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ARTICLE

Burning of MOX Fuels in LWRs; Fuel History Effects on Thermal Properties of Hull and End Piece Wastes and the Repository Performance

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Abstract

The thermal impacts of hull and end piece wastes from the reprocessing of MOX spent fuels burned in LWRs on repository performance were investigated. The heat generation rates in MOX spent fuels and the resulting heat generation rates in hull and end piece wastes change depending on the history of MOX fuels. This history includes the burn-up of UO_2 spent fuels from which the Pu is obtained, the cooling period before reprocessing, the storage period of fresh MOX fuels before being loaded into an LWR, as well as the burn-up of the MOX fuels. The heat generation rates in hull and end piece wastes from the reprocessing of MOX spent fuels with any of those histories are significantly larger than those from UO_2 spent fuels with burn-ups of 45 GWd/THM. If a temperature below 80°C is specified for cement-based materials used in waste packages after disposal, the allowable number of canisters containing compacted hull and end pieces in a package for 45 and 70 GWd-MOX needs to be limited to a value of 0.4 to 1.6, which is significantly lower than 4.0 for 45 GWd-UO_2.

KEYWORDS: MOX-LWR, thermal impact, history of MOX fuels, hull and end piece waste, burn-up, cooling period, cementitious material, geological disposal

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I. Introduction

Commercial mixed oxide fuels for light water reactors (MOX-LWRs) (including demonstration tests) have been used in Western European countries, such as Belgium, France, Germany and Switzerland since the 1960's.[1] The commercial use of MOX fuels in LWRs has started in Japan as well. The extensive use of such fuels will affect waste management because the characteristics of MOX spent fuels differ from those of present-day UO_2 spent fuels.

Bouvier et al. assessed the environmental impact of different fuel cycles for Pressurized Water Reactors (PWRs) and Fast Reactors (FRs). [2] These assessments showed that environmental impacts for a MOX-PWR are substantially higher than those observed for a UO_2 -PWR and FR. Oigawa et al. studied the possible impact of Partitioning and Transmutation (P&T) technology on the management of high-level waste (HLW) for a UO_2-LWR and a MOX-LWR. [3] This study concluded that the emplacement area in the repository site required for HLW generated from the reprocessing of MOX spent fuels was significantly reduced by recycling minor actinides, especially Am-241.

Our previous study demonstrated that the operation of a MOX-LWR increased the number of HLW glass units per GWd by a factor of two in comparison with that of a UO_2 -LWR due to the higher heat generation rate in the MOX HLW.[4] We have also determined the impact of wastes that include transuranic elements (hereafter referred to as TRU waste) on deep geological disposal. Hull and end piece wastes comprised of the debris and residue from shearing and dissolution of spent fuel assemblies were found to be the most troublesome because they have the highest heat generation rate among all types of TRU wastes. [5] The number of canisters containing these wastes loaded in a cement waste package must be decreased from four to around one to avoid

degradation of the cementitious filler materials due to the elevated temperature, mainly caused by the actinides Pu-238 and Am-241. [6)]

In the above studies, a typical set of total Pu content and Pu isotopic compositions for initial MOX fuel have been used to calculate radioactivity and heat generation rates in the wastes from reprocessing of MOX spent fuels. However, the total Pu content and Pu isotopic composition may change depending on the MOX fuel-histories before loading the fuels into an LWR. For example, if the cooling period of UO_2 spent fuels is extended for technical or social reasons, the amounts of Pu-241 and Am-241 initially included in MOX fuels fabricated after reprocessing of these extended-cooling-period UO_2 spent fuels may significantly change because of the relatively short half-life of Pu-241. If the fuel-histories change the Pu isotopes and the Am-241 ratio in the initial MOX fuels, the heat generation rate in the MOX spent fuels and the resulting repository emplacement area for wastes from reprocessing of these MOX spent fuels may be affected.

In the present study, we investigated the thermal effects of the burn-up history of MOX-LWR fuels on a geological disposal system for hull and end piece wastes. We selected the following historical parameters : 1) burn-ups, 2) cooling periods for the UO_2 spent fuels before reprocessing, and 3) storage periods for MOX fuels before they were loaded into an LWR. The impacts of these parameters on the disposal system were evaluated by performing burn-up calculations for MOX fuels and two-dimensional thermal analyses of the galleries and their surrounding rock at depths of 500 m.

II. Calculation Methods and Conditions

Figure 1 shows the flow chart of the present calculation. First, the total Pu content and Pu isotopic composition in initial MOX fuels were calculated using the Pu

isotopic composition in UO_2 spent fuels obtained by burn-up calculations for UO_2 fuels, taking into account various histories of MOX fuels before being loaded into a PWR. The burn-ups of the UO_2 spent fuels, the cooling periods before reprocessing of the spent fuels, and the storage periods for MOX fuels before being loaded into LWRs were chosen as parameters of the MOX fuel-histories. All burn-up calculations were conducted for a fuel pin in a typical 17x17 PWR fuel assembly using the SWAT code system.[7] The heat generation rates in MOX spent fuels were obtained using burn-up calculations considering full MOX cores. Next, the heat generation rate in a canister containing compacted hull and end piece wastes was calculated. Finally, the temperature distributions in a disposal gallery and the surrounding sedimentary rock were evaluated using a two-dimensional finite element method (FEM) as a function of time - up to one thousand years after disposal.

>> Figure 1

1. Heat generation rate in MOX spent fuels

Burn-up calculations for UO_2 fuels with 28, 45 and 70 GWd/THM (gigawatt days per ton of heavy metal) were conducted; enrichments of U-235 were chosen to be 2.6, 4.5 and 6.5 wt.%, respectively.[4] The Pu isotopic compositions in initial MOX fuels were calculated from the above UO_2 spent fuel compositions, assuming the cooling periods for UO_2 spent fuels were 4, 30 and 50 years and the storage periods for the MOX fuels before being loaded into a PWR were 2 and 10 years. **Table 1** shows eighteen cases for MOX fuels with various histories. A notational system was chosen to show the history of MOX fuels before being loaded into a PWR, such as U28G0402, which represents MOX fuels fabricated after a 4 year cooling period of UO_2 spent fuels with a burn-up of

28 GWd/THM, and stored for 2 years before being loaded into a PWR.

The total Pu content of each MOX fuel with these various Pu isotopic compositions was obtained by a parametric survey of burn-up calculations for MOX fuels so the infinite multiplication factor for these fuels would be the same value as for UO_2 fuels at the end of the equilibrium cycle (EOC), assuming a three-batch fuel management. Burn-ups of MOX spent fuels were chosen to be 45 and 70 GWd/THM, as shown in Fig. 1. The isotopic ratio of U-235 was chosen to be 0.225% assuming that the Pu is mixed with depleted U.[8] As an example, **Table 2** shows the initial MOX fuel composition for a burn-up of 45 GWd/THM.

Finally, the heat generation rates in MOX spent fuels were obtained using burn-up calculations of MOX fuels with the initial fuel compositions shown in Table 2. Any other conditions for burn-up calculations such as the initial composition of structure materials and the neutron flux were selected as in our previous study.[6]

>>Table 1

>>Table 2

2. Heat generation rate in a canister containing compacted hull and end piece waste

Hull and end piece wastes are comprised of the debris and residues from shearing and dissolution of the spent fuel assemblies, which are composed of fuel rod cladding and nozzles. Such debris and residues are compressed and put into stainless steel canisters.[5] Using the heat generation rate in MOX spent fuels obtained in the previous section, the heat generation rate in the canister was calculated from the total decay heat released from activated structural materials and impurities, and the fission

products (FPs) and actinides adhering to the hulls. The cooling period for MOX spent fuels, the volume of a canister and the weight of waste in a canister were chosen in the same manner as in the 2nd TRU report.[5)]

To select the accompanying ratio of FPs and actinides adhering to hulls, the 2nd TRU report and other reports on the radioactivity of hulls are available, which determined these ratios by dissolution experiments of spent fuel pins taken from an LWR. Since those specimens used in the dissolution experiment may have had different features from hulls generated from a reprocessing plant operation, we tentatively used the values adopted in the 2nd TRU report and assumed they are based on reprocessing plant conditions. These values are shown in **Table 3**.

>>Table 3

3. Thermal analyses of disposal galleries and surrounding rock

The canisters containing compacted hull and end piece wastes are put into a waste package. One waste package can hold up to four canisters. The package is then filled with cement-based materials.[5)] The waste packages are then stacked in disposal galleries having a circular- or horseshoe-shaped cross section.[5)]

In the present study, the temperature profiles of disposal galleries and the surrounding rock were obtained by using general purpose software for two-dimensional thermal analysis.[9)] This analysis was conducted by assuming heat conduction in the same manner as in the 2nd TRU report. The waste packages having the heat generation rate determined in the previous section were to be disposed of in multiple galleries having circular cross sections, as shown in **Figure 2**. Waste packages with the same heat generation rates were assumed to be placed throughout the galleries

for the sake of simplicity. The cooling period for canisters prior to disposal was chosen to be 25 years as in the 2nd TRU report.[5] The earth's surface was chosen as the upper boundary of the numerical calculation, which has a fixed temperature of 15℃, while the lower boundary is taken to be at a depth of 1500 m. The geothermal gradient is assumed to be 3℃/100 m.[5]

>>Fig. 2

Figure 3 illustrates a more detailed view of the gallery and the surrounding rock. In our thermal analysis, the allowable number of canisters packed in a waste package is chosen as the index of repository performance. The number of canisters in a waste package for each case listed in Table 1 was appropriately selected so the temperature of the cementitious materials after disposal would not exceed 80 ℃. For an engineered barrier that uses cementitious materials, the number of waste packages and tunnel spacing should be established such that a uniform temperature (< 80 ℃) is maintained in order to prevent cement alteration as this reduces its sorption function.[5] The time dependences of the temperature at point A in Fig. 3 after disposal were calculated to determine the allowable number of canisters in a waste package. The details of this thermal analysis method are described in our previous study.[6]

>> Fig. 3

The values of thermophysical properties for components used in galleries and surrounding sedimentary rock were selected in the same manner as in our previous study.[6] The values for the sedimentary rock were chosen to be those for

the design of a geological repository for HLW and TRU wastes. Unfavorable thermodynamic conditions were examined for comparison. These values are listed in **Table 4**. Temperature profiles in the disposal gallery and the surrounding rock, and the allowable number of canisters in a waste package were obtained for these two sets of values for the sedimentary rock.

>>Table 4

III. Results and Discussion

1. Heat Generation Rate in MOX Spent Fuels

Figures 4, 5 and 6 show the heat generation rates in MOX spent fuels with burn-ups of 45 and 70 GWd/THM, with 4 years of cooling after discharge, and having various histories before being loaded into a PWR. These figures indicate that the heat generation rate in MOX spent fuels varies depending on their histories such as 1) the burn-up of UO_2 spent fuels, 2) their cooling period, and 3) the storage period for the MOX fuel before being loaded into a PWR.

First, when the burn-up of UO_2 spent fuels increases, the heat generation rate in MOX spent fuels fabricated after reprocessing of these UO_2 spent fuels also increases, as shown in Fig. 4. For example, the heat generation rate for the U70G0410 case (burn-up of UO_2 spent fuel is 70 GWd/THM) is 1.4 times (Fig. 4(a)) and 1.3 times (Fig. 4(b)) larger than that for the U28G0410 case (burn-up of UO_2 spent fuel is 28 GWd/THM).

Secondly, when the cooling periods of UO_2 spent fuels are extended, the heat generation rate in MOX spent fuels fabricated after reprocessing of these UO_2 spent

fuels decreases, as shown in Fig. 5. For example, the heat generation rate for the U45G5010 case (cooling period for the UO_2 spent fuel is 50 years) is 0.8 times (Fig. 5(a) and (b)) that for the U45G0410 case (cooling period for the UO_2 spent fuel is 4 years).

Finally, when the storage period for MOX fuel before loading into a PWR is extended, the heat generation rate in MOX spent fuel increases as shown in Fig. 6. For example, the heat generation rate for the U45G0410 case (storage period of the MOX fuel is 10 years) is 1.2 times (Fig. 6 (a) and (b)) larger than that for the U45G0402 case (storage period of MOX fuel is 2 years).

Among the eighteen histories shown in Table 1, the U70G0410 case has the highest overall heat generation rate in MOX spent fuel, and the U28G5002 case has the lowest heat generation rate for the same MOX burn-up cases. These variations in heat generation rates in MOX spent fuel are mainly caused by differences in heat generation from Pu-238, as shown in Figs. 4, 5 and 6. The causes for the variations in heat generation from Pu-238 will be discussed in Sec. III-4.

>> Fig. 4

>> Fig. 5

>> Fig. 6

2. Heat Generation Rate in Compacted Hull and End Piece Wastes

Figure 7 shows the heat generation rates in a canister containing compacted hull and end pieces for cases of MOX fuel with burn-up of 45 GWd/THM, as a function of time after reprocessing of MOX spent fuel. Among the eighteen cases listed in Table 1, the lowest heat value is obtained for the U28G5002 case and the highest heat value is obtained for the U70G0410 case.

The major nuclides that contribute to the heat generation rates are Co-60, Pu-238, Am-241, Cm-244, and FPs such as Sr-90 and Cs-137. In particular, for the U70G0410 case, the contributions of Pu-238 (half-life 88 years) and Am-241 (half-life 432 years) to the heat generation rates after disposal are significantly larger than that of the others if the cooling period for the canister is 25 years, as described in the 2nd TRU report[5]. The heat generation from Pu-238 for the U70G0410 case is about 7.4 times that of the U28G5002 case, while the heat generation from Am-241 for the U70G0410 case is about 1.6 times that of the U28G5002 case. Heat generation from other nuclides is almost independent of the histories of the MOX fuels.

>> Fig. 7

Figure 8 shows the heat generation rates in a canister containing compacted hulls and end pieces as a function of time after reprocessing of MOX spent fuels. The heat generation rate calculated for 45 GWd-UO_2 and the results listed in the 2nd TRU report are presented for comparison. The results for UO_2 spent fuel with a burn-up of 45 GWd/THM agrees exactly with that presented in the 2nd TRU report[5], as indicated by the dashed line in Fig. 8.

The difference of the heat generation rates in the wastes from MOX spent fuels between the U28G5002 and U70G0410 cases mainly originate from heat generation from Pu-238, as shown in Fig. 7. Therefore, the difference in these two cases decreases with increasing time, as shown for the period of a few hundred years after disposal. The heat generation rates in all MOX fuel cases are significantly larger than that of 45 GWd-UO_2, as shown in Fig. 8.

>> Fig. 8

3. Thermal Effects on the Disposal System

Temperature profiles in disposal galleries and their surrounding bedrock were evaluated as a function of time after disposal. The cooling period for canisters prior to disposal was chosen to be 25 years as described in the 2nd TRU report.[5] The number of canisters in a waste package was selected for each MOX fuel having a different history before being loaded into a PWR so the peak temperature of the cementitious filler materials after disposal would not exceed 80°C. By noting the number of canisters, the extent of the thermal effects after disposal can be judged.

Figure 9 shows temperatures at points A and B as a function of time after disposal for the lowest heat value (U28G5002) and the highest heat value (U70G0410) among the eighteen cases for 45 GWd-MOX fuels listed in Table 1. Point A is located at the center of the waste-package region and point B is located at the midpoint between two adjacent galleries as shown in Fig. 3. When MOX fuels are fabricated after reprocessing of UO_2 spent fuels with a burn-up of 28 GWd/THM, a cooling period of 50 years, and being stored for 2 years before being loaded into a PWR (U28G5002), the allowable number of canisters loaded in a waste package is 1.2 to 1.6. When the burn-up of UO_2 spent fuel is 70 GWd/THM, with a cooling period of 4 years, and the MOX fuel is stored 10 years before being loaded into a PWR (U70G0410), the number of canisters is only 0.5 to 0.7. This results from the heat generation from Pu-238 for the U70G0410 case, which is significantly larger than that for the U28G5002 case. For the case of U28G5002, however, the temperatures at both points A and B after 100 years following disposal are higher than those for the U70G0410 case. If the long-term high temperature in the galleries and the surrounding rock affect ground water flow due to thermal convection

and the integrity of cementitious materials, the higher temperature for U28G5002 case after 100 years following disposal may have an impact on the safety assessment for the disposal system.

>> Fig. 9

Figure 10 shows the allowable number of canisters in a waste package, depending on the fuel histories of MOX fuels. The allowable number of canisters gradually increases with the extension of cooling periods for UO_2 spent fuels. On the other hand, the number of canisters linearly decreases if the burn-up of UO_2 fuels increases or the storage period for MOX fuels before loading is extended to 10 years. In all cases, the number of canisters decreases when decay heat from Pu-238 in MOX spent fuels increases, and *vice versa*, which suggests that Pu-238 is one of major nuclides determining the allowable number of canisters.

Figure 11 depicts the allowable number of canisters in a waste package as a function of burn-up of MOX fuel. The allowable number of canisters decreases with burn-up of MOX fuel in all MOX fuel cases, and it varies from 0.4 to 1.6, depending on histories of MOX fuels before being loaded into a PWR and the thermo-physical properties of the surrounding rock. These values of the allowable number of canisters from 0.4 to 1.6 are much lower than that for the reference 45 GWd-UO_2 case (4.0), which indicates that burning of MOX fuels causes a decrease in the allowable number of canisters in a waste package by a factor of more than 2.5, an aspect of the thermal property for disposal. In actual waste packaging, only whole canisters are allowed to be packed within a waste package, so the canister and waste package will be sized accordingly.

>> Fig. 10

>> Fig. 11

4. Actinides Behavior

The fact that heat generation from Pu-238 varies depending on the history of the MOX fuel can be an important issue for introducing MOX fuels into LWRs when determining the thermal impact on deep geological disposal of TRU wastes, as shown in the previous sections. In this section, the causes for the variations in heat generation from Pu-238 and its effects on the geological disposal of TRU wastes will be described.

As a function of time, **Fig. 12** shows the amount of Pu isotopes and Am-241 per ton of heavy metals after discharge of UO_2 spent fuels from a PWR. The burn-ups of UO_2 spent fuels shown in Figs. 12 (a) and (b) are 45 GWd/THM. The left side in these figures shows the cooling period of UO_2 spent fuels; the right side illustrates the storage period of MOX fuels before being loaded into a PWR. The cooling periods of the UO_2 spent fuel are 4 years as shown in Fig. 12 (a) and 50 years in Fig 12 (b). The periods between the reprocessing of the UO_2 spent fuels and MOX fuels fabrication are not considered in this study. The amounts of Pu-241 (half-life 14 years) and Am-241 (a daughter nuclide of Pu-241) obviously change during the several decades of cooling the UO_2 spent fuels and the storage of the MOX fuels, while the amounts of other Pu isotopes have little change. When the cooling period of the UO_2 spent fuels is 4 years (Fig. 12 (a)), most Pu-241 in the UO_2 spent fuels is transferred to the initial MOX fuels, so the amount of Am-241 increases somewhat with an increase in the storage period of the MOX fuels. On the other hand, when the cooling period of UO_2 spent fuels is 50 years (Fig. 12 (b)), the amount of Pu-241 transferred to MOX fuels is extremely small, so the amount of Am-241 hardly increases even if the storage period for MOX fuels is extended to 10 years. The amount of Am-241 after a 10-year storage period for MOX

fuels and a cooling period of 4 years for UO_2 spent fuels (0.60 kg/THM) is ten times that for the case of a 50-year cooling period (0.06 kg/THM), as shown in Figs. 12 (a) and (b). These results clarify the reason that the amount of Am-241 included in initial MOX fuels for the U45G0410 case is the largest among the other cases with a burn-up of 45 GWd/THM for UO_2 spent fuels.

>> Fig. 12

Figure 13 represents the chain of actinide nuclide generation and depletion. Am-241 is transmuted into Pu-238, according to the transition chain : Am-241→Am-242→Cm-242→Pu-238 during MOX fuel burning. **Figure 14** shows the amount of (a) Pu-238 and (b) Cm-242 as a function of burn-up up to 45 GWd/THM in a PWR for MOX fuels fabricated after reprocessing of UO_2 spent fuels with a burn-up of 45 GWd/THM. The amount of Pu-238 increases with burn-up of MOX fuels only when the MOX fuel is fabricated after the reprocessed UO_2 spent fuels have cooled 4 years and have been stored 10 years before being loaded into a PWR (U45G0410). The amount of Cm-242, which is produced from Am-241 and is a parent nuclide for Pu-238, also markedly increases with burn-up of MOX fuels for the U45G0410 case. Thus, the large amount of Am-241 in the initial MOX fuels for the U45G0410 case, as illustrated in Fig. 12, must cause an increase in the amount of Pu-238 in MOX spent fuels, which results in the high heat generation rate for hull and end piece wastes. These results indicate that decreasing the amount of Am-241 in initial MOX fuels reduces the heat generation rate for hull and end piece wastes and allows an increase in the capacity of a disposal gallery.

However, it should be noted that the reduction of Am-241 in initial MOX fuels directly

leads to increasing the amount of Am-241 in HLW from reprocessing of UO_2 spent fuels unless innovative technologies such as partitioning and transmutation technology of minor actinides are applied. If the amount of Am-241 included in HLWs is high, the HLW cooling periods required for the use of compacted bentonite after disposal must be extended. Inagaki et al. reported that a longer storage period of vitrified waste, over 50 years prior to final disposal, is required if the cooling period of UO_2 spent fuels before reprocessing is extended to 30 years.[4)]

>> Fig. 13

>> Fig. 14

IV. Conclusions

The thermal impacts of the history of MOX-LWR fuels on a geological disposal system for hull and end piece wastes were investigated. The heat generation rate in MOX spent fuels was calculated by assuming a variety of histories: 1) the burn-up of UO_2 spent fuels from which the Pu is obtained, 2) the cooling period before reprocessing of the UO_2 spent fuels and 3) the storage period of fresh MOX fuels before being loaded into an LWR. Although the heat generation rates in a canister containing hull and end pieces varies depending on those histories, the main course of the difference is due to the change of the amount of Pu-238 in the waste.

Assuming a maximum temperature of 80°C for cement-based materials used in waste packages after disposal, the allowable number of canisters in a package is limited to a value of 0.4 to 1.6 for all MOX fuel cases, which is much smaller than the value of four for the 45 GWd-UO_2 case shown in the 2nd TRU report.

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Table captions

Table 1 MOX fuels with various histories before loading into a PWR

Table 2 Initial MOX fuel compositions (wt. %)

Table 3 Calculation conditions for heat generation rates in hull and end piece waste

Table 4 Values of thermophysical properties for components of the engineered barrier and the surrounding sedimentary rocks

Figure captions

Figure 1 Flow chart of the present calculation

Figure 2 Schematic of the analytical system having two-dimensional thermal conductions

Figure 3 Cross-sectional view of a gallery and its surrounding rock. Point A is located at the center of the waste-package region and point B is located at the midpoint between two adjacent galleries.

Figure 4 Heat generation rates in MOX spent fuels having 4 years of cooling after discharge, depending on burn-ups of UO_2 spent fuels before reprocessing. Burn-ups of MOX fuels are (a) 45 and (b) 70 GWd/THM. The cooling periods of UO_2 spent fuels are 4 years and the storage periods of MOX fuels before loading are 10 years.

Figure 5 Heat generation rates in MOX spent fuels having 4 years of cooling after discharge, depending on cooling periods of UO_2 spent fuels before reprocessing. Burn-ups of MOX fuels are (a) 45 and (b) 70 GWd/THM. The burn-ups of UO_2 spent fuels are 45 GWd/THM and the storage periods of MOX fuels before loading are 10 years.

Figure 6 Heat generation rates in MOX spent fuels having 4 years of cooling after discharge, depending on the storage periods of the MOX fuels before being loaded into an LWR. Burn-ups of MOX fuels are (a) 45 and (b) 70 GWd/THM. The burn-ups of UO_2 spent fuels are 45 GWd/THM and the cooling periods of UO_2 spent fuels are 4 years.

Figure 7 Evolution of heat generation rates in a canister containing compacted hulls and end pieces from MOX spent fuels with burn-ups of 45 GWd/THM and the contribution of the main nuclides. Horizontal axis represents cooling time after reprocessing.

Figure 8 Evolution of heat generation rates in a canister containing compacted hulls and end pieces from reprocessing of UO_2 and MOX spent fuels. Horizontal axis represents cooling time after reprocessing.

Figure 9 Temperatures at points A and B as a function of time after disposal. Burn-ups of MOX spent fuel are 45 GWd/THM. The upper and lower figures represent temperatures calculated by using thermophysical properties of surrounding rock a) and b) as shown in Table 4, respectively.

Figure 10 Allowable number of canisters in a waste package as a function of a) burn-up of UO_2 spent fuels, b) cooling period of UO_2 spent fuels, c) storage period of MOX fuels before loading into an LWR. The burn-ups of MOX fuels are 45 GWd/THM. Thermophysical data for

rock are from Table 4(a).

Figure 11 Allowable number of canisters in a waste package as a function of burn-up for MOX spent fuels. Solid lines are obtained by using thermophysical data presented in Table 4(a), while dashed lines are obtained by using thermophysical data listed in Table 4(b).

Figure 12 Amount of Pu isotopes and Am-241 as a function of time after discharge of UO_2 spent fuels from a PWR. Burn-ups of UO_2 spent fuels are 45 GWd/THM. The cooling period of the UO_2 spent fuels is (a) 4 years and (b) 50 years.

Figure 13 Chain of actinide nuclide generation and depletion.

Figure 14 Amount of (a) Pu-238 and (b) Cm-242 in MOX fuels as a function of burn-up of MOX fuel up to 45 GWd/THM.

Table 1　MOX fuels with various histories before loading into a PWR

	UO_2 spent fuel		MOX fuel
	Burn-up (GWd/THM)	Cooling period (years)	Storage period before loading in PWR (years)
U28G0402	28	4	2
U28G0410			10
U28G3002		30	2
U28G3010			10
U28G5002		50	2
U28G5010			10
U45G0402	45	4	2
U45G0410			10
U45G3002		30	2
U45G3010			10
U45G5002		50	2
U45G5010			10
U70G0402	70	4	2
U70G0410			10
U70G3002		30	2
U70G3010			10
U70G5002		50	2
U70G5010			10

Table 2 Initial MOX fuel compositions (wt. %)

(Burn-ups of MOX fuel are 45 GWd/THM)

	U-235	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Am-241	Pu(Total)
U28G0402	0.225	90.914	0.092	5.267	2.067	0.923	0.419	0.093	8.768
U28G0410	0.225	88.404	0.111	6.766	2.654	0.807	0.539	0.494	10.876
U28G3002	0.225	89.702	0.093	6.530	2.569	0.328	0.520	0.033	10.040
U28G3010	0.225	88.865	0.095	7.079	2.783	0.242	0.564	0.148	10.762
U28G5002	0.225	89.348	0.084	6.922	2.723	0.133	0.552	0.013	10.414
U28G5010	0.225	89.023	0.082	7.143	2.808	0.093	0.569	0.057	10.695
U45G0402	0.225	90.609	0.195	5.259	2.054	1.041	0.511	0.105	9.061
U45G0410	0.225	87.781	0.240	6.895	2.691	0.929	0.670	0.569	11.425
U45G3002	0.225	89.166	0.202	6.699	2.637	0.380	0.651	0.038	10.570
U45G3010	0.225	88.215	0.207	7.311	2.876	0.282	0.711	0.173	11.387
U45G5002	0.225	88.750	0.185	7.153	2.820	0.155	0.696	0.016	11.009
U45G5010	0.225	88.384	0.179	7.400	2.915	0.109	0.720	0.067	11.324
U70G0402	0.225	89.377	0.435	5.502	2.318	1.259	0.756	0.127	10.271
U70G0410	0.225	85.999	0.543	7.313	3.078	1.139	1.005	0.698	13.078
U70G3002	0.225	87.409	0.468	7.255	3.122	0.476	0.998	0.048	12.318
U70G3010	0.225	86.239	0.482	7.962	3.424	0.355	1.095	0.218	13.318
U70G5002	0.225	86.832	0.431	7.830	3.388	0.196	1.077	0.020	12.923
U70G5010	0.225	86.385	0.420	8.118	3.511	0.139	1.117	0.085	13.305

Table 3　Calculation conditions for heat generation rates in hull and end piece waste

Cooling period of MOX spent fuel	4 years	
Volume of one canister	0.194 m^3	
Weight of waste per canister	480 kg	
Accompanying ratio of FPs and actinides adhering to hulls (%)	Tc	3
	Ru/Rh	5
	Other FPs	0.3
	Actinides	0.2

Table 4　Values of thermophysical properties for components of the engineered barrier and the surrounding sedimentary rocks

		Density ($Mg\ m^{-3}$)	Thermal conductivity ($W\ m^{-1}\cdot K^{-1}$)	Specific heat ($kJ\ kg^{-1}\cdot K^{-1}$)
Support		2.50	2.56	1.05
Invert		2.35	2.56	1.05
Buffer material		1.71	0.78	0.590
Waste package		2.84	3.73	0.971
Sedimentary rock	a)	2.35	2.40	1.30
	b)	1.50	1.60	1.00

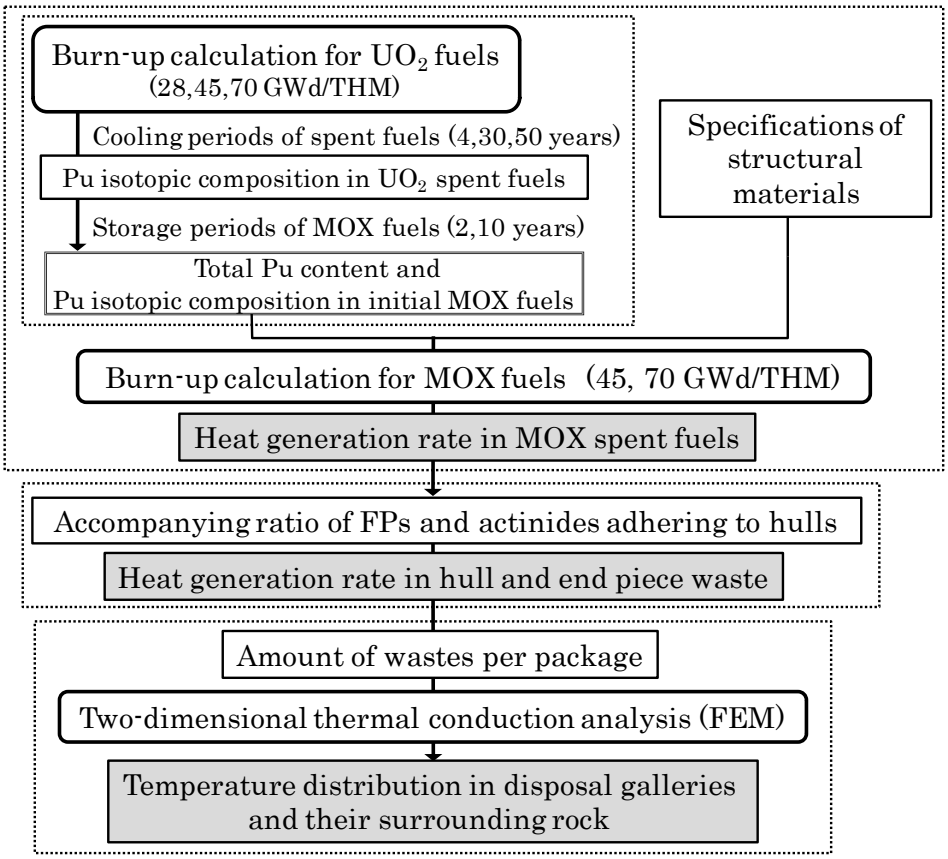
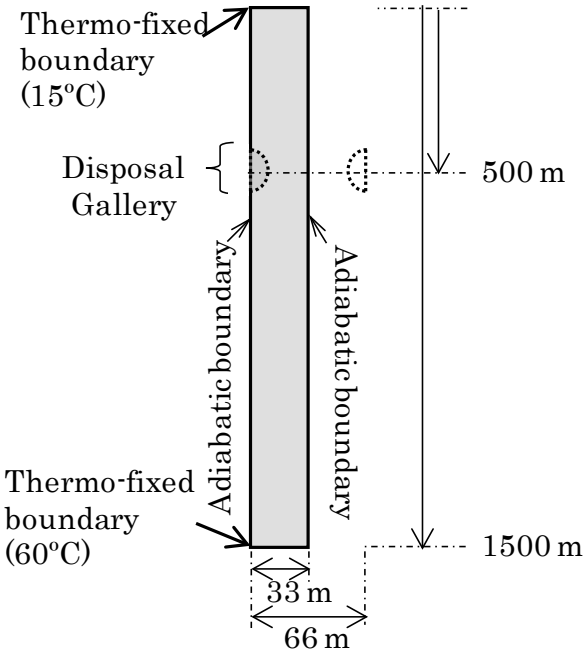


Figure 1　Flow chart of the present calculation


Thermo-fixed
boundary
(15°C)
Disposal
Gallery
500 m
Adiabatic boundary
Adiabatic boundary
Thermo-fixed
boundary
(60°C)
1500 m
33 m
66 m


Land surfa
Multiple
disposal
galleries
Rock

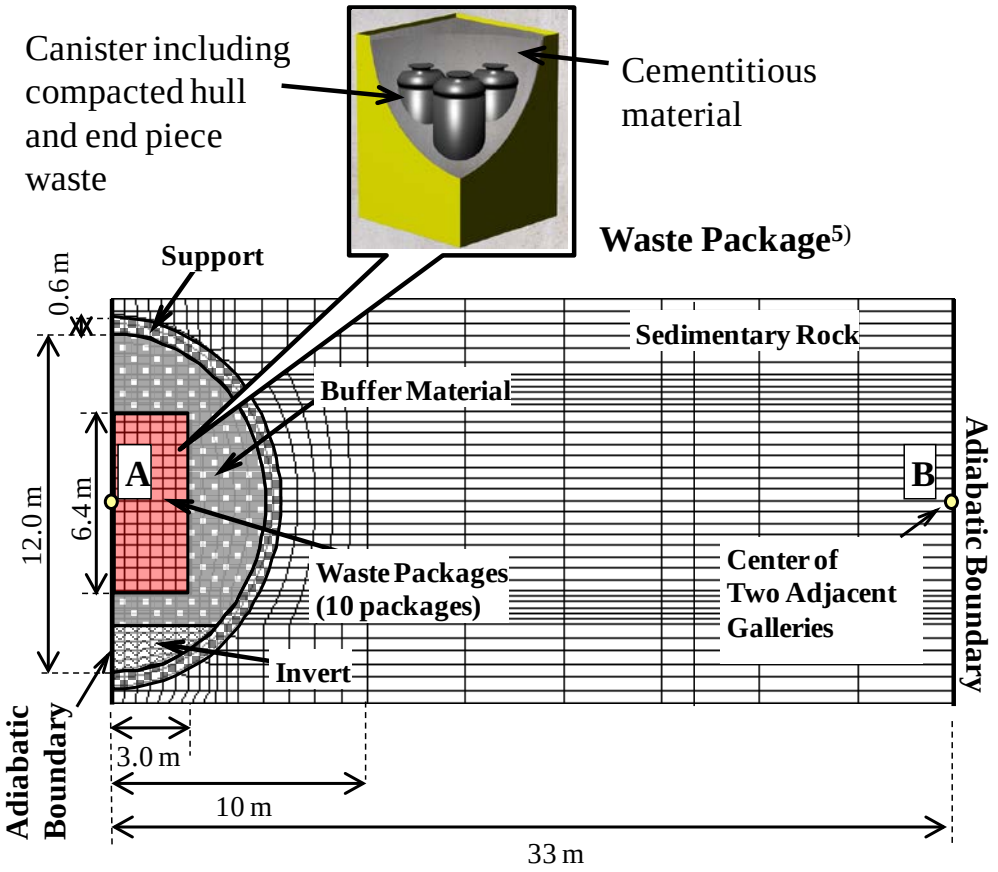


Figure 3　Cross-sectional view of a gallery and its surrounding rock

Point A is located at the center of the waste-package region and point B is located at the midpoint between two adjacent galleries.

(Waste Package: 1.2 m×1.2 m×1.6 m = 2.3 m^3)

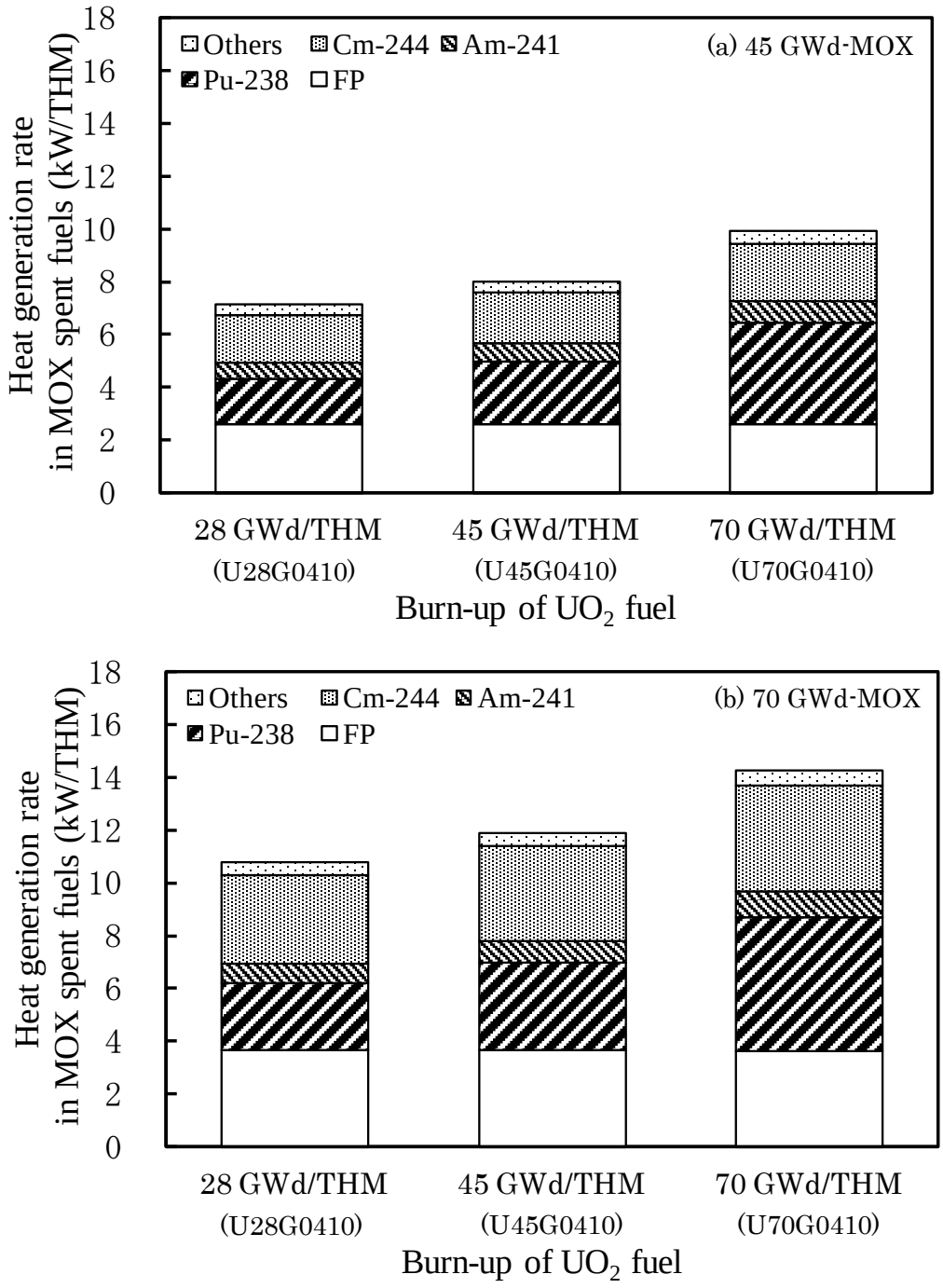


Figure 4 Heat generation rates in MOX spent fuels having 4 years of cooling after discharge, depending on burn-ups of UO_2 spent fuels before reprocessing. Burn-ups of MOX fuels are (a) 45 and (b) 70 GWd/THM. The cooling periods of UO_2 spent fuels are 4 years and the storage periods of MOX fuels before loading are 10 years.

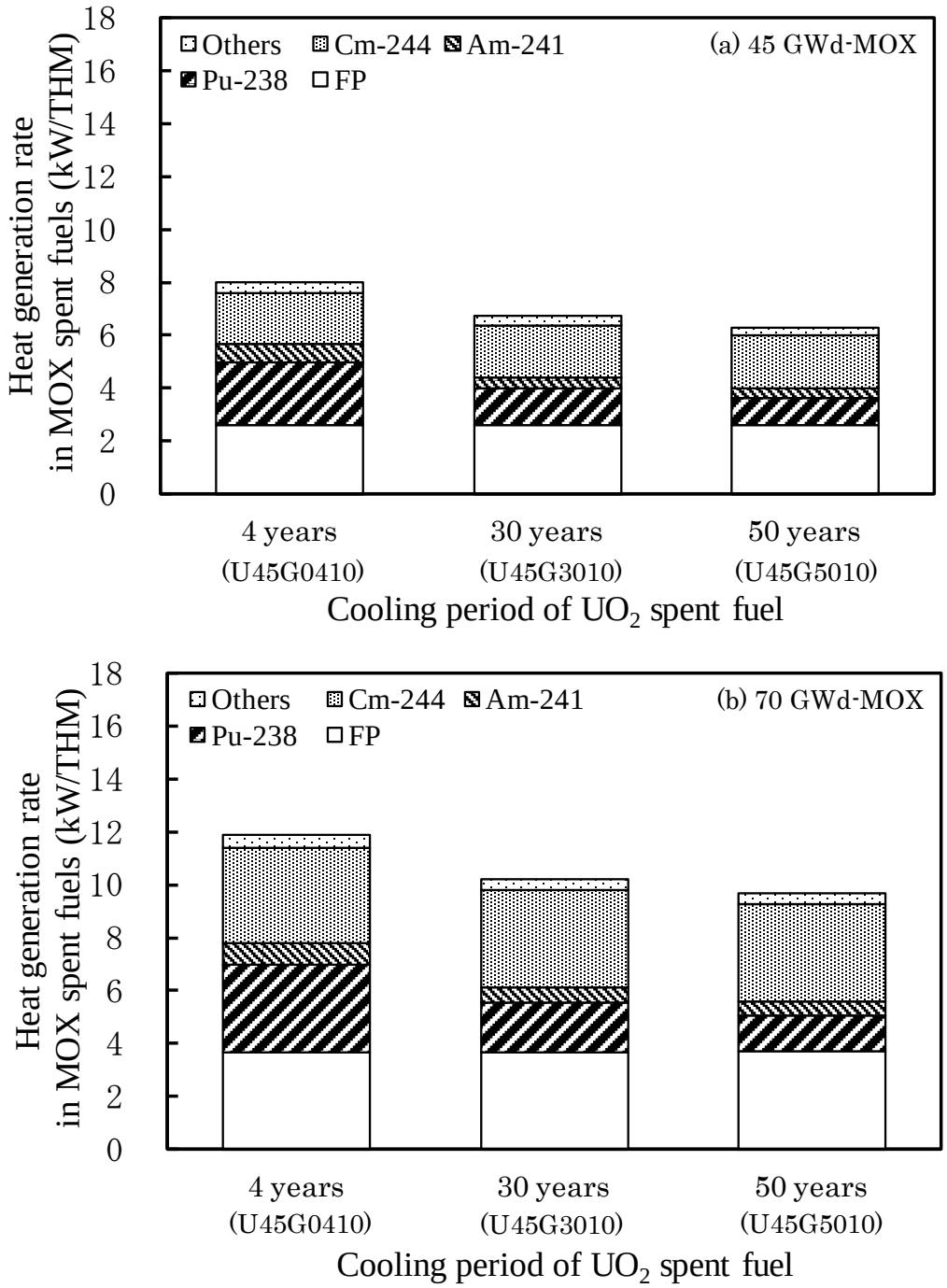


Figure 5 Heat generation rates in MOX spent fuels having 4 years of cooling after discharge, depending on cooling periods of UO_2 spent fuels before reprocessing. Burn-ups of MOX fuels are (a) 45 and (b) 70 GWd/THM. The burn-ups of UO_2 spent fuels are 45 GWd/THM and the storage periods of MOX fuels before loading are 10 years.

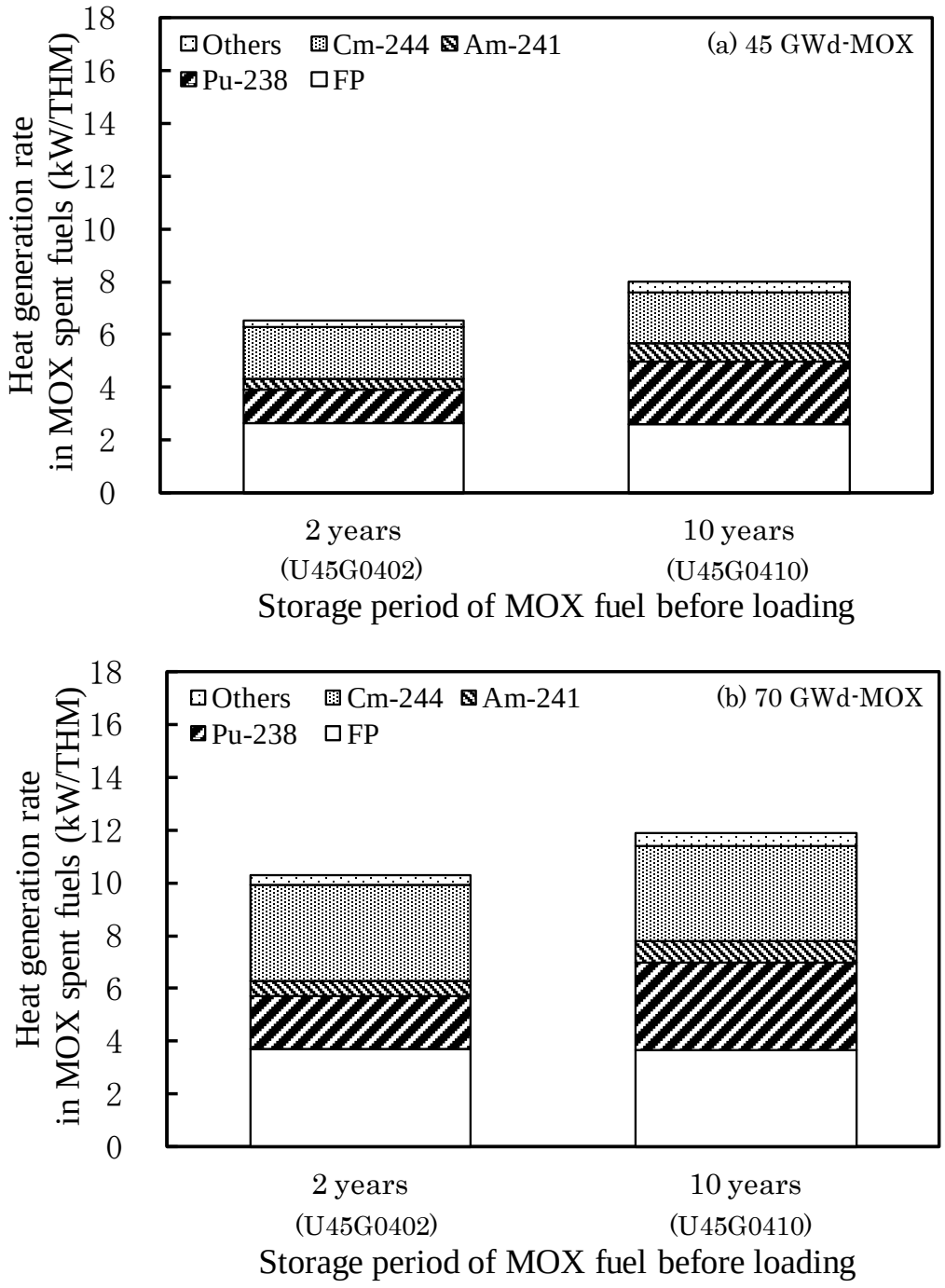


Figure 6 Heat generation rates in MOX spent fuels having 4 years of cooling after discharge, depending on the storage periods of the MOX fuels before being loaded into an LWR. Burn-ups of MOX fuels are (a) 45 and (b) 70 GWd/THM. The burn-ups of UO_2 spent fuels are 45 GWd/THM and the cooling periods of UO_2 spent fuels are 4 years.

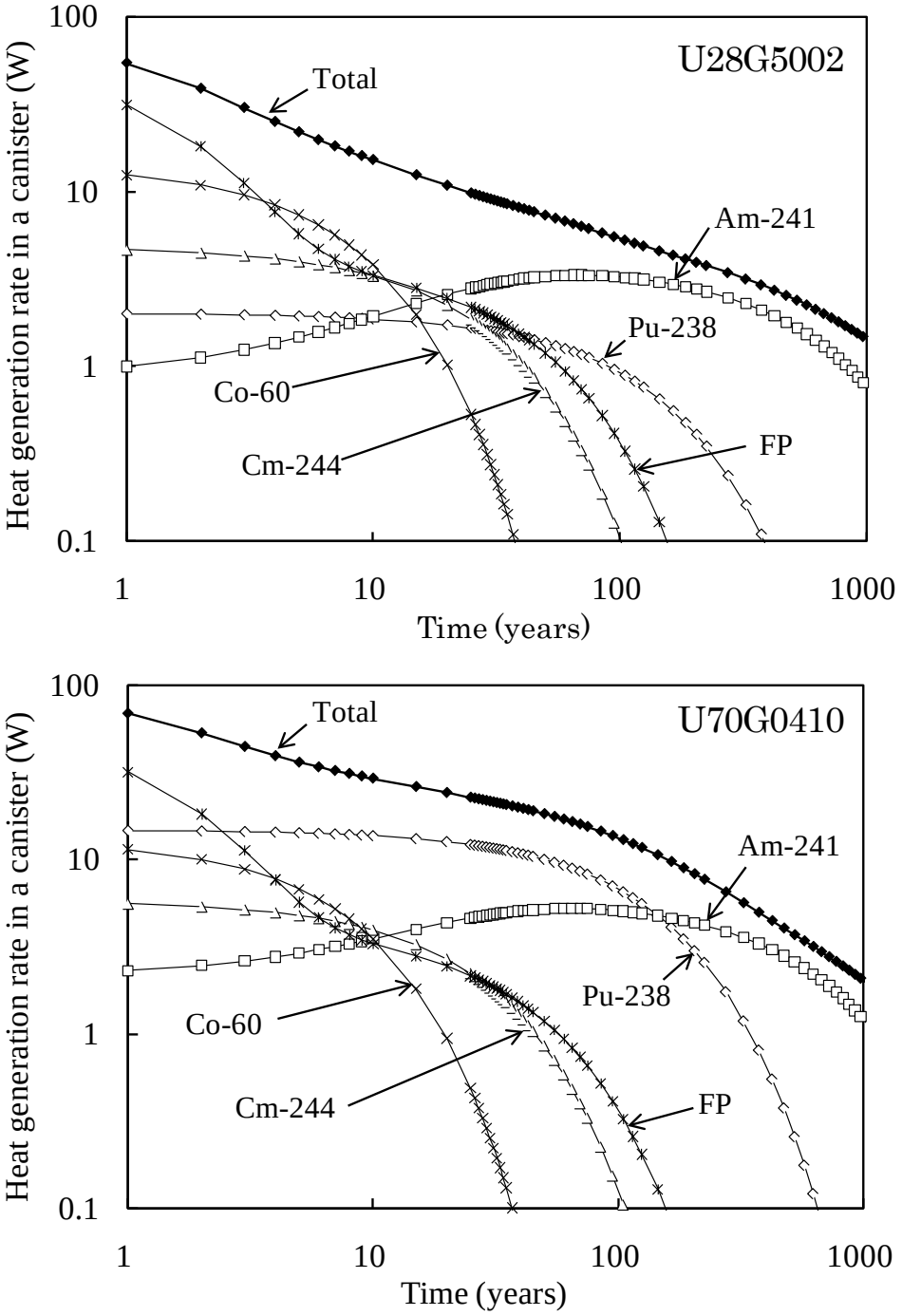


Figure 7　Evolution of heat generation rates in a canister containing compacted hulls and end pieces from MOX spent fuels with burn-ups of 45 GWd/THM and the contribution of the main nuclides. Horizontal axis represents cooling time after reprocessing.

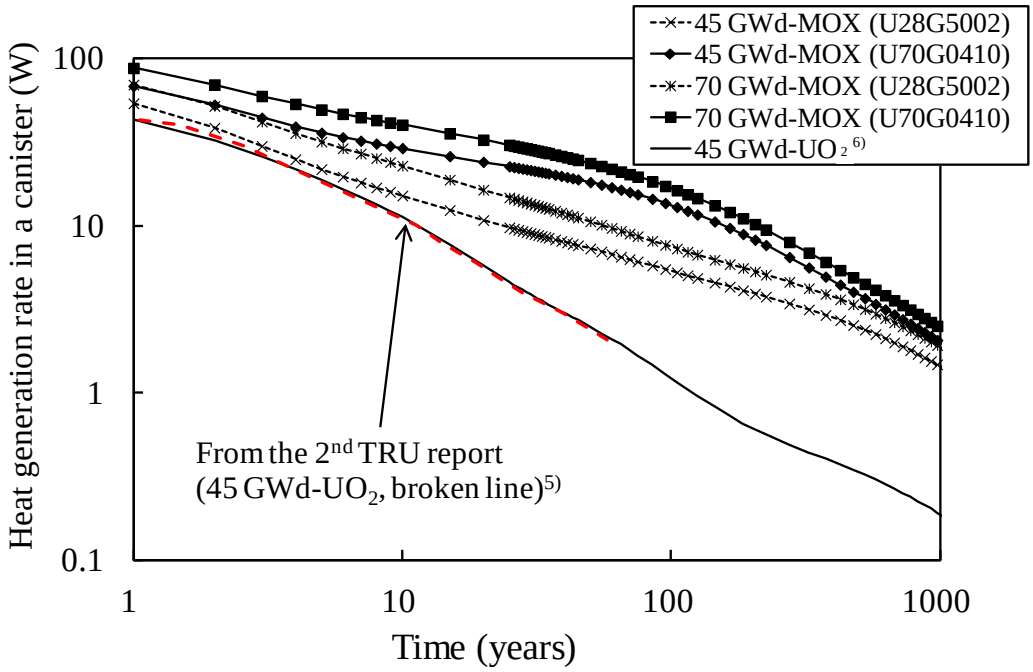


Figure 8　Evolution of heat generation rates in a canister containing compacted hulls and end pieces from reprocessing of UO_2 and MOX spent fuels.　Horizontal axis represents cooling time after reprocessing.

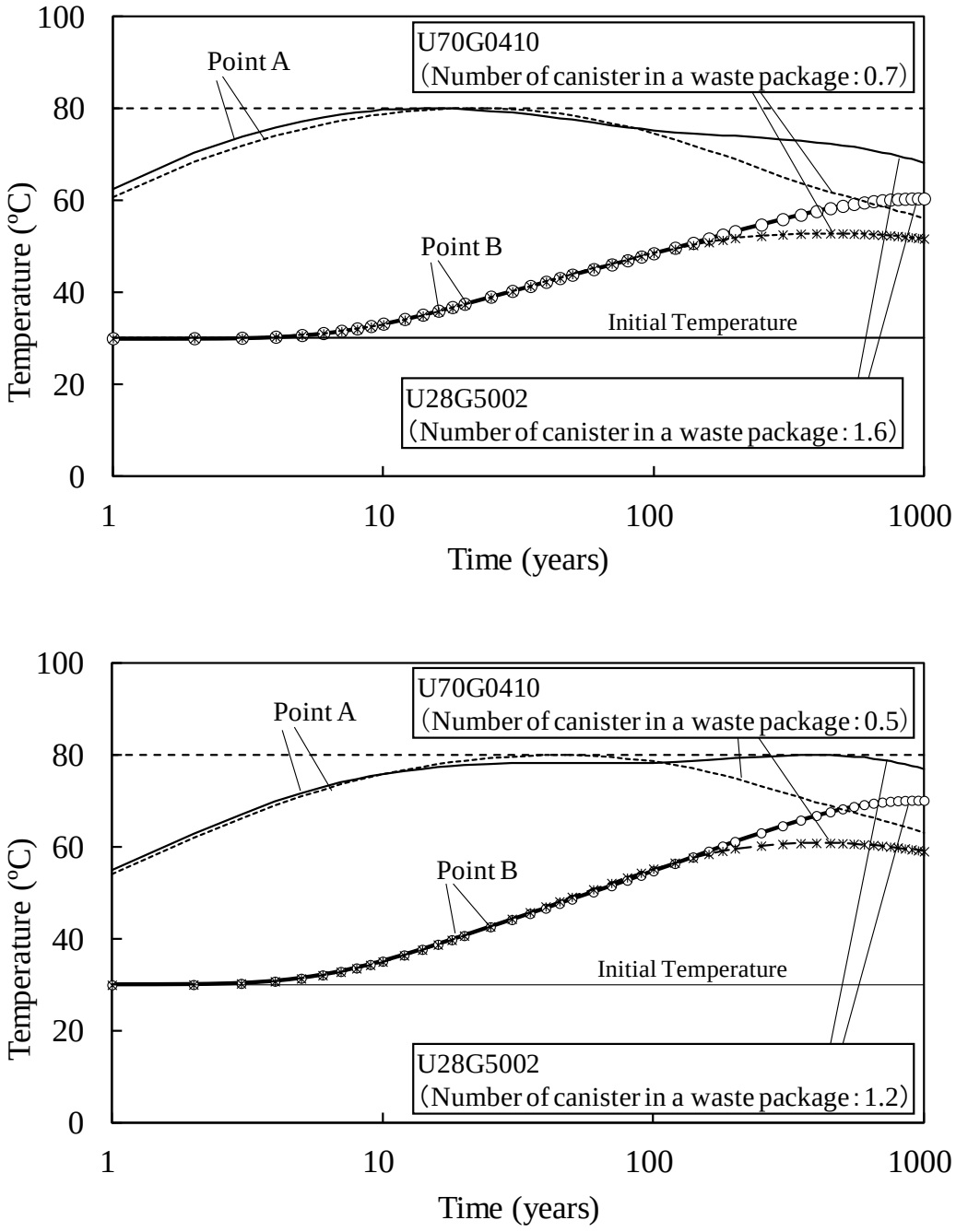


Figure 9　Temperatures at points A and B as a function of time after disposal.

Burn-ups of MOX spent fuel are 45 GWd/THM. The upper and lower figures represent temperatures calculated by using thermophysical properties of surrounding rock a) and b) as shown in Table 4, respectively.

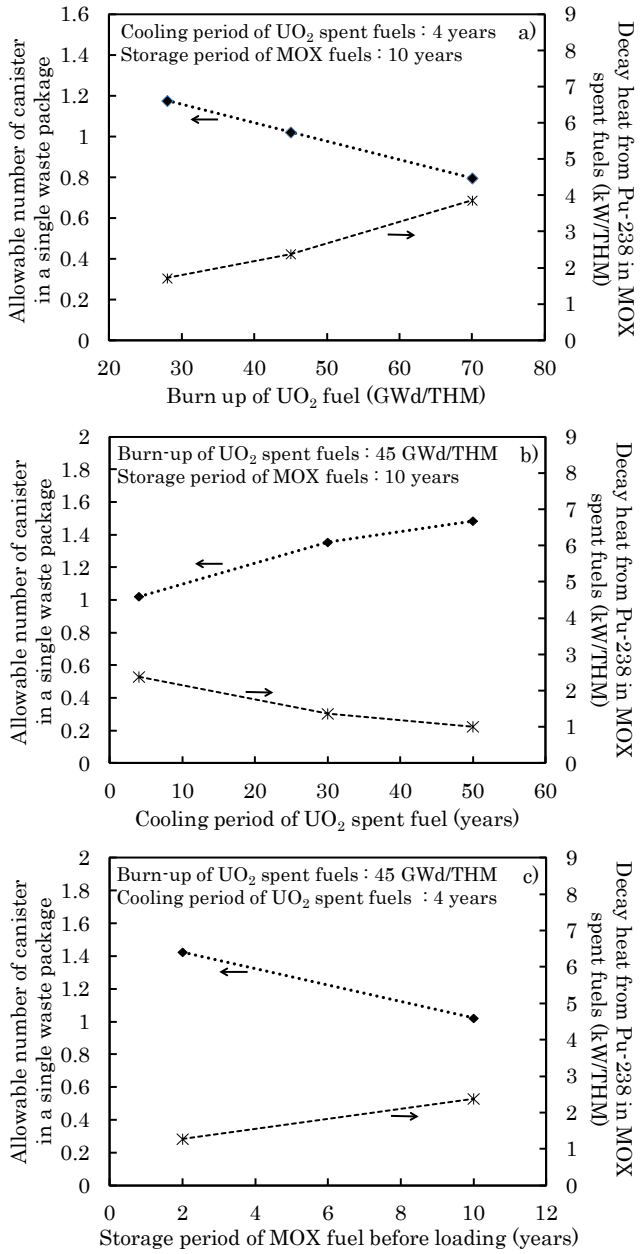


Figure 10　Allowable number of canisters in a waste package as a function of a) burn-up of UO_2 spent fuels, b) cooling period of UO_2 spent fuels, c) storage period of MOX fuels before loading into an LWR.　The burn-ups of MOX fuels are 45 GWd/THM.　Thermophysical data for rock are from Table 4-a).

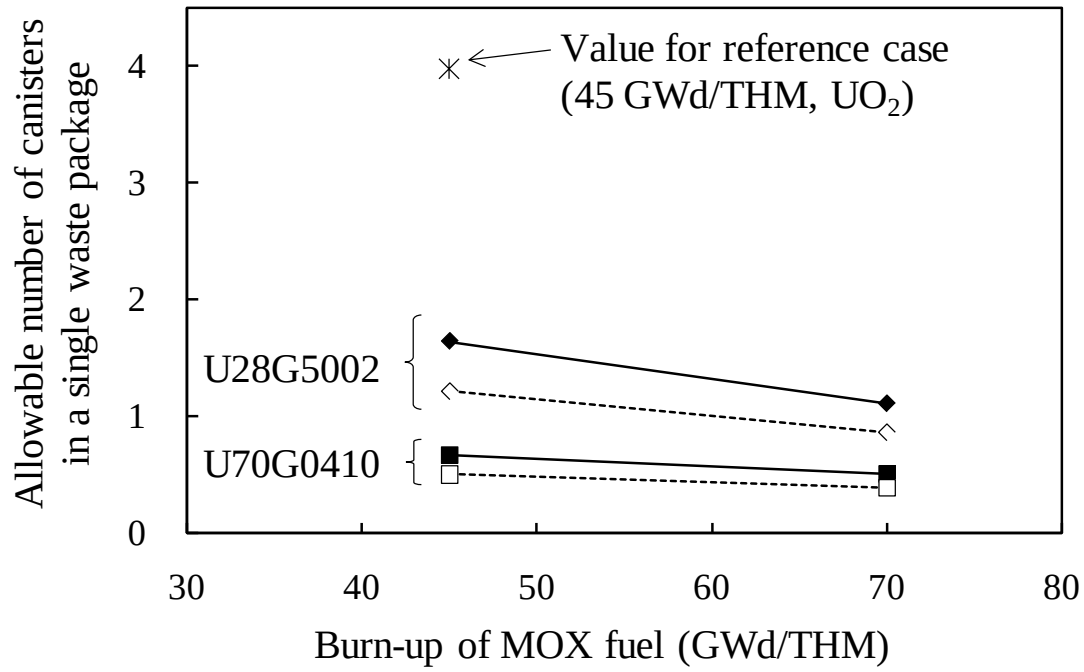


Figure 11　Allowable number of canisters in a waste package as a function of burn-up for MOX spent fuels.　Solid lines are obtained by using thermophysical data presented in Table 4-a), while dashed lines are obtained by using thermophysical data listed in Table 4-b).

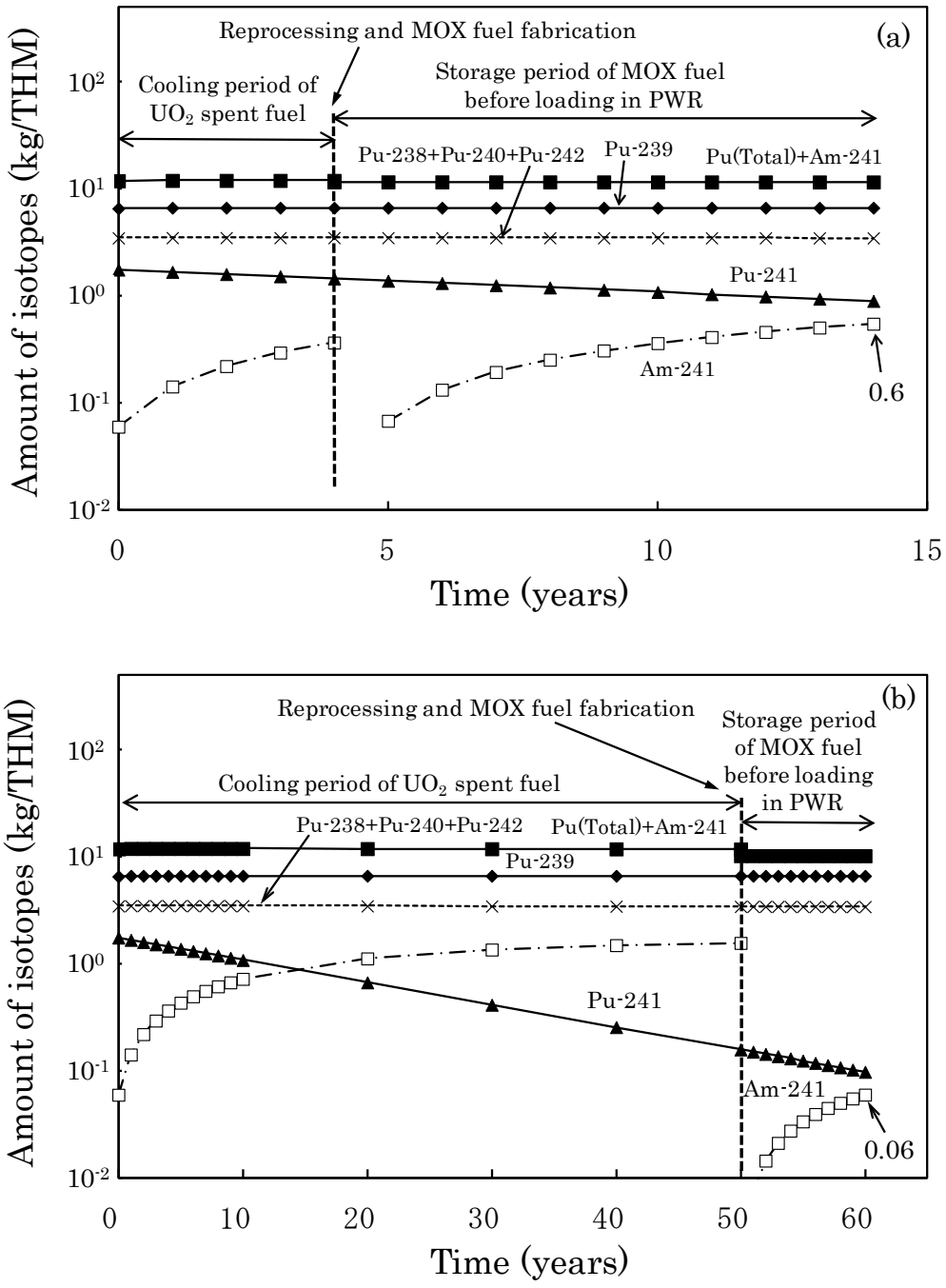


Figure 12　Amount of Pu isotopes and Am-241 as a function of time after discharge of UO_2 spent fuels from a PWR.　Burn-ups of UO_2 spent fuels are 45 Wd/THM.

The cooling period of the UO_2 spent fuels is (a) 4 years and (b) 50 years.

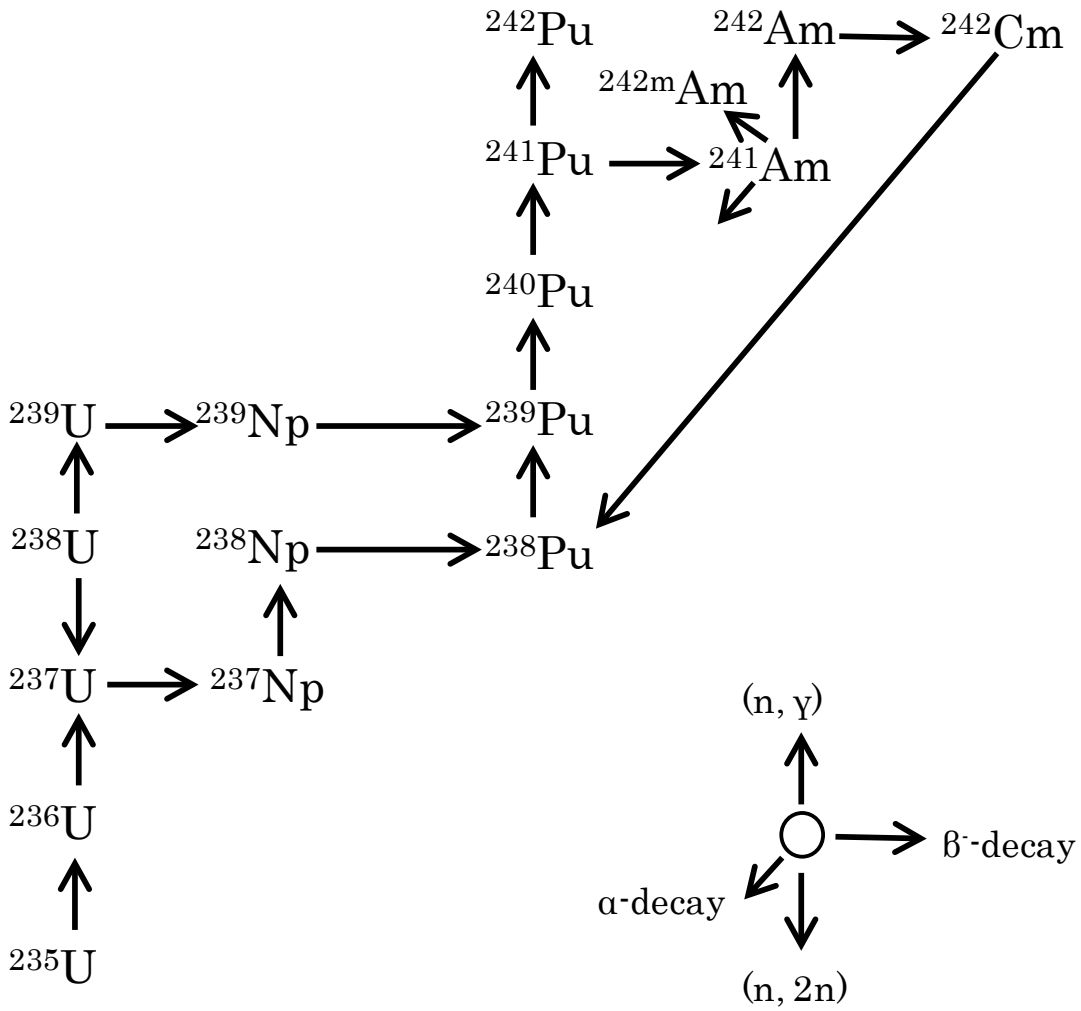


Figure 13　Chain of actinide nuclide generation and depletion.

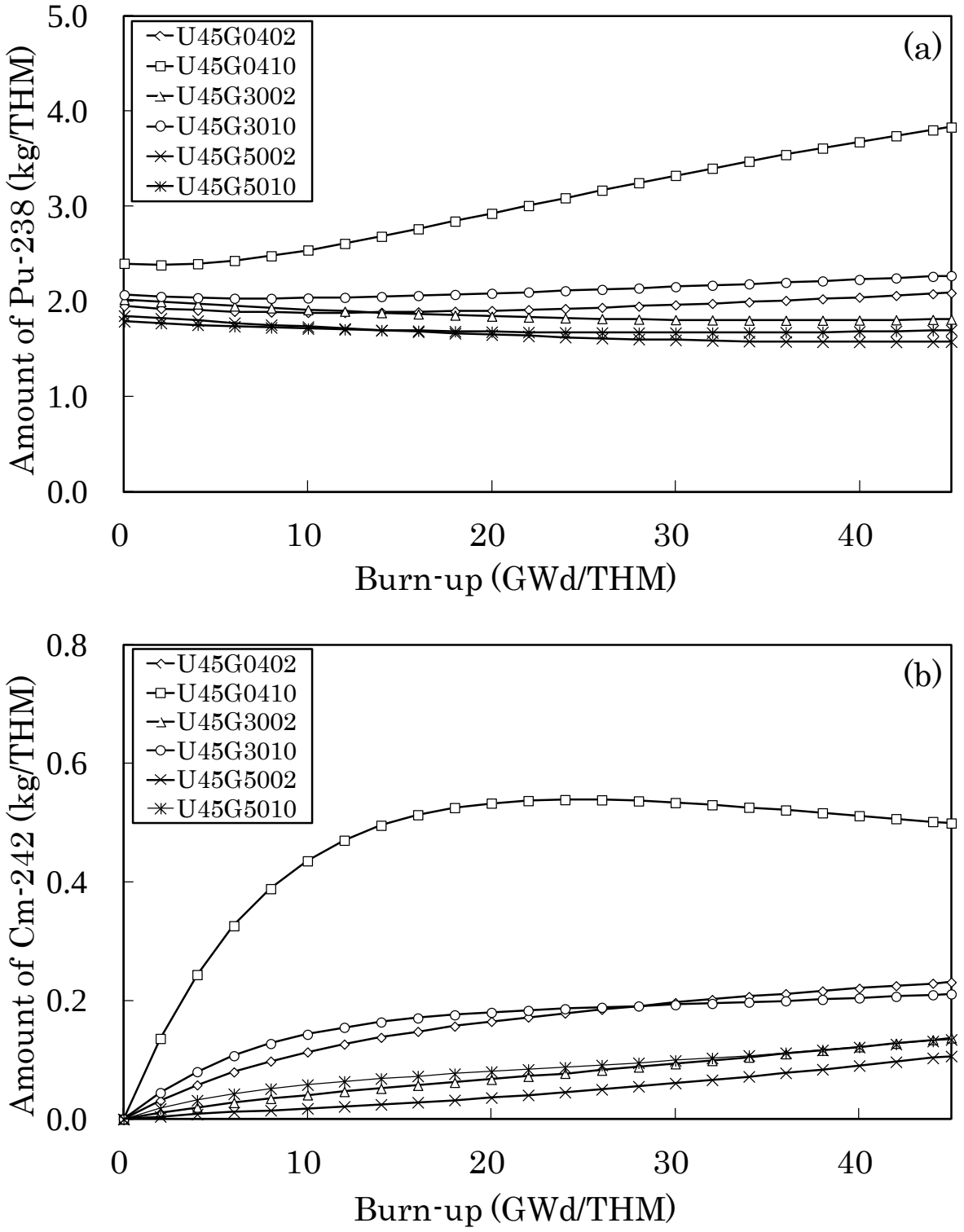


Figure 14　Amount of (a) Pu-238 and (b) Cm-242 in MOX fuels as a function of burn-up of MOX fuel up to 45 GWd/THM.