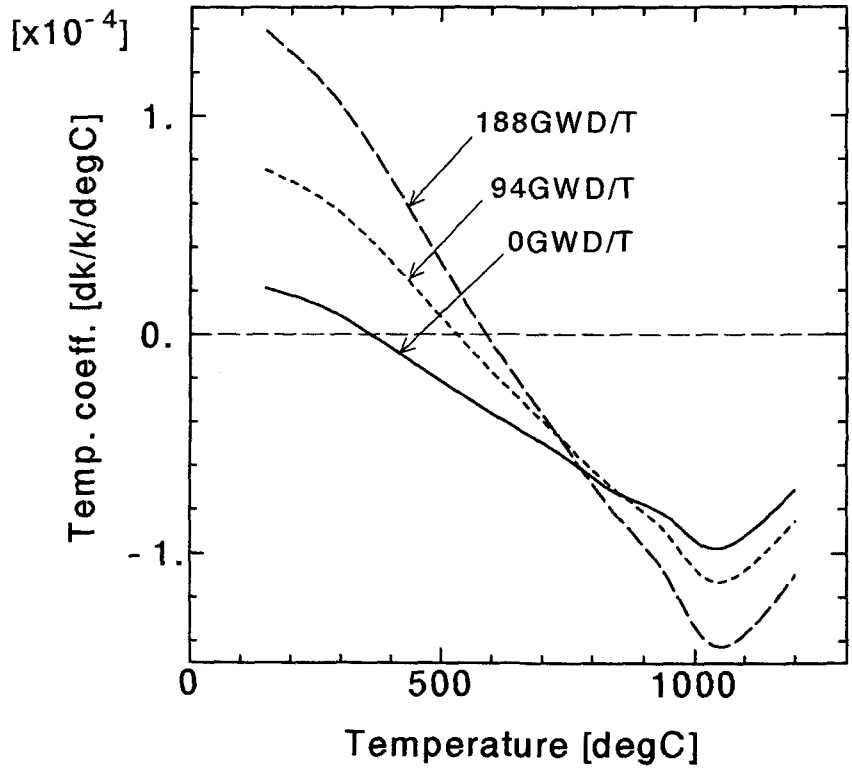

Fig. 3.1.4 Isothermal temperature coefficients of MA+Pu fuel (50% of fissile Pu/(MA+Pu), 0.3g Pu/ball)

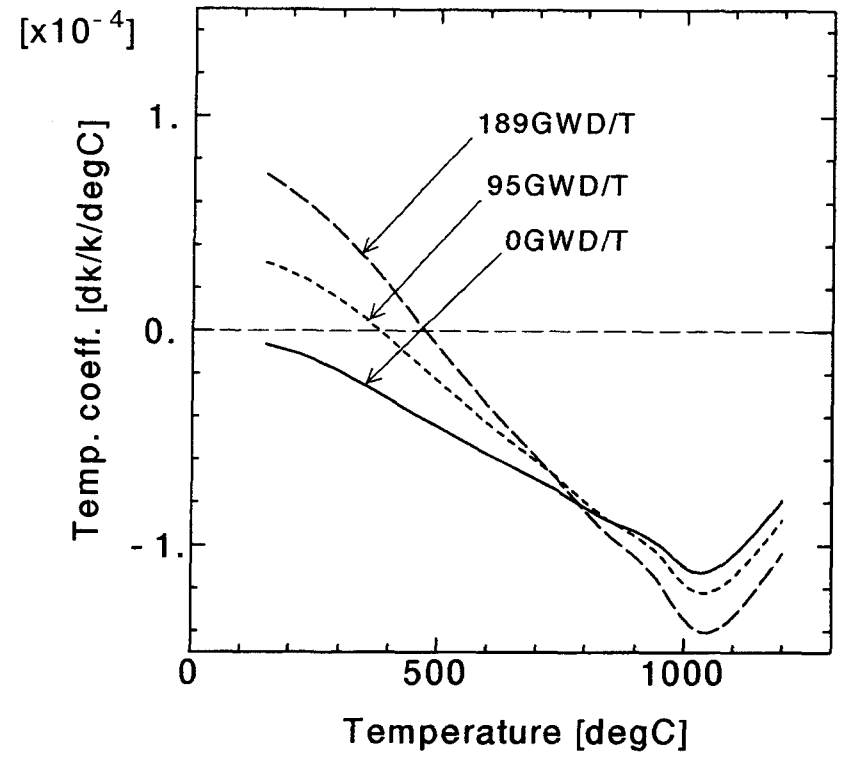

Fig. 3.1.5 Isothermal temperature coefficients of MA+Pu fuel (50% of fissile Pu/(MA+Pu), 0.5g Pu/ball)

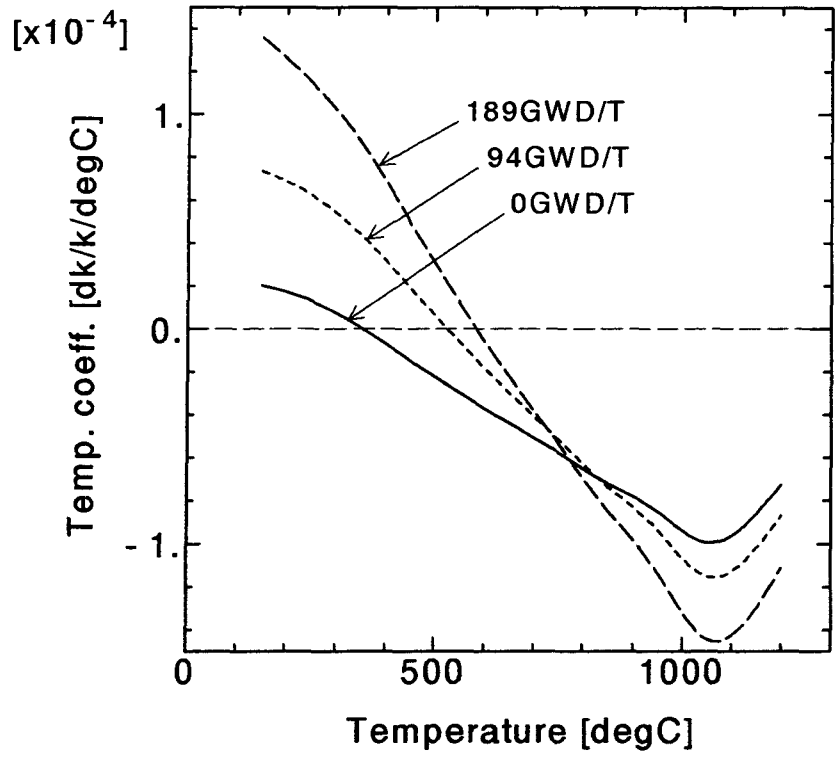

Fig. 3.1.6 Isothermal temperature coefficients with low density of MA kernel (50% of fissile Pu/(MA+Pu), 0.3g Pu/ball, 4g/cc of MA kernel density)

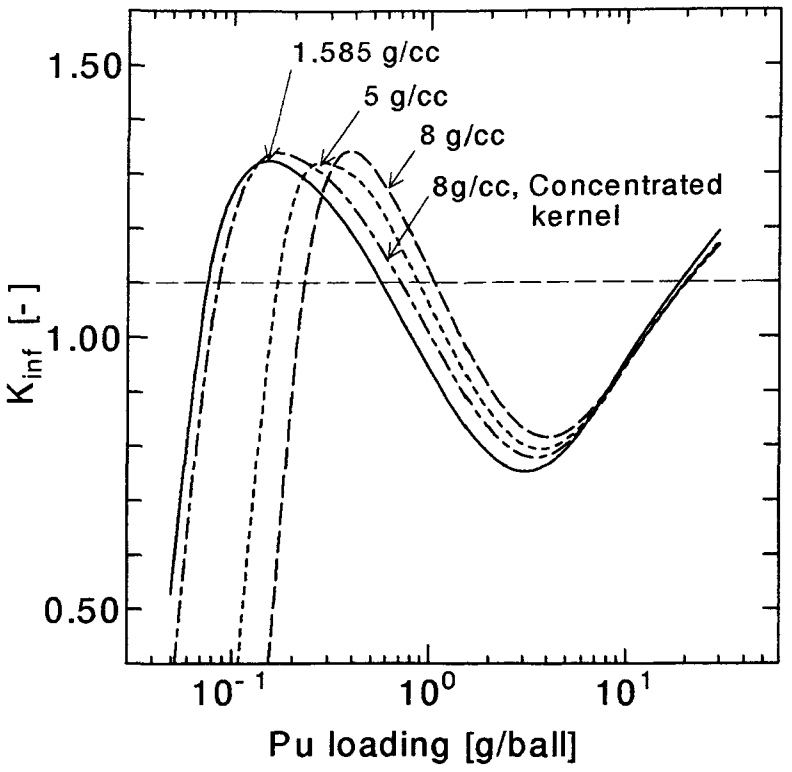

Fig. 3.1.7 Infinitive multiplication factors in different Pu kernel specification (50% of fissile Pu/(MA+Pu))

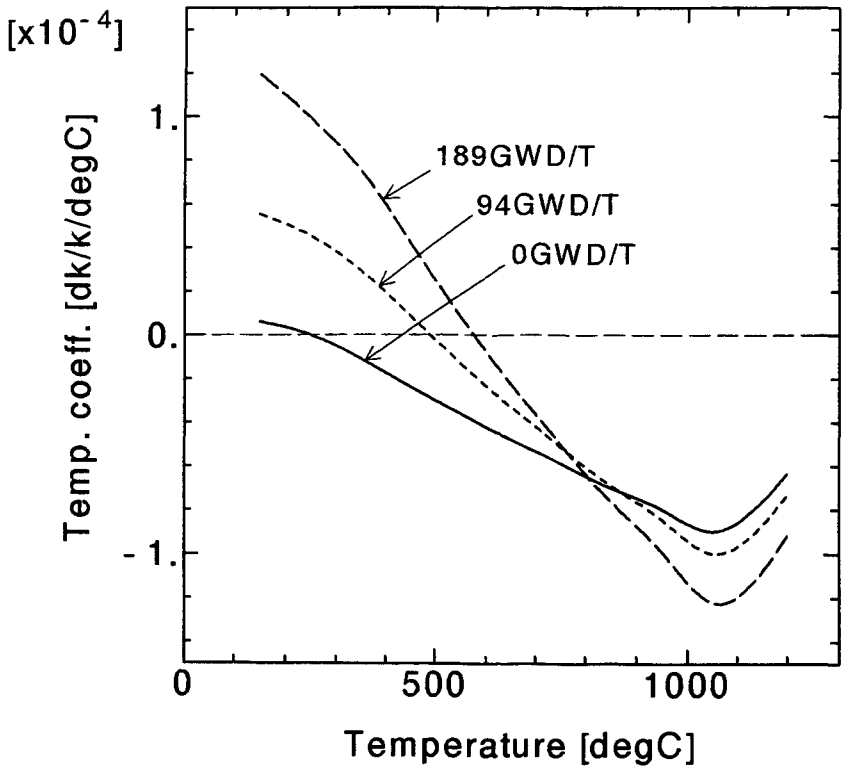

Fig. 3.1.8 Isothermal temperature coefficients with high Pu kernel density (50% of fissile Pu/(MA+Pu), 0.5g Pu/ball, 5g/cc of Pu kernel density)

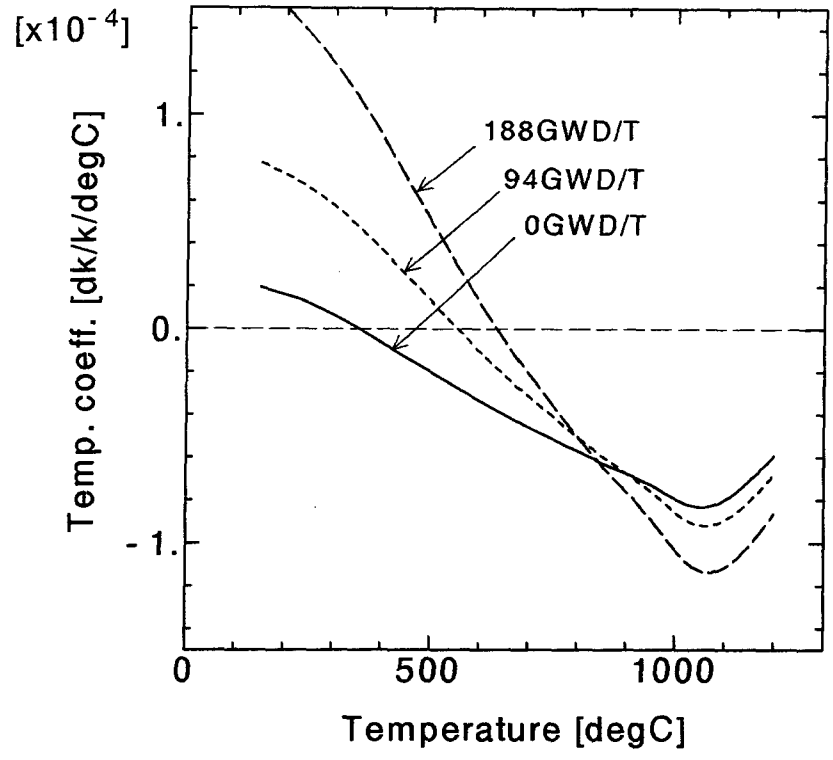

Fig. 3.1.9 Isothermal temperature coefficients with high Pu kernel density (50% of fissile Pu/(MA+Pu), 0.5g Pu/ball, 8g/cc of Pu kernel density)

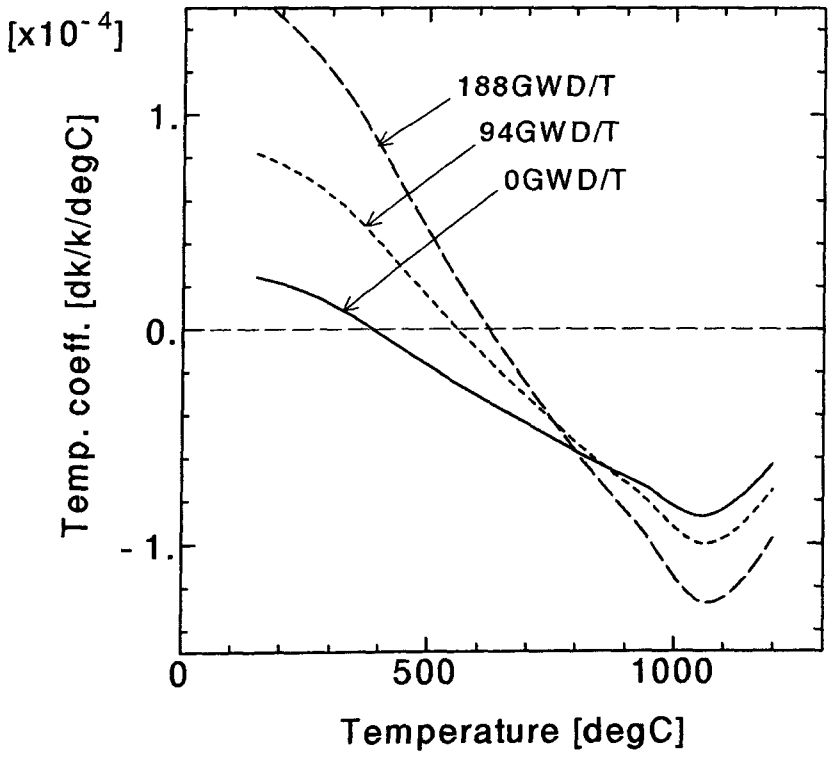

Fig. 3.1.10 Isothermal temperature coefficients with concentrated kernel (50% of fissile Pu/(MA+Pu), 0.3g Pu/ball)

3.2 Temperature coefficients of MA+Pu fuel with Th

It is expected that the Th would improve the isothermal temperature coefficients of MA transmutation reactors because its resonance absorption may play an important role to temperature coefficients. The addition of Th to the fuel would bring resonance neutron absorption. Moreover, Th produces less MA by neutron absorption than U. It would be a suitable resonance absorber for MA transmutation HTGRs. Therefore, isothermal temperature coefficients of MA transmutation reactor with Th have been evaluated. To clear the effect of Th, isothermal temperature coefficients of Pu+Th and Pu+MA+Th fuel have been calculated.

(1) Infinitive multiplication factor

Th acts as a neutron absorber in a thermal reactor. Therefore, its effects on k_{inf} have been calculated. In the calculation, isotopic compositions of Pu and MA etc. are based on the compositions of reprocessed LWR fuel as shown in Table 2.1. The ratio of fissile Pu to Pu+MA is 50%. A comparison of k_{inf} with and without Th is shown in Fig. 3.2.1. In the figure, the hatched line shows the k_{inf} without Th. The solid line shows the k_{inf} with Th. Th is dispersed in the fuel ball as coated particles with ThO_2 kernel. The effective cross section of Th is obtained by resonance calculation. The amount of Th is ten times that of Pu. It means that the ratio of fissile Pu to total heavy metal is about 5%.

The maximum value of k_{inf} with Th is smaller than that without Th because of the increase in neutron absorption by Th. This figure shows that the fuel with Th which contains between 0.06 g and 0.3 g of Pu/ball may achieve criticality. Therefore, the following calculations are carried out based on the 0.3g Pu and 3g Th per fuel ball.

(2) Effect on isothermal temperature coefficient

To clear the effect of Th, isothermal temperature coefficients of Pu fuel and Pu+Th fuel have been calculated. A comparison of the isothermal temperature coefficients of Pu fuel and Pu+Th fuel are shown in Fig. 3.2.2. The hatched line shows the isothermal temperature coefficients of Pu fuel which contains 0.3 g Pu/ball. The solid line shows the isothermal temperature coefficients of Pu+Th fuel which contains

0.3g Pu and 3g Th/ball. The figure shows that the addition of Th shifts the isothermal temperature coefficients towards the positive direction below 800°C.

The addition of Th brings three effects. The first one is the increase in resonance absorption by Th. The second one is a harder neutron spectrum due to the increase in the heavy metal loading. The third one is an increase in the neutron absorption by Th in the thermal energy region. The first and the second one will make the isothermal temperature coefficients negative. The third one will make the isothermal temperature coefficients positive because the neutron absorption cross section of Th in the thermal energy region changes according to an 1/v law. The change in cross section means that the neutron absorption by Th will decrease with an increase in the temperature due to the shift of the thermal neutron spectrum to the higher energy side. From the results as shown in Fig. 3.2.2, it is expected that the third effect would be dominant.

To clear which effect is dominant, doppler and moderator coefficients have been calculated. The doppler coefficient is calculated changing the fuel temperature at a constant moderator temperature. The moderator coefficient is calculated changing the moderator temperature at a constant fuel temperature.

Figure 3.2.3 shows the isothermal, the doppler and the moderator coefficients at the beginning of the burnup cycle. The power density is 3W/cc and ^{135}Xe is considered. The doppler coefficient is negative in the whole temperature region but its value is small. Therefore, the moderator temperature coefficient is dominant in the isothermal temperature coefficients. It is clear that the effects of Th neutron absorption cross section, which changes according to 1/v law, makes the isothermal temperature coefficients positive.

(3) Effect on isothermal temperature coefficients of Pu+MA fuel

To clear the effect of Th on Pu+MA fuel, isothermal temperature coefficients with Pu, MA and Th fuel have been calculated. Figure 3.2.4 shows the isothermal temperature coefficients for different Th loading. It is also shows that the addition of Th makes the isothermal temperature coefficients positive. The higher Th loading brings larger isothermal temperature coefficients in the low temperature region. It also means that the neutron absorption by Th, which decreases with an increase in

temperature, makes the isothermal temperature coefficients positive. The effect is enhanced by a high Th loading.

The doppler and the moderator temperature coefficients are also calculated as shown in Fig. 3.2.5. The fuel contains 0.3g Pu, 0.12g MA and 3g Th/ball. The doppler coefficient is negative but small. The moderator coefficient is dominant in the isothermal temperature coefficient.

Figure 3.2.6 shows the comparison of the doppler and of the moderator coefficient of the cases with MA and without MA. The figure shows that there is no significant difference of the doppler coefficients between the cases with MA and without MA. This is because the amount of Th in the fuel balls is the same in both cases. It is concluded that the resonance absorption by Th does not play an important role in isothermal temperature coefficients.

The moderator coefficients show large differences. This is caused by MA. The addition of MA brings a more steep change in the moderator coefficients.

From the above calculations it is clear that the resonance absorption of Th is not of big importance for the isothermal temperature coefficients. It is also confirmed that it is important to make the moderator coefficients negative to achieve more negative isothermal temperature coefficients.

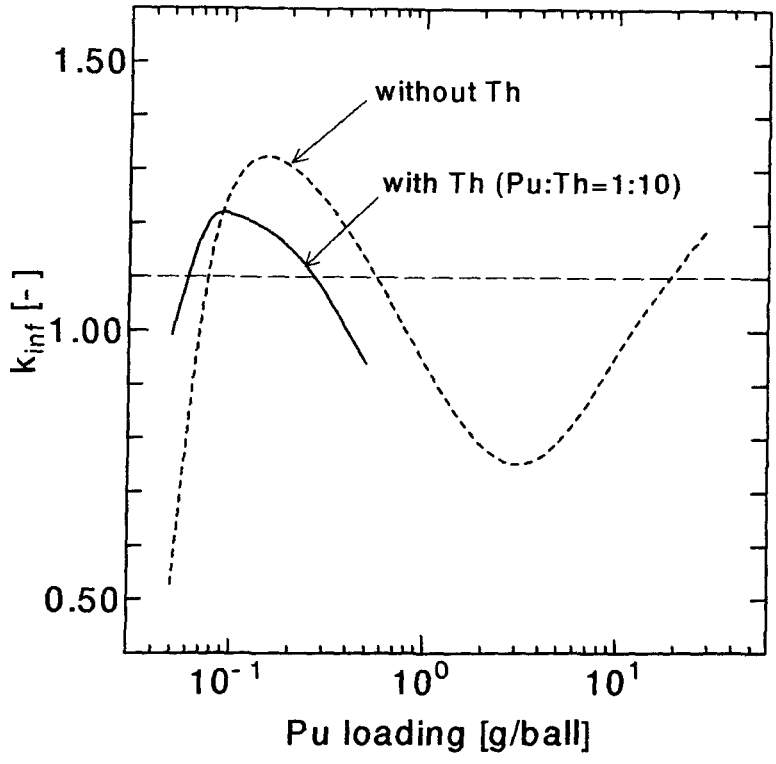

Fig. 3.2.1 Infinitive multiplication factors of Pu+MA fuel in different heavy metal loading with and without Th

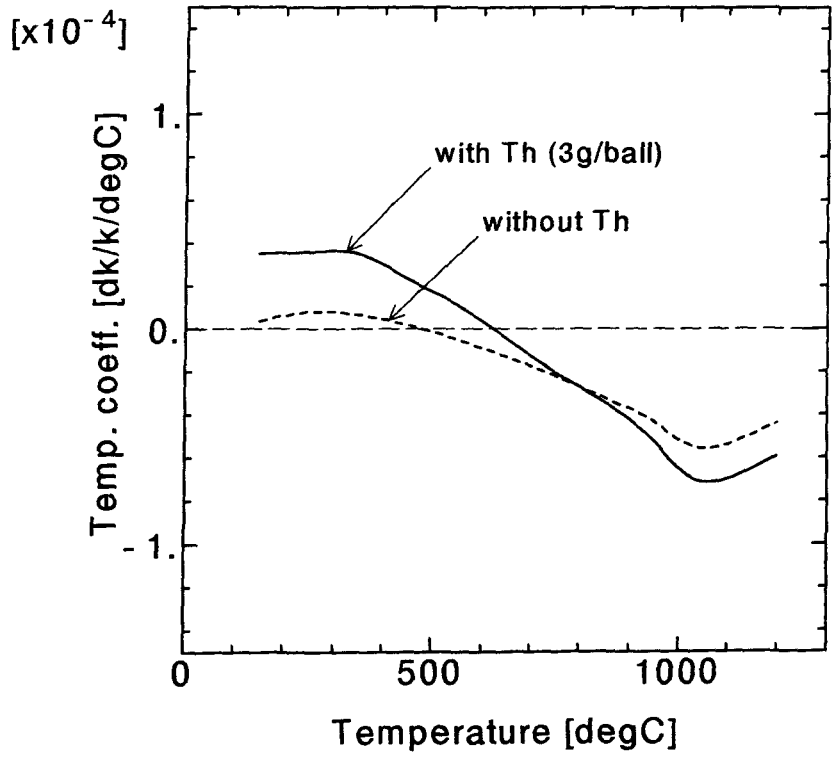

Fig. 3.2.2 Comparison of isothermal temperature coefficients of Pu and Pu+Th fuel (0.3g Pu/ball)

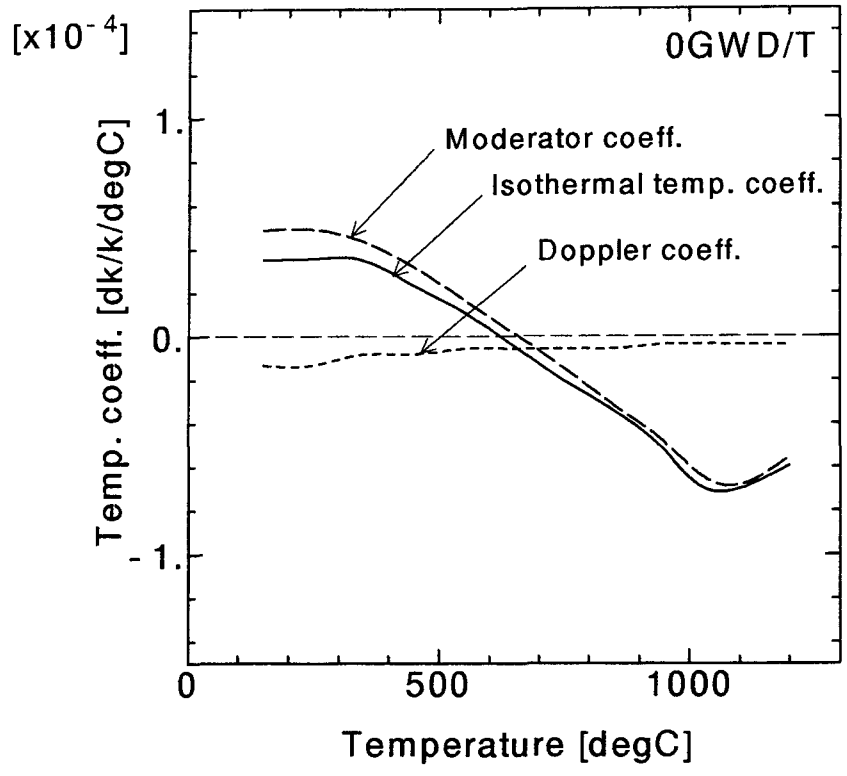

Fig. 3.2.3 Doppler and moderator coefficients of Pu+Th fuel (0.3g Pu and 3g Th/ball)

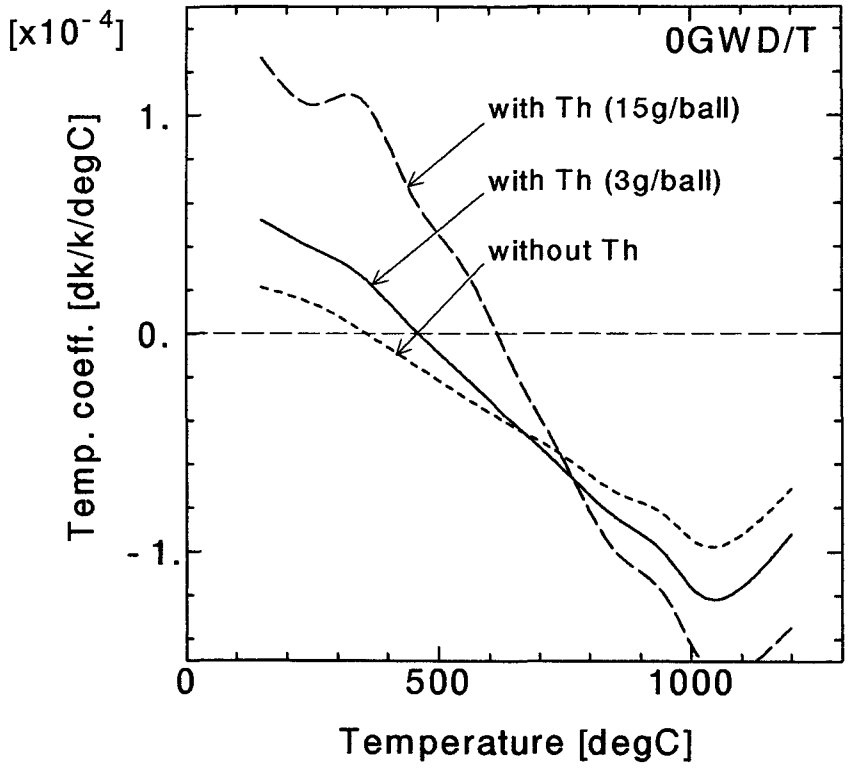

Fig. 3.2.4 Isothermal temperature coefficients of Pu+MA+Th in different Th loading (0.3g Pu and 0.12g MA/ball)

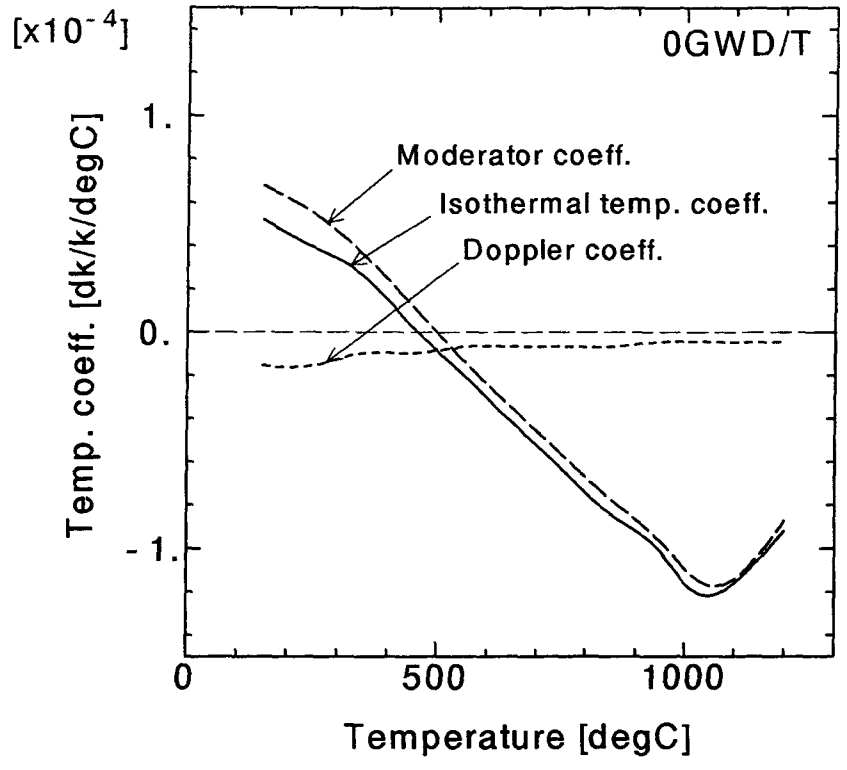

Fig. 3.2.5 Doppler and moderator coefficients of Pu+MA+Th fuel (0.3g Pu, 0.12g MA and 3g Th/ball)

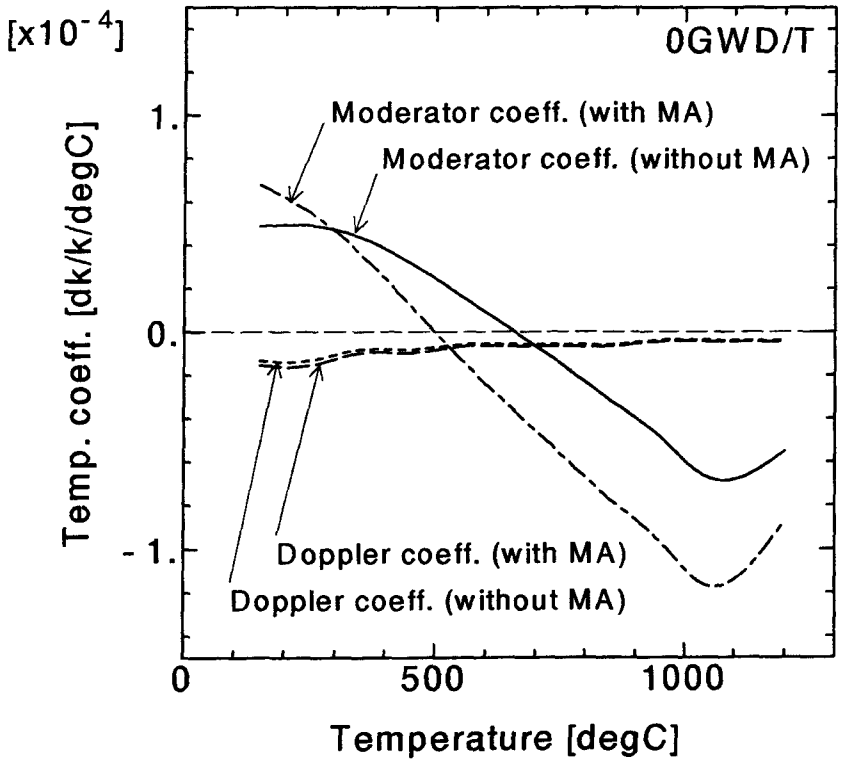

Fig. 3.2.6 Comparison of doppler and moderator coefficients with and without MA (0.3g Pu, 0.12g MA and 3g Th/ball)

4. Characteristics of temperature coefficients of Pu fuel

Today, large stockpiles of plutonium have been accumulated worldwide, resulting from irradiated reactor fuel and from military programs. HTGRs have the possibility to reduce the stockpile of Pu because of a high fuel burnup and a good neutron economy. The Pu burning by HTGRs would have a possibility not only to obtain a high Pu burning ratio but also to achieve direct disposal of discharged fuel because of its high burnup ratio of Pu. Therefore, the characteristics of HTGRs as Pu burning reactors have been evaluated.

To evaluate the characteristics, temperature coefficients and burnup characteristics of Pu-fueled HTGRs are calculated. Then, temperature coefficients and burnup characteristics of Pu+^{238}U fueled HTGRs are also calculated.

4.1 Characteristics of temperature coefficients of Pu fuel without resonance material

As already shown in section 3.1, much heavy metal loading in a fuel ball brings more negative temperature coefficients. From the Fig. 3.1.1, therefore, the cases of 0.5g, 0.8g and 1.0g l of Pu loading per fuel ball have been calculated.

(1) Infinitive multiplication factor

Changes in k_{inf} of the cases of 0.5g Pu/ball, 0.8g Pu/ball and 1.0g Pu/ball are shown in Fig. 4.1.1. The k_{inf} of 0.5g Pu/ball decreases with increase in burnup. The value of the k_{inf} is higher than 1.1 up to the burnup of about 600 GWD/T. It is considered that the k_{inf} above 1.1 would achieve criticality considering neutron leakage. The fuel could achieve more than the burnup of 600 GWD/T. The initial value of the k_{inf} of 0.8g Pu/ball is less than the value of 0.5g Pu/ball. The k_{inf} decreases with increase in burnup, but the change is smaller than that of 0.5g Pu/ball. The k_{inf} of 1.0g Pu/ball is also less than the value of 0.8g Pu/ball. The change of the k_{inf} is flat and is about 1.2 . In view of k_{inf}, therefore, each fuel could achieve more than 600 GWD/T of burnup.

(2) Change in temperature coefficients with burnup

Isothermal temperature coefficients of 0.8g Pu/ball and 1.0g Pu/ball are shown in Figs 4.1.2 and 4.1.3, respectively. The isothermal temperature coefficients of 0.5g Pu/ball are already shown in Fig. 3.1.3. In each case, the isothermal temperature coefficients decrease with an increase in temperature. The maximum value appears at low temperature. It increases with an increase in burnup. With increase in the Pu loading, the isothermal temperature coefficients decrease. The effect of ^{135}Xe is small with high Pu loading because of its low neutron flux. This is why high Pu loading brings more negative temperature coefficients. These figures show that the higher Pu loading per fuel ball brings a longer burnup period in which isothermal temperature coefficients are negative.

Changes in the maximum isothermal temperature coefficients of each case are shown in Fig. 4.1.4. The maximum isothermal temperature coefficients of 0.5g Pu/ball becomes 0.0 at about 50 GWD/T. The maximum isothermal temperature coefficients of 0.8g Pu/ball and 1.0g Pu/ball become 0.0 at about 300 GWD/T and about 420 GWD/T, respectively.

It is expected that the burnup with zero isothermal temperature coefficients would be an average burnup of the reactor which has zero temperature coefficients. Therefore, with continuous refueling, it is also expected that the discharged fuel burnup of the reactor would be double of the average burnup of the reactor. It means that the fuel of 0.5g Pu/ball would achieve about 100 GWD/T of burnup of the discharged fuel with negative temperature coefficients. The fuels of 0.8g Pu/ball and 1.0g Pu/ball would also achieve about 300 GWD/T and 420 GWD/T of burnup of discharged fuel with negative temperature coefficients. It also shows that much heavy metal loading into the fuel ball brings higher burnup with negative temperature coefficients. 0.8g Pu/ball could achieve about 2 times the burnup of 0.5g Pu/ball. 1.0g Pu/ball could achieve 4 times or more burnup of 0.5g Pu/ball.

(3) Burnup characteristics of Pu

Changes in the amount and composition of Pu of 0.8g Pu/ball and 1.0g Pu/ball are shown in Figs. 4.1.5 and 4.1.6, respectively. In the both figures, ^{239}Pu decreases rapidly with increase in burnup. ^{241}Pu and ^{242}Pu increase with an increase in burnup due

to the neutron absorption of ^{240}Pu or ^{241}Pu. However, the increases in these Pu are small. The total amount of Pu decreases in both cases.

The burnup characteristics of these reactors are shown in Table 4.1.1. A reactor power and a power density of 200 MW and 3 W/cc are expected. The core average burnup is considered as a burnup where the isothermal temperature coefficients becomes zero. The discharged fuel burnups are evaluated as twice the core average burnup. The cycle length is considered as the period in which the discharged fuel burnup is achieved.

In the Pu burning ratio per cycle, 0.1g Pu/ball shows a higher value than that of 0.8g Pu/ball. However, the Pu burning ratio per year and the normalized amount of burned Pu show a similar value in both cases.

The Pu burning performance by LWRs is also shown in the Table[8]. These reactors are not optimized as Pu burning reactors. However, the results would show similar values for MOX-fueled LWRs. The Pu burning ratio and the normalized amount of burned Pu are considerably smaller in the LWRs than in the HTGR.

It is considered that burning PU by HTGRs offers the possibility to achieve a high Pu burning ratio. It would contribute not only to a reduction of the Pu -stockpile but would also reduce the reprocessing of Pu fuels and fuel fabrication.

Table 4.1.1 Characteristics of Pu burning reactors

Reactor type	HTGR		LWR	
	0.8g Pu/ball	1.0g Pu/ball	BWR[1)]	PWR[2)]
Thermal power (MW)	200	200	3030	3030
Core average burnup (GWD/T)	150	210	-	-
Discharged fuel burnup (GWD/T)	300	420	20	24
Cycle length (EFPD)	430	760	1095	730
Pu burning ratio (%/year)	28	21	14	17
Normalized amount of burned Pu (kg/GW year)	403	378	33	66

1) Pu-depleted U fuel, 1.5wt% of Pu contents
2) Pu-depleted U fuel, 2.6wt% of Pu contents

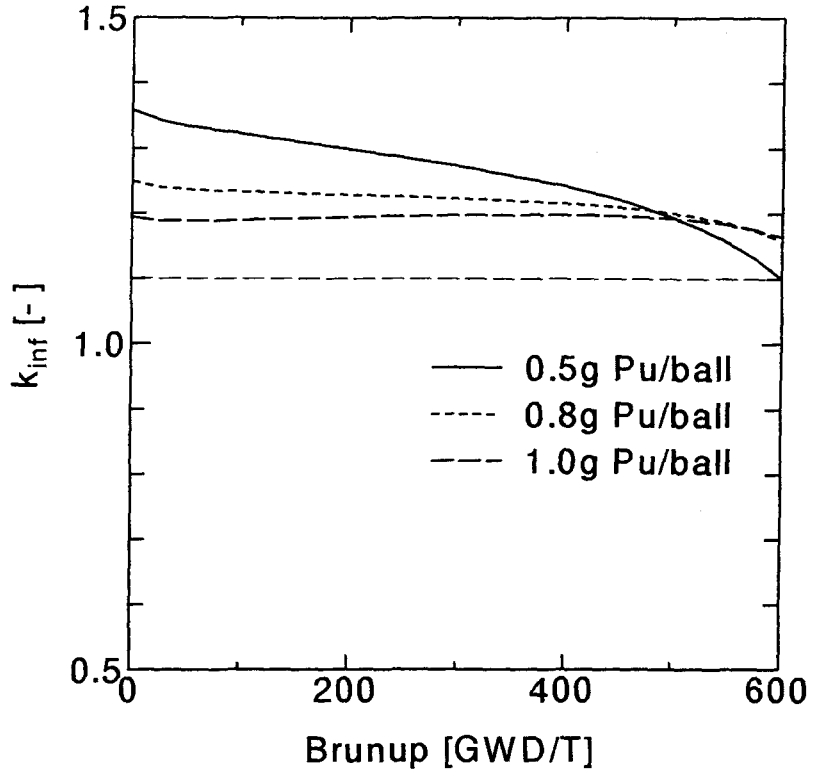

Fig. 4.1.1 Change in infinitive multiplication factors of Pu fuel in different Pu loading

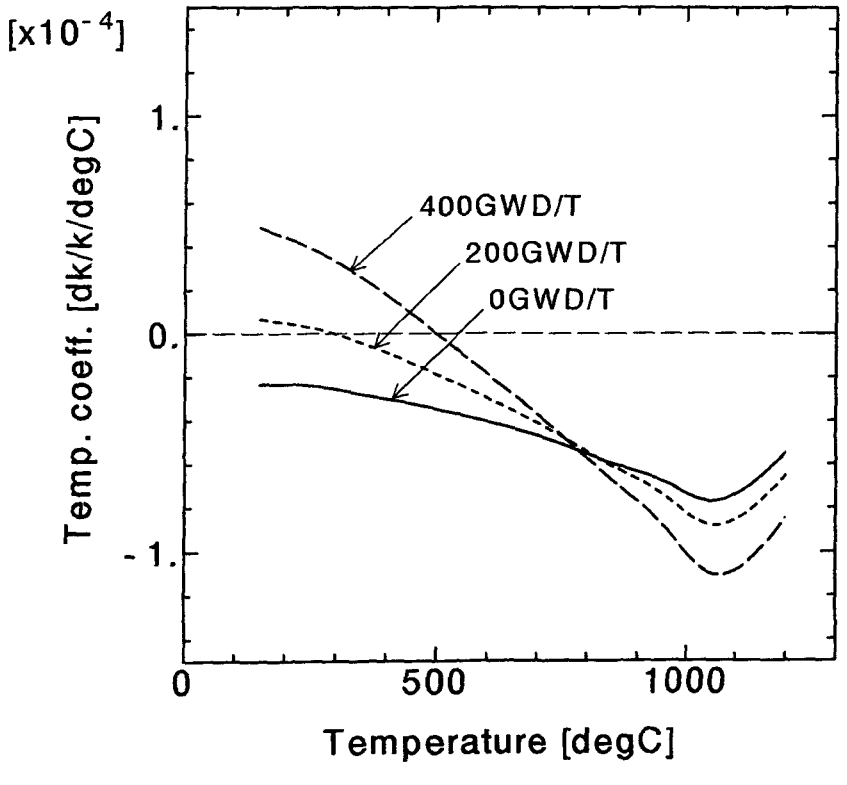

Fig. 4.1.2 Change in isothermal temperature coefficients of 0.8g Pu/ball

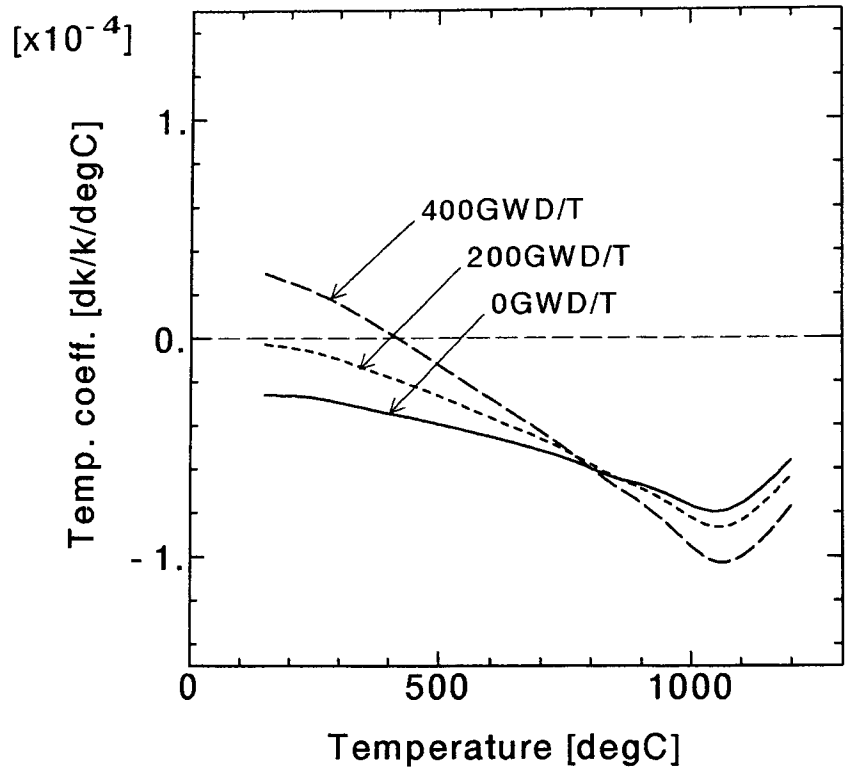

Fig. 4.1.3 Change in isothermal temperature coefficients of 1.0g Pu/ball

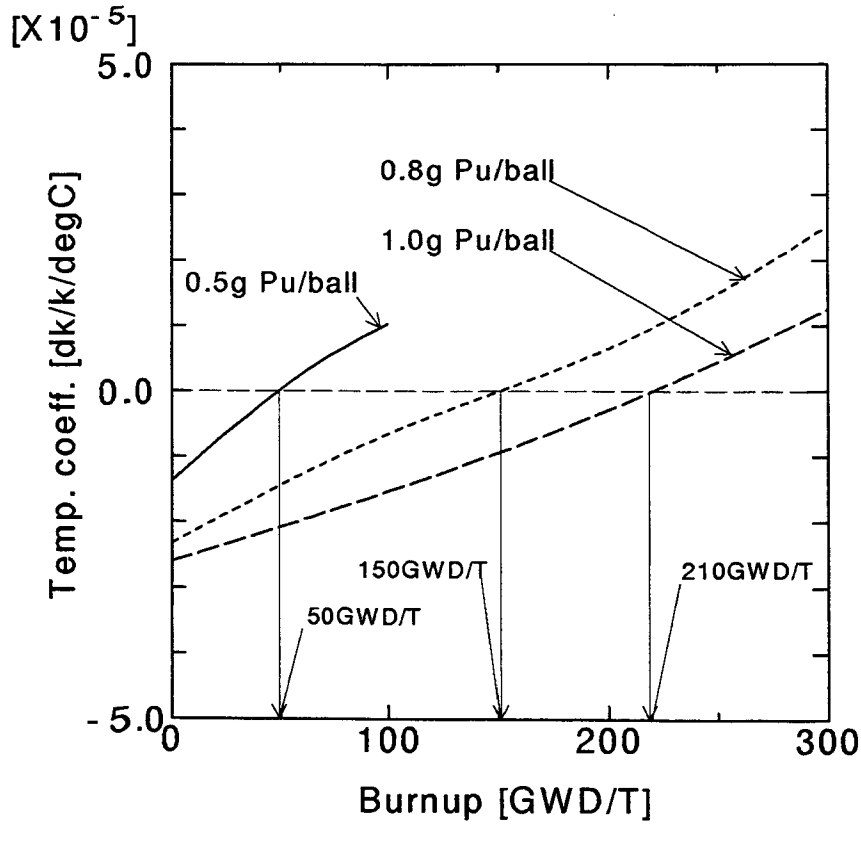

Fig. 4.1.4 Change in maximum isothermal temperature coefficients with burnup in each Pu loading

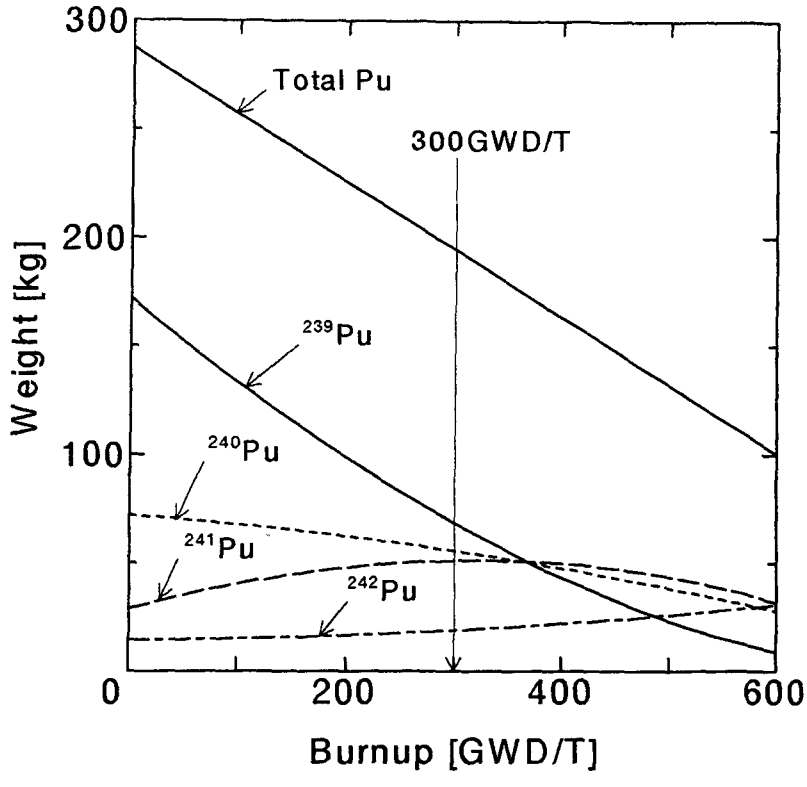

Fig. 4.1.5 Change in amount and composition of Pu of 0.8g Pu/ball

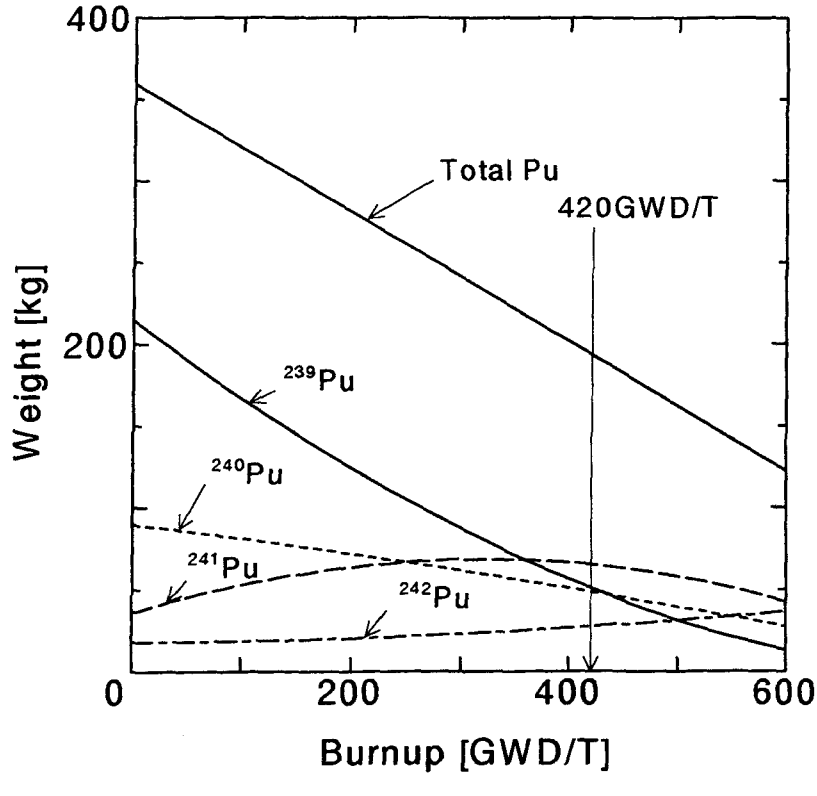

Fig. 4.1.6 Change in amount and composition of Pu of 1.0g Pu/ball

4.2 Characteristics of temperature coefficients and burnup performance of Pu+U fuel

The burnup characteristics of Pu-fueled reactors have been evaluated in the above section. In the Pu-fueled reactors, burnup is restricted by the period in which the isothermal temperature coefficients are negative. To obtain a higher burnup for a higher Pu burning ratio, it is necessary to obtain the longer burnup period with negative isothermal temperature coefficients. For this purpose, ^{238}U is utilized as a resonance absorber. ^{238}U has a smaller thermal absorption cross section and a larger resonance integral than Th^{232} . It is expected that ^{238}U would improve the isothermal temperature coefficients. However, the amount of ^{238}U should be small because ^{238}U produces Pu by neutron absorption. It is important to optimize the amount of ^{238}U to achieve a higher Pu burning ratio.

^{238}U is added to the fuel as natural U. The fuel ball contains CFPs with PuO_2 kernels and CFPs with UO_2 kernels. The isotopic composition of Pu and the specification of the fuel are shown in Table 2.1.

To clear the effect of U on the reactivity, k_{inf} for different heavy metal loadings with different ratios of U to Pu are calculated. The k_{inf} of Pu+U fuel in different Pu loading are shown in Fig. 4.2.1. In the figure, the solid line shows the value of Pu fuel without U. The dotted line shows the value of Pu+U fuel whose ratio of Pu:U is 1:1, the hatched line shows the value of Pu+U fuel whose ratio of Pu:U is 1:2.

At an increase in the ratio of U, the k_{inf} decreases and its peak shifts to left side. Considering the leakage of neutrons, k_{inf} above 1.1 would achieve criticality. In the case that the ratio of Pu:U is 1:1 or 1:2, the Pu loading, which would achieve criticality, is 0.07g to 1g Pu/ball and 0.06g to 0.8g Pu/ball, respectively.

From the results of the previous sections, much heavy metal loading brings negative temperature coefficients. Therefore, characteristics of 0.5g Pu/ball and 0.8g Pu/ball in different ratio of Pu:U are evaluated.

4.2.1 Characteristics of 0.5g Pu/ball in different U loading

Figure 4.2.2 shows the change in k_{inf} of 0.5g Pu/ball with burnup in different U loading. In the figure, the burnup period is expressed in Effective Full Power Days (EFPD) because there is a large difference in the heavy metal loading per fuel ball in

each fuel specification. With increase in the U loading, the initial values of k_{inf} decrease. The k_{inf} of each case is higher than 1.1 by the burnup of 500 EFPD. Considering the leakage of neutrons, k_{inf} above 1.1 would achieve criticality. From the viewpoint of k_{inf}, it is expected that each case would achieve more than the burnup of 500 EFPD.

Isothermal temperature coefficients of 0.5g Pu/ball with 0.5g U/ball and 1.0g U/ball are shown in Figs 4.2.3 and 4.2.4, respectively. The isothermal temperature coefficients of 0.5g Pu/ball without U are already shown in Fig. 3.1.3. In the Fig. 3.1.3, 99 GWD/T and 198 GWD/T correspond to 90 EFPD and 180 EFPD, respectively. Here, the isothermal temperature coefficients decrease with increase in U loading. In the Figs 3.1.3 and 4.2.3, isothermal temperature coefficients at 90 EFPD have positive values in the low temperature region, However, in the Fig 4.2.4, the isothermal temperature coefficients at 90 EFPD are negative in the whole temperature region.

The comparison of isothermal temperature coefficients of different U loading at 0 EFPD and 180 EFPD are shown in Figs 4.2.5 and 4.2.6, respectively. These figures show that the addition of U decreases the isothermal temperature coefficients in the whole temperature region. The effect of U is constant during the burnup because the decrease in U is small.

The changes in the maximum isothermal temperature coefficients with burnup for different U loadings are shown in Fig. 4.2.7. The maximum isothermal temperature coefficients increase with increase in burnup. The maximum isothermal temperature coefficients of 0.0g U/ball, 0.5g U/ball and 0.8g U/ball become zero at 35 EFPD, 65 EFPD and 124 EFPD, respectively. It is considered that the residence time of the discharged fuel is twice the average core residence time of the fuel with continuous refueling. Therefore, the residence time of the discharged fuel of 0.0g U/ball, 0.5g U/ball and 1.0g U/ball become 70 EFPD, 130 EFPD and 240 EFPD, respectively.

The change in the total amount of Pu in each case is shown in Fig. 4.2.8. With an increase in the burnup, the total amount of Pu is decreased in each case. In the case of 0.0g U/ball, 91% of Pu remains at 70 EFPD, which is a core residence time of the discharged fuel. In the case of 0.5g U/ball, the decrease in the total amount of Pu is slower than that of 0.0g U/ball. It is because of the Pu production from neutron absorption by ^{238}U. 86% of the Pu remains at 130 EFPD. In the case of 0.8g U/ball,

the decrease in the total amount of Pu is also slower than that of 0.0g U/ball and 0.5g U/ball. It is also because of Pu production from neutron absorption of ^{238}U. In this case, 77% of the Pu remains at 240 EFPD which is the core residence time of the discharged fuel.

From the figure, the followings are cleared. The case of 0.0g U/ball shows the most rapid Pu burning. However, it can burn only 9% of Pu because of its short core residence time of the fuel. The fuels with Pu+U show slower Pu burning due to Pu production from ^{238}U. With increase in the amount of U, Pu burning becomes slower. However, Pu burning per cycle become higher with increase in the amount of U. It is owing to the long core residence time of the fuel.

The utilization of U is effective to burn Pu because of its improvement of the isothermal temperature coefficients.

4.2.2 Characteristics of 0.8g Pu/ball in different U loading

In the previous section, it became clear that much heavy metal loading improves the isothermal temperature coefficients. To evaluate the effect on Pu burning performance of much heavy metal loading, the cases of 0.8g Pu/ball with U are also calculated.

Figure 4.2.9 shows the changes in k_{inf} of 0.8g Pu/ball in different U loadings. Each case shows a lower initial value of k_{inf} than that of 0.5g Pu/ball with the same ratio of U to Pu as shown in Fig. 4.2.2. However, the changes in k_{inf} with burnup are more flat because of much heavy metal loading. The cases of 0.0g U/ball and 0.8g U/ball would achieve more than 900 EFPD. The case of 0.8g U/ball shows about 1.1 or higher value of k_{inf} by 900 EFPD. After 900 EFPD, it decrease below 1.1. Therefore. it is expected that 0.8g U/ball would achieve about 1000 EFPD of burnup from the viewpoint of k_{inf} with continuous refueling.

The change in the isothermal temperature coefficients with burnup of 0.8g U/ball and 1.6g U/ball are shown in Figs. 4.2.10 and 4.2.11, respectively. The change in isothermal temperature coefficients of 0.8g Pu/ball without U are already shown in Fig. 4.1.2. In the figure, 200 GWD/T and 400 GWD/T correspond to 288 EFPD and 576 EFPD, respectively. From the figures, isothermal temperature coefficients are decreased with an increase in the U loading in the whole temperature range and in every burnup step. The effects of ^{238}U on the isothermal temperature coefficients at 0

EFPD and 576 EFPD are shown in Figs 4.2.12 and 4.2.13, respectively. Figure 4.2.12 shows that the isothermal temperature coefficients are decreased with increase in U loading in the whole temperature region. The decrease in the isothermal temperature coefficients are larger than those shown in Fig. 4.2.5. It is because of the difference in the amount of U added into the fuel ball. For a higher burnup, the isothermal temperature coefficients in the low temperature region also decrease with an increase in the amount of U.

The change in the maximum isothermal temperature coefficients in each case are shown in Fig. 4.2.14. The figure also shows that the isothermal temperature coefficients decrease with an increase in the amount of U. The isothermal temperature coefficients of 0.0g U/ball, 0.8g U/ball and 1.6g U/ball become zero at 215 EFPD, 380 EFPD and 600 EFPD in the same manner as stated section 4.1, respectively.

0.0g U/ball and 0.8g U/ball achieve about 430 EFPD and 760 EFPD of core residence time of fuels, respectively.

In the case of 1.6g U/ball, 1120 EFPD of the core residence time of the fuel would be achieved from the viewpoint of isothermal temperature coefficients. However, the core residence time of the fuel is about 1000 EFPD from the viewpoint of k_{inf} as stated before. The shorter period should be the core residence time of the fuel.

The change in the total amount of Pu in each case is shown in Fig. 4.2.15. The initial amount of Pu is 360 kg in each case. The total amount of Pu decreases in each case. In the case of 0.0g U/ball, the total amount of Pu decreases more rapidly. It remains 67% of Pu at 430 EFPD. In the case of 0.8g U/ball, the decrease in the total Pu is slower than that of 0.0g U/ball. It is because of Pu production from neutron absorption of ^{238}U. However, 51% of Pu remains at 760 EPFD. In the case of 1.6g U/ball, the decrease in the total amount of Pu is also slower than that of 0.0g U/ball and 0.8gU/ball. However, the 43% of Pu remains at 1000 EFPD.

Less U brings rapid burning of Pu. However, the burning ratio of Pu per cycle is small due to its short core residence period of fuel. Much U loading means slower Pu burning due to Pu production from U. However, the burning ratio of Pu per cycle become higher with increase in U loading due to its long core residence time of the fuels.

Table 4.2.1 shows characteristics of Pu burning reactors with Pu+U fuel. By an Increase in the Pu loading and U loading, the cycle length, and the Pu burning ratio per cycle are increased. It is because of a longer cycle length due to much heavy metal loading and increase in ^{238}U as a resonance absorber. However, the Pu burning ratio per year and the normalized amount of burned Pu decrease with increase in U loading. It is considered that the Pu production by neutron absorption of U brings less Pu burning per year. The Pu contents in discharged fuel are decreased with an increase in the U loading. The longer cycle length due to U loading burns much Pu in the fuel ball.

Therefore, to achieve much Pu burning per year, less Pu loading without U loading would be suitable. To achieve higher burnup and less residual Pu in a discharged fuel, much Pu loading and much U loading would be suitable. The specification of the heavy metal loading should be chosen according to the purpose of the reactor.

Table 4.2.1 Characteristics of Pu burning reactors with Pu+U fuel

Pu loading (g/ball)	0.5			0.8		
U loading (g/ball)	0.0	0.5	1.0	0.0	0.8	1.6
thermal power (MW)	200	200	200	200	200	200
Cycle length (EFPD)	70	130	240	430	760	1000
Pu burnup ratio (%/cycle)	9	14	23	33	49	57
Pu burnup ratio (%/year)	47	39	35	28	24	21
Normalized amount of burned Pu (kg/GW year)	423	351	315	403	346	302
Pu contents in discharged fuel (g/ball)	0.46	0.43	0.39	0.54	0.41	0.34

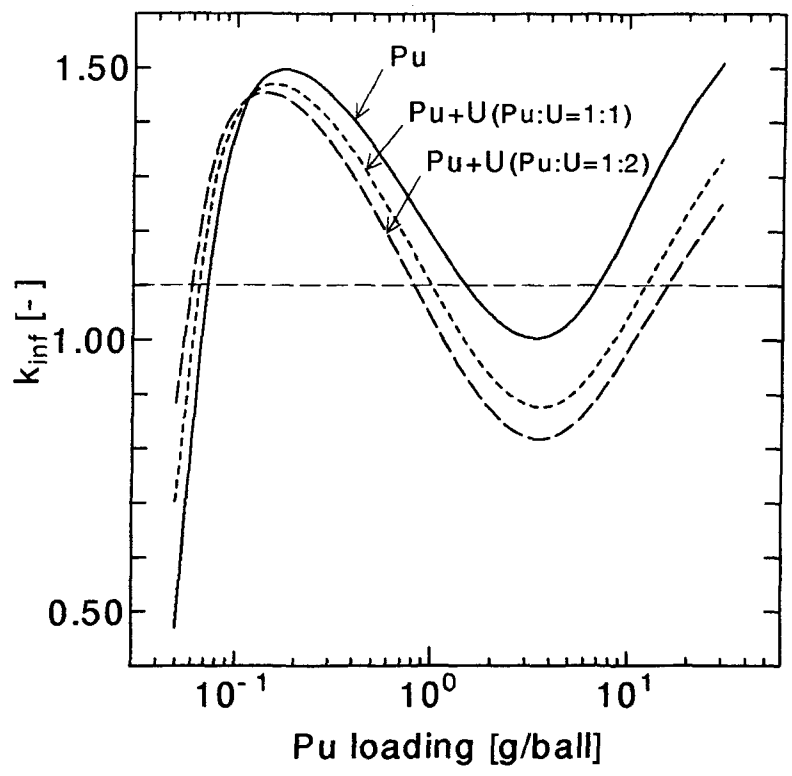

Fig. 4.2.1 Infinitive multiplication factor of Pu+U fuel in different U loading

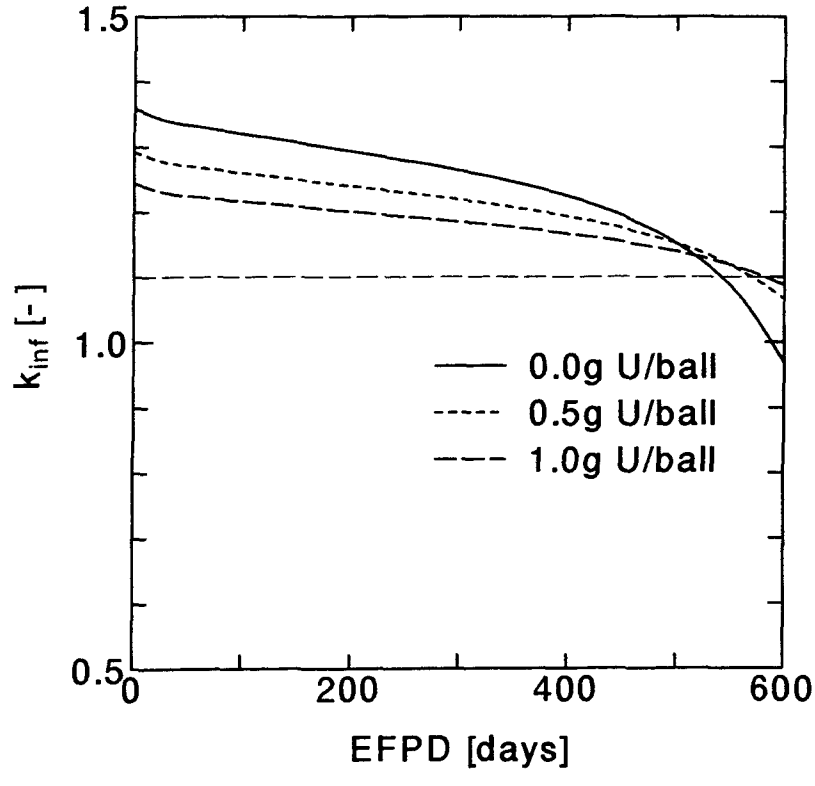

Fig. 4.2.2 Change in infinitive multiplication factor of 0.5g Pu/ball with different amounts of U

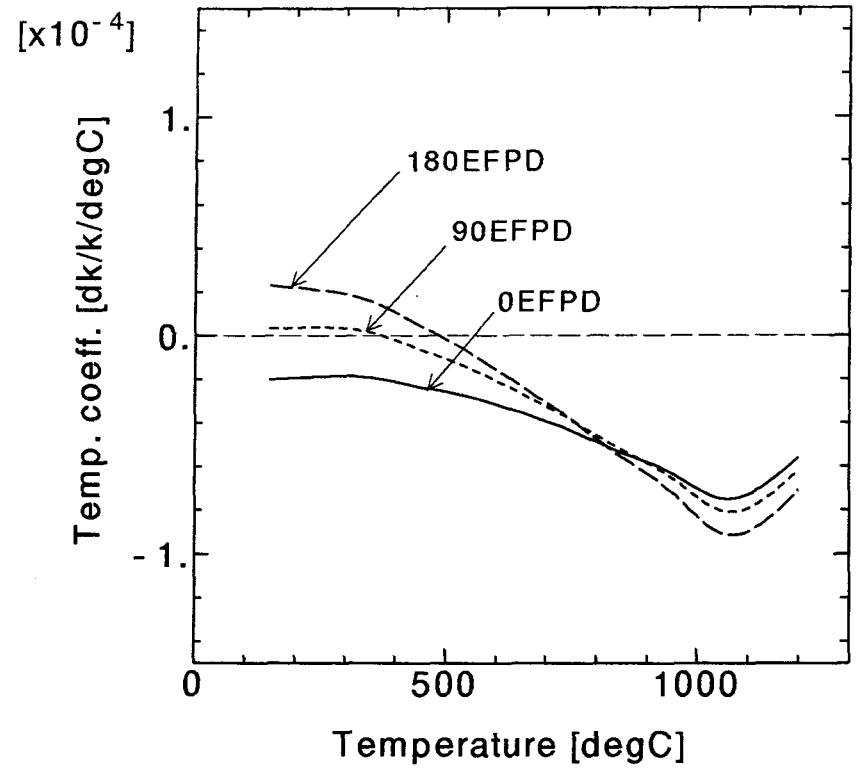

Fig. 4.2.3 Change in isothermal temperature coefficients with burnup of 0.5g Pu and 0.5g U/ball

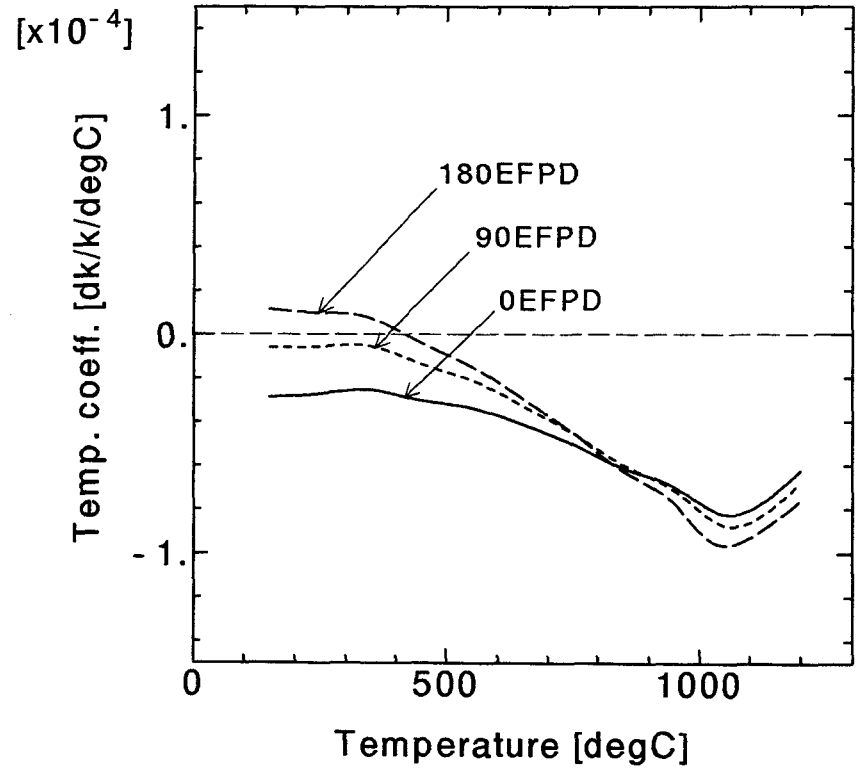

Fig. 4.2.4 Change in isothermal temperature coefficients with burnup of 0.5g Pu and 1.0g U/ball

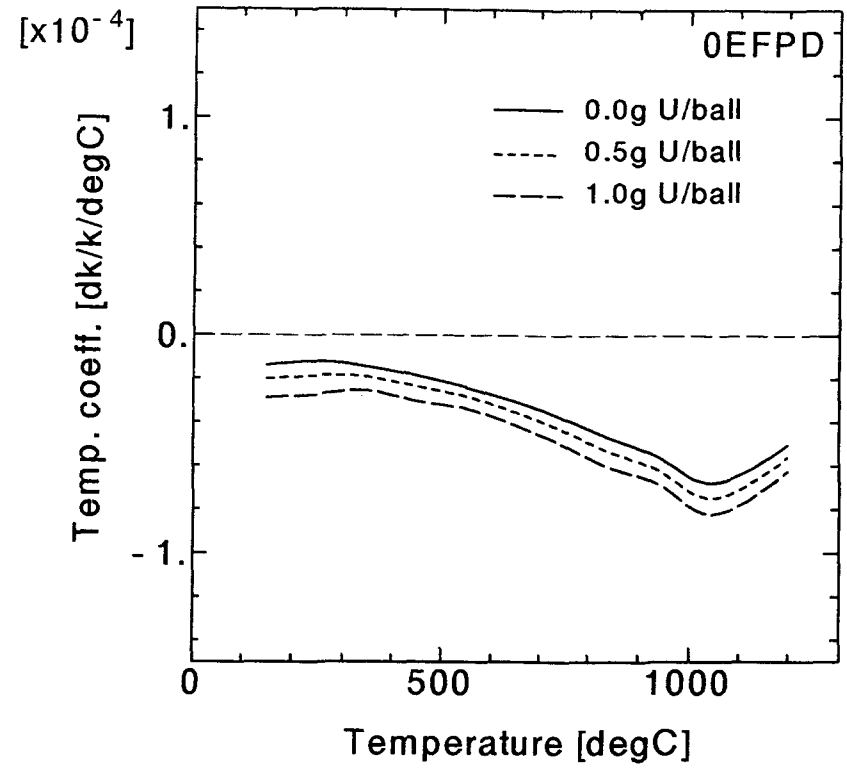

Fig. 4.2.5 Isothermal temperature coefficients of 0.5g Pu/ball at 0EFPD for different U loadings

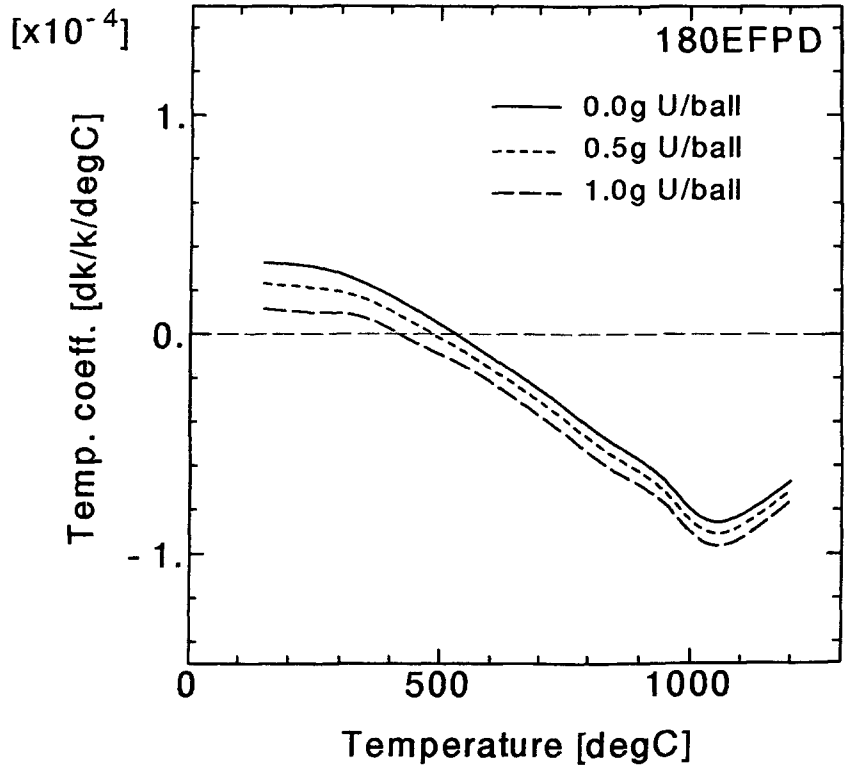

Fig. 4.2.6 Isothermal temperature coefficients of 0.5g Pu/ball at 180EFPD for different U loading

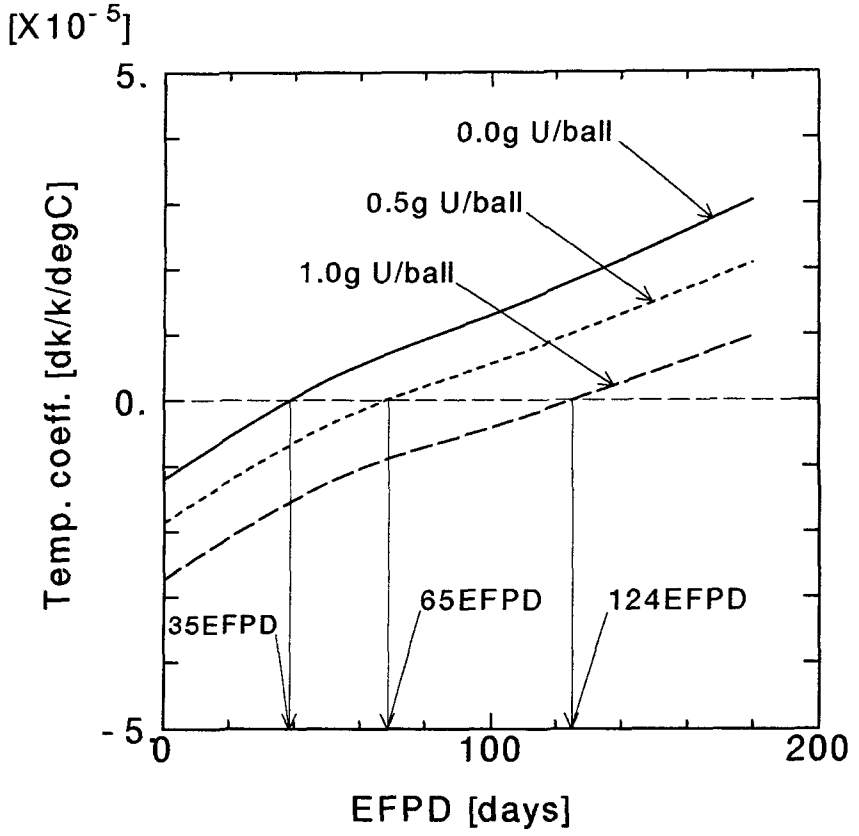

Fig. 4.2.7 Change in the maximum isothermal temperature coefficients of 0.5g Pu/ball for different U loading

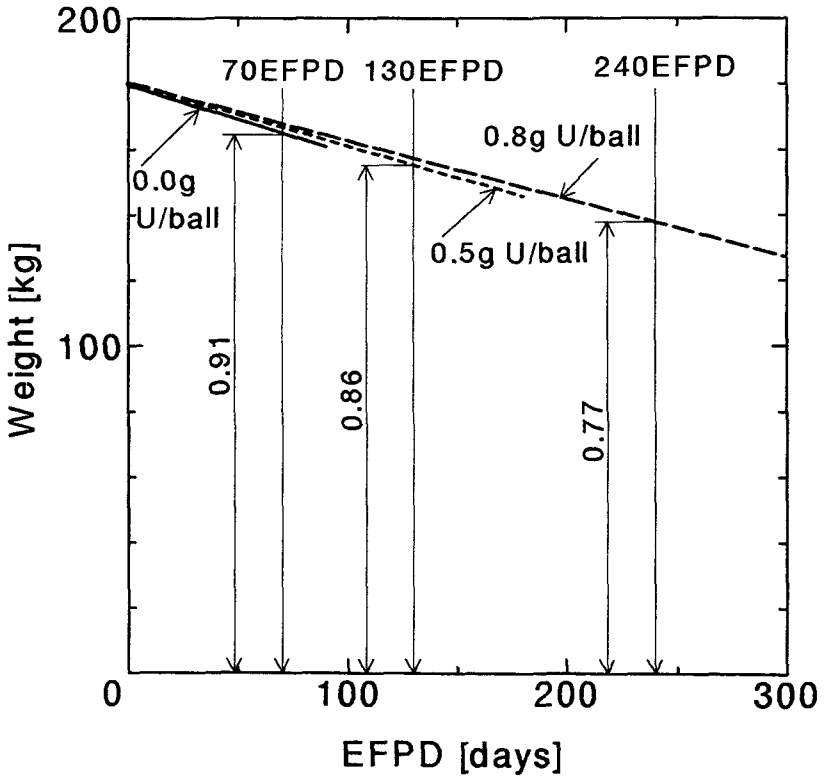

Fig. 4.2.8 Change in total Pu at 0.5g initial Pu/ball with different U loading

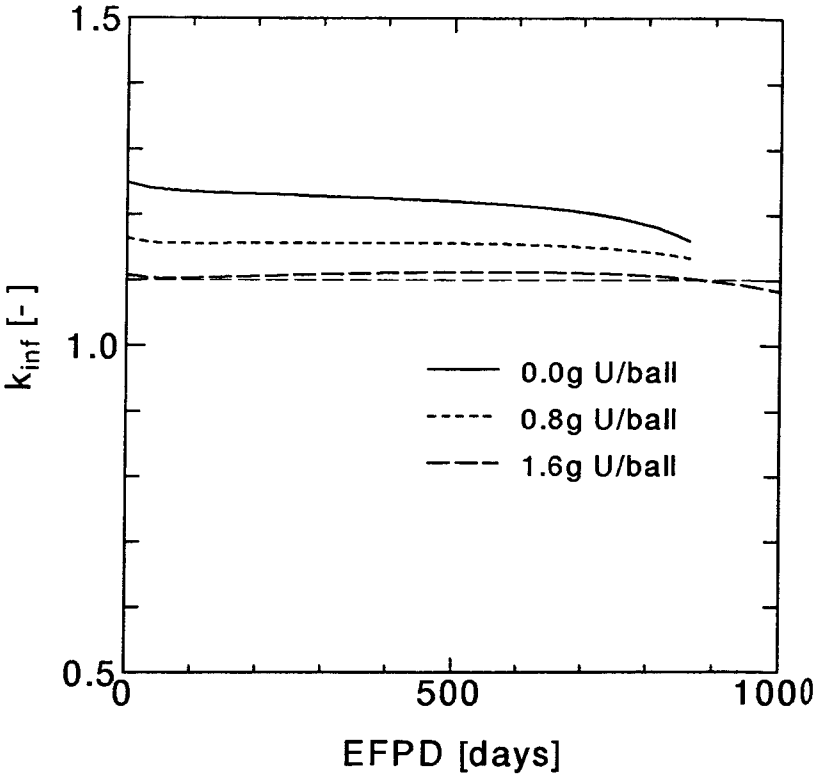

Fig. 4.2.9 Change in the infinitive multiplication factor for 0.8g Pu/ball with different U loadings

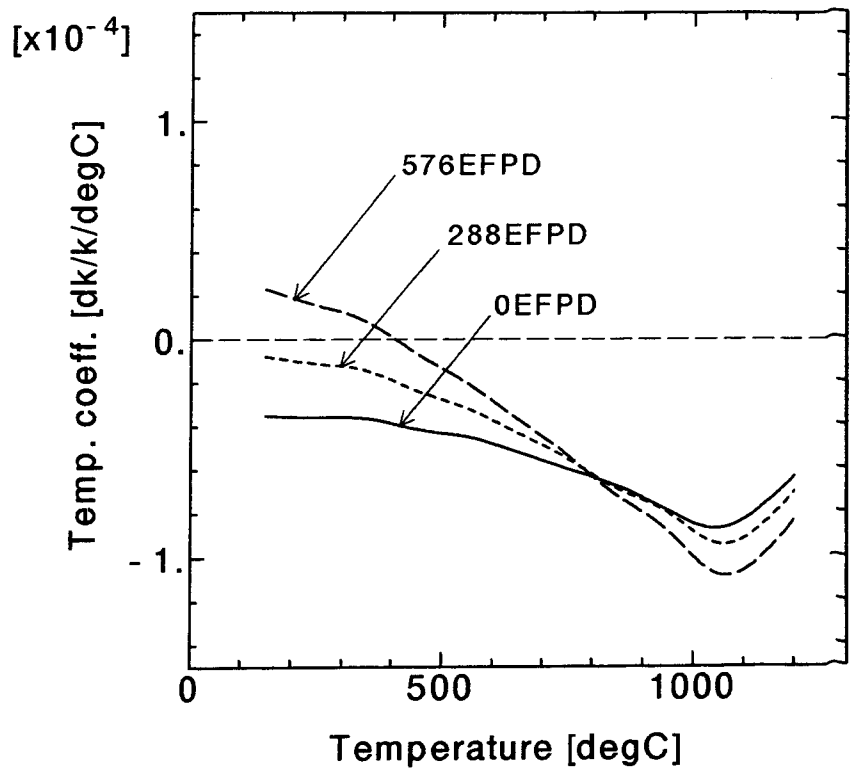

Fig. 4.2.10 Isothermal temperature coefficients of 0.8g Pu and 0.8g U/ball

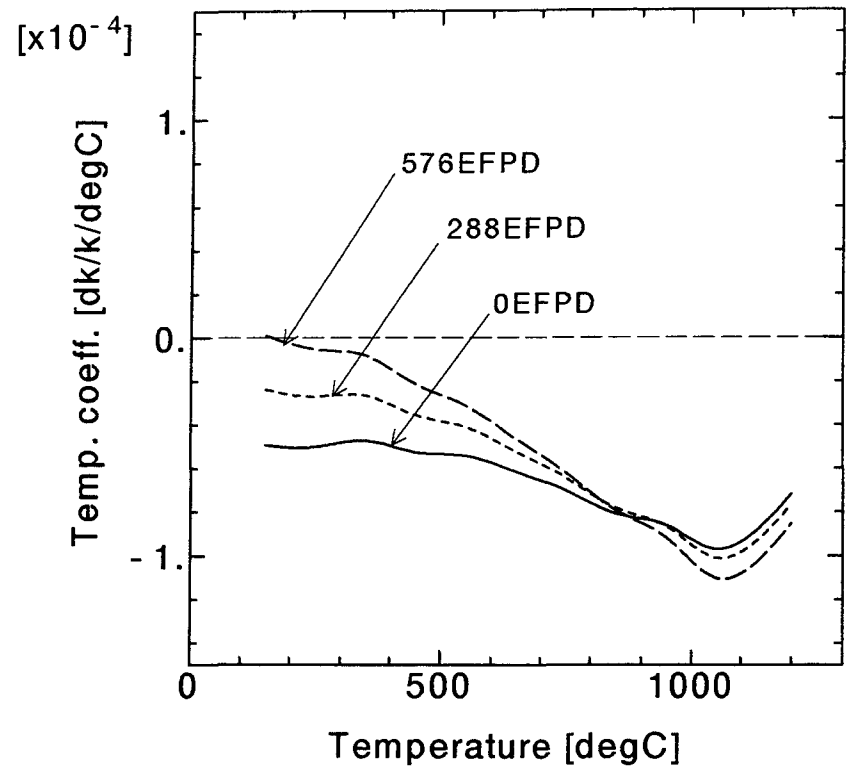

Fig. 4.2.11 Change in the isothermal temperature coefficients of 0.8g Pu and 1.6g U/ball

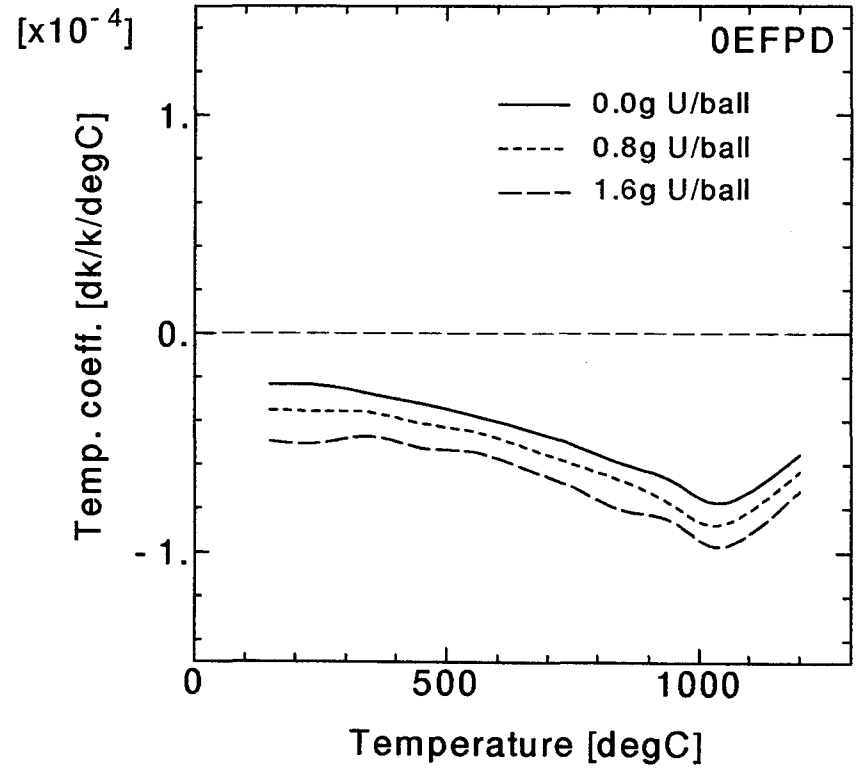

Fig. 4.2.12 Isothermal temperature coefficients of 0.8g Pu/ball with different U loading at 0 EFPD

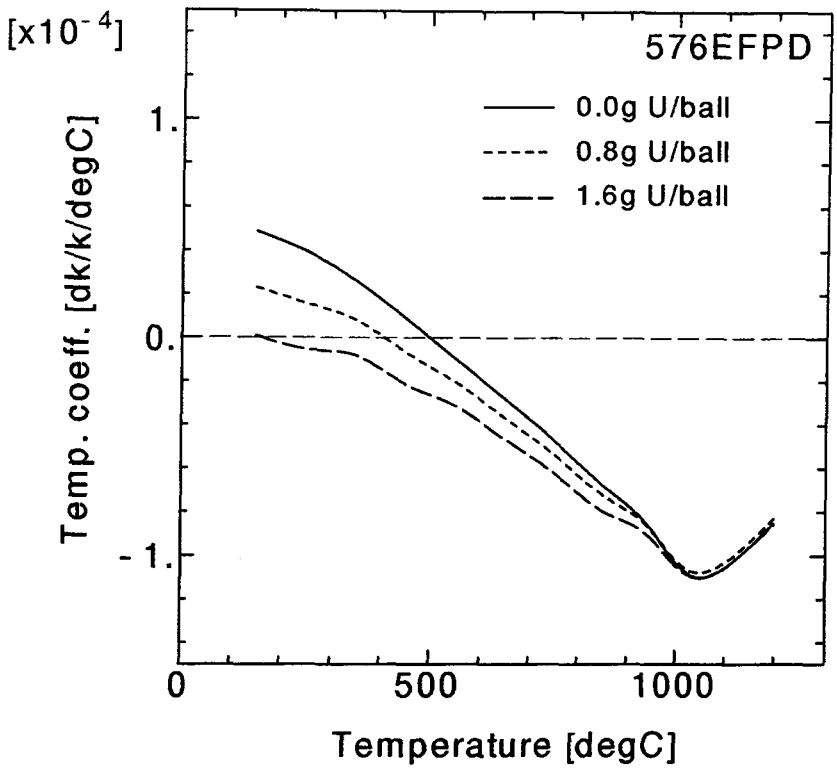

Fig. 4.2.13 Isothermal temperature coefficients of 0.8g Pu/ball with different U loading at 576EFPD

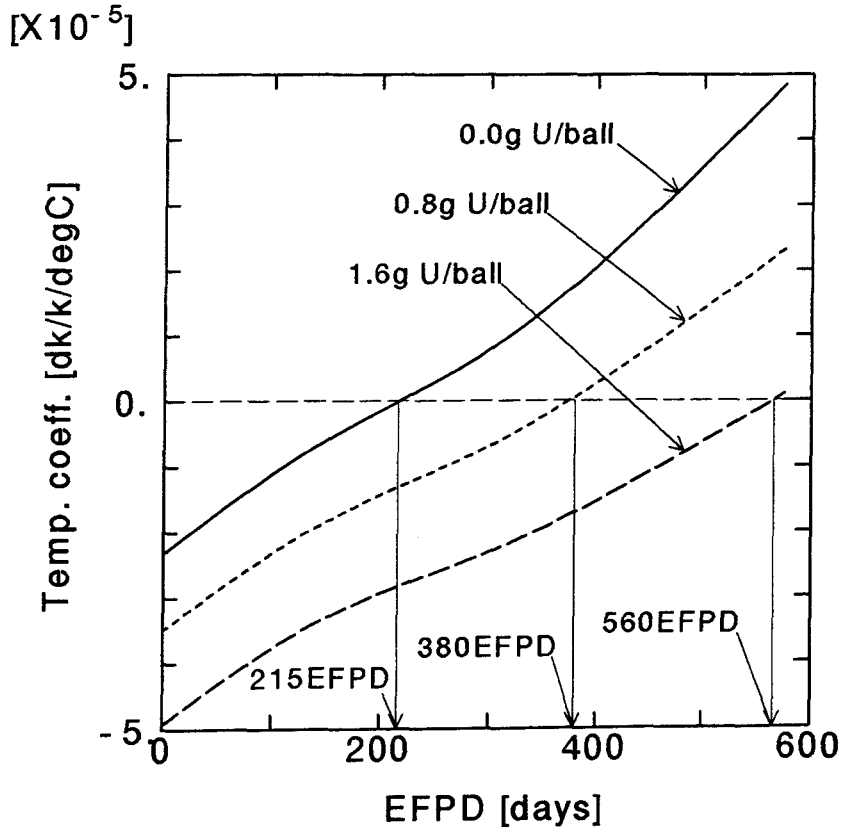

Fig. 4.2.14 Change in maximum isothermal temperature coefficients of 0.8g Pu/ball with different U loading

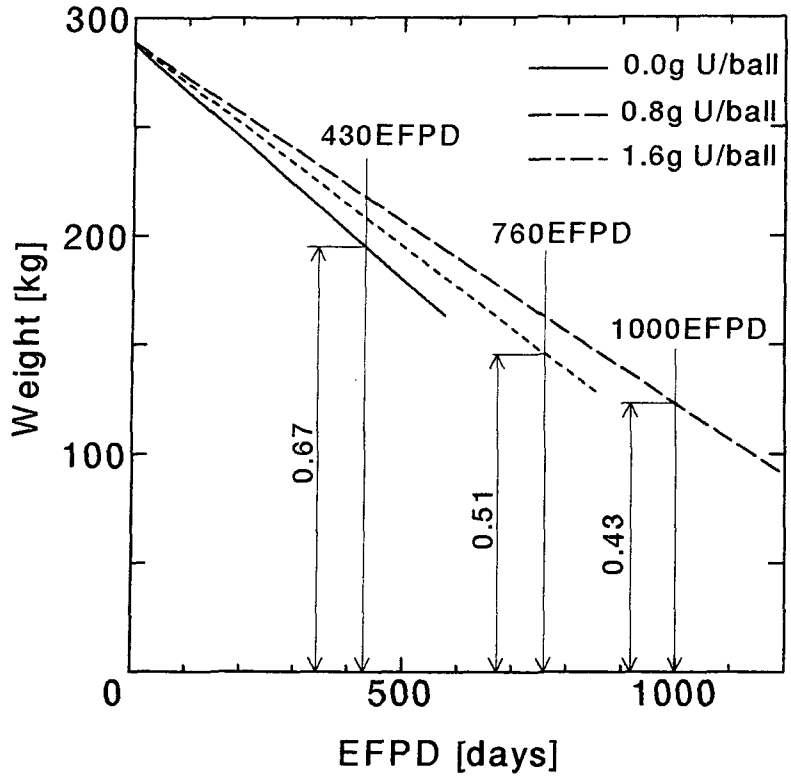

Fig. 4.2.15 Change in the total amount of Pu at 0.8g initial Pu/ball with different U loading

4.3 Effect of U on isothermal temperature coefficients

In the previous section, it became clear that the addition of U as a resonance absorber is effective to improve the isothermal temperature coefficients. Therefore, the effects of U on the isothermal temperature coefficients have been investigated in more detail.

The addition of U brings resonance absorption of neutrons. In order to clear this effect, doppler and moderator coefficients have been evaluated. The doppler coefficients are calculated as the temperature coefficients at a constant moderator temperature, varying the fuel temperature. The moderator coefficients then are the temperature coefficients at a constant fuel temperature, varying the moderator temperature.

The doppler, moderator and isothermal temperature coefficients of 0.8g Pu and 0.8g U/ball at 0 EFPD are shown in Fig. 4.3.1. The figure shows that the doppler coefficients are negative but small in the whole temperature range. The moderator coefficients are more negative than the doppler coefficients. Therefore, the moderator coefficients play a dominant role in the isothermal temperature coefficients.

The change in the number density of U during burnup is very small due to its small absorption cross section. It means that the doppler coefficients would show a nearly constant value during burnup. Therefore, the change in the isothermal temperature coefficients during burnup are mainly caused by the change in the moderator coefficients.

The doppler, moderator and isothermal temperature coefficients of 0.8g Pu and 1.6g U/ball at 0 EFPD are shown in Fig. 4.3.2. Compared to the Fig. 4.3.1, the doppler coefficients are more negative. It is because of a high amount of U in the fuel ball. The moderator coefficients have a value similar to the case of 0.8g Pu and 0.8g U/ball. The isothermal temperature coefficients are more negative due to larger doppler coefficients.

These figures show that the addition of U makes the isothermal temperature coefficients negative on account of its resonance neutron absorption. However, the effect is not dominant. During burnup, doppler coefficients would be nearly constant because the number density of U changes very small. Therefore, the increase in the isothermal temperature coefficients with increase in burnup results from the increase in

the moderator coefficients with increase in burnup. The moderator coefficients are owing to the change in neutron flux with burnup. In the calculation, the power density is kept constant (3 W/cm^3). With increase in burnup, the amount of fissile material decreases. Thus, the neutron flux increases to keep the power density constant. The higher neutron flux enhances the effect of ^{135}Xe. Therefore, the isothermal temperature coefficients become positive with increase in burnup. The power density is an important parameter for the isothermal temperature coefficients.

It is said that the giant resonance cross section of ^{239}Pu at 0.3 eV plays an important role in the temperature coefficients. However, although the amount of ^{239}Pu decreases with increase in burnup, the isothermal temperature coefficient becomes large. Therefore, it is clear that the ^{239}Pu does not play an important role on the temperature coefficients.

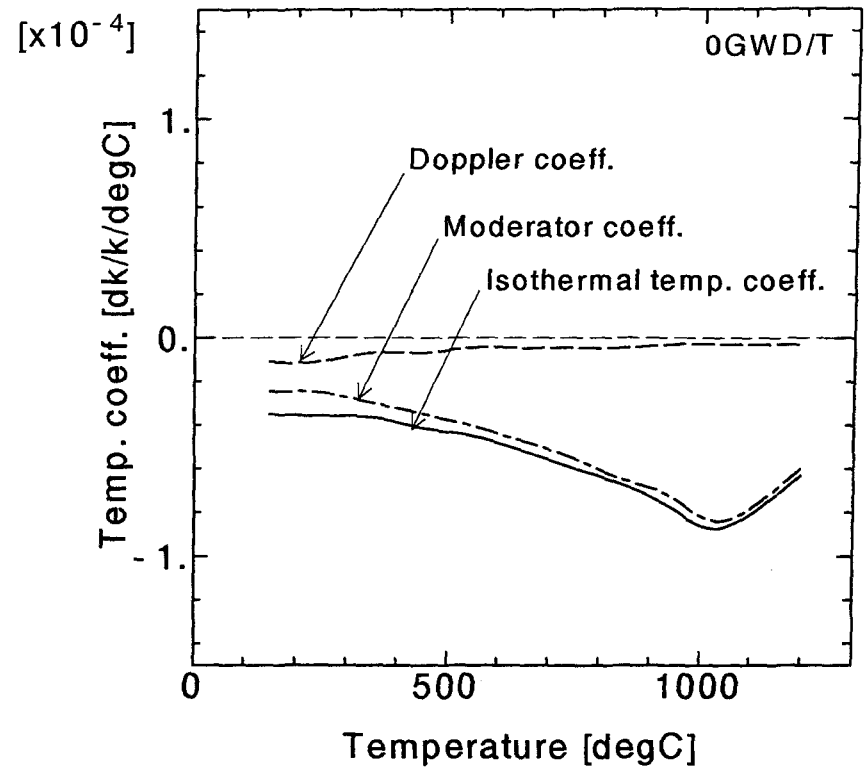

Fig. 4.3.1 Doppler, moderator and isothermal temperature coefficients of 0.8g Pu and 0.8g U/ball at 0 GWD/T

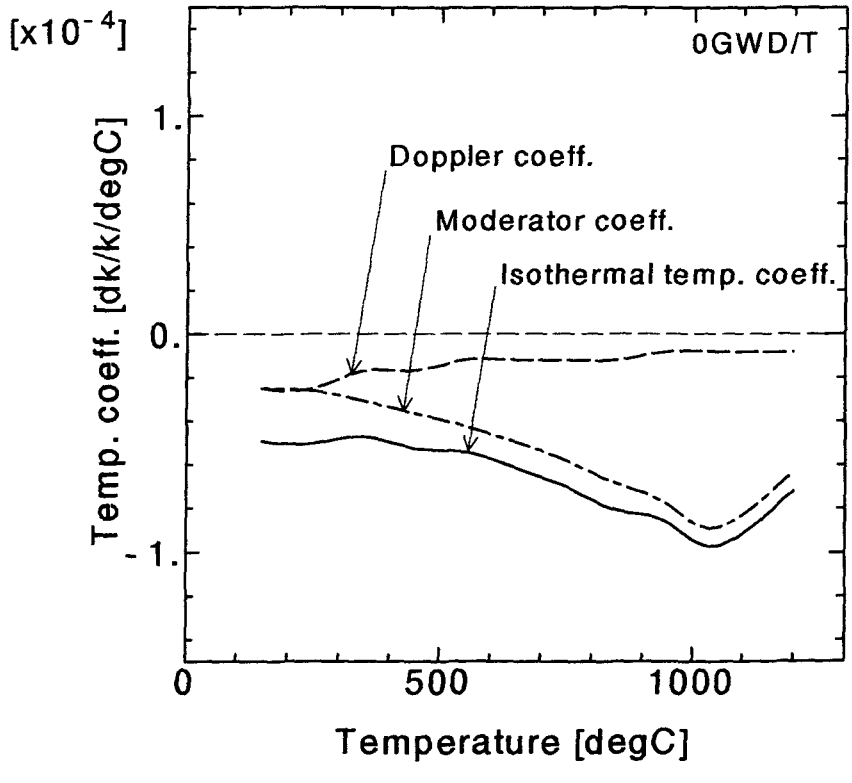

Fig. 4.3.2 Doppler, moderator and isothermal temperature coefficients of 0.8g Pu and 1.6g U/ball at 0 GWD/T

5. Conclusion

The MA transmutation HTGRs have the possibility to achieve a high MA transmutation ratio. To investigate some safety aspects of the MA transmutation HTGRs, the isothermal temperature coefficients have been evaluated for different fuel specifications, with and without resonance absorber materials.

By this study, it becomes clear that for Pu+MA fuel, the period in which the isothermal temperature coefficients are negative is too short to achieve a high MA transmutation ratio. It is necessary to utilize resonance absorber material to extend the burnup period, aiming at a high MA transmutation ratio. Therefore, the effects of Th and U are evaluated.

As a result, it becomes clear that Th could not improve the isothermal temperature coefficients. Using a relatively high amount of U^{238} as breed material could make the isothermal temperature coefficients negative, which brings a higher fuel burnup. High burnup is also expected for MA transmutation HTGRs. Therefore, utilizing U and a high heavy metal loading would improve the isothermal temperature coefficients of MA transmutation HTGRs and would bring a higher MA transmutation ratio.

For the Pu burning HTGRs, a higher heavy metal loading with U brings a higher Pu burning ratio per burnup cycle. Less heavy metal loading without U brings a short burnup cycle and a smaller Pu burning ratio per cycle. However, it would burn a high amount of Pu per year because there is no Pu production from U.

So there are two options for Pu burning HTGRs. For burning Pu as much as possible, fuel of low Pu loading without U is expected. The fuel aims to reduce the stockpile of Pu as fast as possible. For utilizing Pu effectively, the fuel with a high heavy metal loading and U is adequate. The fuel achieves a long burnup cycle and a high burnup of Pu per cycle. The fuel also contributes to reduce the fuel reprocessing procedure and has a possibility for direct disposal of discharged fuel.

The improvement of the isothermal temperature coefficients utilizing U is mainly caused by the resonance absorption of U. However, the isothermal temperature coefficients become positive with an increase in burnup due to the change in the thermal neutron flux which enhances the effect of ^{135}Xe. The change in the neutron

flux is inevitable with burnup. It is impossible to reduce the effect by utilizing U. The power density is an important parameter for the isothermal temperature coefficients.

There still are many items to be considered, i.e., burnup analysis by core calculation, countermeasures to water ingress accident, irradiation performance of fuel, reactor dynamic analysis and so on. However, the concept of the HTGRs with Pu+U - fuel for actinide burning reactors is one possible way to achieve a high burning ratio of actinides. The study should be continued.

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