Impacts of a High-Burnup Spent Fuel
on a Geological Disposal System Design

D. K. Cho, Y. Lee, J.Y. Lee, H.J. Choi, J.W. Choi
Korea Atomic Energy Research Institute
150, Deokjin-dong, Yuseong-gu, Daejeon-city
Republic of Korea

ABSTRACT

The influence of a burnup increase of a spent nuclear fuel on a deep geological disposal system was evaluated in this study. First, the impact of a burnup increase on each aspect related to thermal and nuclear safety concerns was quantified. And then, the tunnel length, excavation volume, and the raw materials for a cast insert, copper, bentonite, and backfill needed to constitute a disposal system were comprehensively analyzed based on the spent fuel inventory to generate 1 Terawatt-year (TWa), to establish the overall effects and consequences on a geological disposal. As a result, impact of a burnup increase on the criticality safety and radiation shielding was shown to be negligible. The disposal area, however, is considerably affected because of a higher thermal load. And, it is reasonable to use a canister such as the Korean Reference Disposal Canister (KDC-1) containing 4 spent fuels up to 50 GWD/MtU, and to use a canister containing 3 spent fuels beyond 50 GWD/MtU. Although a considerable increased, 33 % in the tunnel length and 30 % in the excavation volume, was observed as the burnup increases from 50 to 60 GWD/MtU, because a decrease in the canister needs can offset an increase in the excavation volume, it can be concluded that a burnup increase of a spent fuel is not a critical concern for a geological disposal of a spent fuel.

INTRODUCTION

The technology related to a deep geological disposal as a long-term spent nuclear fuel management strategy has been under development worldwide. A longer cycle operation of nuclear reactors and a corresponding higher discharge burnup of a spent fuel has been pursued to make the nuclear industry competitive with regard to electricity generation. If the burnup of a spent fuel increases, however, the associate increase in the radioactivity, decay heat, and nuclide inventory could affect: (i) the thermal behaviour in relation to the temperature in the buffer and host rock surrounding a disposal canister; (ii) the dose rate in the radiation shielding; (iii) the criticality assurance; (iv) repository layout such as the disposal tunnel and hole spacing. These impacts on a deep geological disposal system design for a spent fuel were comprehensively evaluated in this study.

REFERENCE SPENT FUEL AND DISPOSAL SYSTEM

Spent Nuclear Fuel

The 17×17 Westinghouse type fuel design was considered as a reference spent fuel. Because the discharge burnup and some other parameters such as the actinide concentration which could affect the criticality concern of a disposal system are dependent on the initial ^{235}U enrichment, sets of enrichments and corresponding burnups were determined first through the Linear Reactivity Model[1]. According to this model, the mean reactivity for an n-batch core is expressed as in Eq. (1).

$$\rho_s = \frac{1}{n} \sum_{j=1}^{n} \rho_j$$
$$= \frac{1}{n} [n\rho_0 - \frac{n(n+1)}{2} AB_c] \tag{1}$$

where, n = number of batchs,

ρ_0 = reactivity of a fresh fuel,

A = reactivity decrease constant as a function of the burnup,

B_c = cycle burnup.

And, the reactivity of the fuel which is burned during n-cycle is expressed in Eq. (2).

$$\rho_n = (1 - \frac{2n}{n+1} \rho_0) \tag{2}$$

The excess reactivity of a fresh fuel with an initial [235]U enrichment of 4.0 wt.% was revealed to be 0.230 $\Delta\rho$ in an equilibrium xenon condition, by a calculation by using the SAS2 module[2] in the SCALE5 code package[3]. And the corresponding discharge burnup for a *3*- and *4*-batch core was shown to be ~55 and ~59 GWD/MtU, respectively, by substituting ρ_0 with 0.023 in Eq. (2) and comparing the value of ρ_n with the reactivity value for each burnup derived by the SAS2 calculation. Hereafter, a burnup means the discharge burnup. Because these are the values without considering the neutron leakage from the core, the burnup of a spent fuel discharged from a commercial reactor core becomes less. Based on these values and the spent fuel burnup data in Korea (Korea operates twenty nuclear power plants), 50 GWD/MtU was chosen for a 4.0 wt.% fuel. Similarly, 40 and 60 GWD/MtU with a respective enrichment of 3.2 and 4.5 wt.% were chosen as the reference spent fuels.

Disposal System

A reference repository was assumed to be constructed at 500 meters below the surface in a crystalline rock. Conceptually, the repository mainly consists of disposal area and connections to the ground level, as shown in Figure 1. Disposal area consists of disposal tunnels, panel tunnels, and central tunnels. Only the disposal tunnel was taken into account in the quantification for a comparison throughout the study. The vertical disposal concept such as the KBS-3 design was considered, where the canister containing the intact spent fuels is emplaced in a borehole, as shown Figure 1. The canister is surrounded by a bentonite buffer to retard a radionuclide migration from a canister. It was also assumed that an immediate backfilling after a canister emplacement would be implemented. In this concept, a determination of the disposal tunnel and hole spacings for satisfying the temperature limit is very important in a repository design.
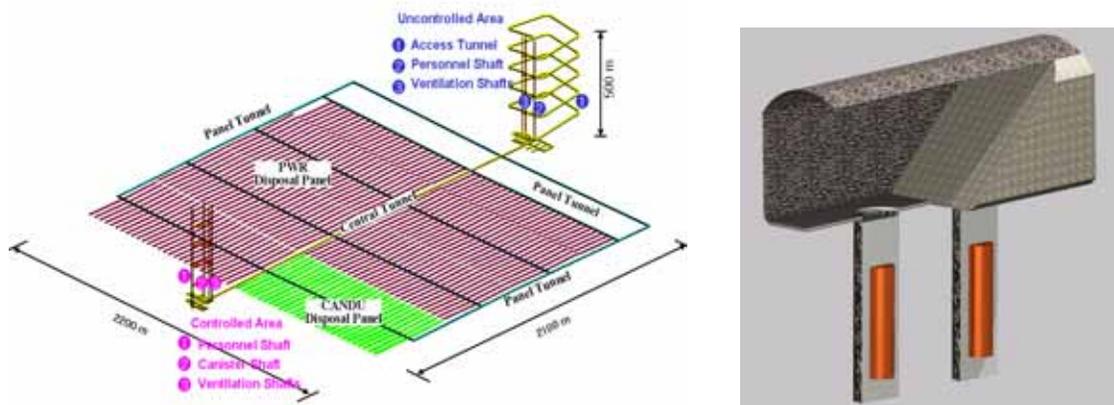

Figure 1. Layout of the vertical disposal system and view of the disposal tunnel.

SENSITIVITY OF THE KEY PARAMETERS

Spent Fuel Inventory

When the discharge burnup of a spent fuel is B, the amount of fuel required to generate W electricity is simply expressed in Eq. (3).

$$A = 3.65 \times 10^5 \frac{W}{B \cdot \varepsilon} \quad (3)$$

where, A = amount of fuel in unit of MtU,
   W = electricity in unit of TWa,
   B = discharge burnup of spent fuel in unit of GWD/MtU,
   ε = thermal efficiency.

In Eq. (3), it is clear that the inventory of a spent fuel decreases as the burnup increases. It can be easily understood that 17% of a spent fuel inventory is decreased to generate an equivalent amount of energy, if the burnup increases from 50 to 60 GWD/tHM. Thermal efficiency was assumed to be 0.33 when the amount of spent fuel was quantified.

Decay Heat and Buffer Temperature

Decay heat is one of the most important factors for the long-term management of a spent fuel. It was revealed that a 30% increase of the decay heat was predicted for a 10 GWD/MtU increase by the ORIGEN-ARP[4] calculation. The decay heat from a spent fuel as a function of the burnup after a 40-year cooling, can be expressed by Eq. (4) with an R-Square (R^2) of 0.99;

$$Q(40) = 115 + 12.35\,B + 0.15\,B^2 \quad for \quad 40 \le B \le 60 \quad (4)$$

where $Q(40)$ = total decay heat in unit of W/MtU at 40 years after a discharge,
   B = burnup in unit of GWD/MtU.

The effect of a decay heat increase on the disposal hole spacing with an increasing thermal load was assessed. As a result, the disposal hole spacing for satisfying the maximum buff temperature limit, 100 °C, is revealed to be 6 m for 45 GWD/MtU, ~8.5 m for 50 GWD/MtU, and ~14.2 m for 55 GWD/MtU. This represents the hole spacing increases at an exponential rate with an increasing burnup. This fact implies that the thermal impact by a burnup increase on a long-term spent fuel management is a critical factor for a geological disposal system design. This calculation was undertaken by the NISA computer program[5]. When the thermal effect was evaluated, the Korea reference disposal concept (KDC-1) similar to the KBS-3 design was used as a basis of the disposal system. And, the tunnel spacing and annular bentonite thickness were assumed to be 40 m and 50 cm, respectively.

Criticality and Radiation Shielding

According to the Linear Reactivity Model, the enrichment of ^{235}U should be increased to achieve a longer cycle operation. This results in a reactivity rise of the fresh fuel. However, a reactivity increase in a fresh fuel allows for the reactivity of a spent fuel to be lower, as expected from Eq. (2). Therefore, it is clear that a burnup increase is slightly advantageous for a long-term management of a spent fuel from a criticality safety aspect.
Disposal container should be designed to be below the absorbed dose limit to prevent a radiolysis near the surface of a canister and a subsequent corrosion of the canister. No remarkable change was observed

in the photon spectrum for a 40-year aged spent fuel. When the burnup proceeds form 50 GWD/MtU to 60 GWD/MtU, a 14% increase in the gamma intensity was anticipated by the ORIGEN-ARP calculation. For the KDC-1 canister, the thickness for satisfying the design constraints, 0.5 Gy/hr, was shown to be 48.2 cm for 50 GWD/MtU, and 48.5 cm for 60 GWD/MtU. This means that a burnup increase slightly affects the shielding design, but its effect is manageable.

  Therefore, it can be concluded that the effect of a burnup increase on the criticality and shielding safety is not important for a long-term disposal of a spent fuel.

IMPACTS OF A BURNUP INCREASE ON A GEOLOGICAL DISPOSAL

  From the previous results, it can be summarized that a burnup increase causes the waste inventory to decrease, but the disposal area increases considerably. Therefore, it is necessary to comprehensively evaluate these offsetting effects.

Analysis Procedure

  The procedures applied are as follows. i) Candidate design for assuring a structural integrity under a deep geological environment and satisfying the absorbed dose limit was proposed, through mechanical and shielding analyses, for a respective disposal canister accommodating 3, 4 and 5 spent fuels. ii) Disposal tunnel and hole spacings were calculated for each proposed canister as a function of the surface heat flux converted from the thermal load. iii) A program was developed to assess the spent fuel inventory, number of assemblies, canisters, and disposal holes, to generate an equivalent amount of energy. This program can also calculate an excavation volume, tunnel length, and the total amount of a raw material for a canister component, buffer, and backfill. vi) Finally, a comprehensive analysis to establish the trends when the burnup was varied from 40 to 60 GWD/MtU was implemented with a reference spent fuel inventory needed to generate an equivalent amount of electricity, 1 TWh.

Proposed Disposal Canister

        Structural analyses were implemented to propose the candidate canister design for assuring a structural integrity for normal and abnormal cases. For the normal case, it was assumed that an external load of 12 MPa, namely, a hydraulic pressure of 5 MPa and a bentonite swelling pressure of 7 MPa, was applied to the entire surface of the container[6]. For the extreme case, it was assumed that a bentonite swelling pressure of 7 MPa was partially applied to the container. The constraints of the safety factor taken into account for the normal and abnormal conditions are 1.0 and 2.0, respectively[7].
  The specifications and performance parameters of the conceptual designs for satisfying the design constraints proposed through this study are listed in Table 1. DGN #3 contains three assemblies and DGN #5 has five assemblies. The top-view of each canister can be inferred from the results from the NISA calculation in Figure 2. Each canister design consists of two major components: a massive cast insert and a 5 cm-thick corrosion-resistant copper outer shell. The insert provides a mechanical strength and a radiation shielding, and it holds the fuel assemblies in a fixed configuration. The axial dimensions are exactly the same as the KDC-1. The von Mises stress distribution is illustrated in Figure 2. As shown in Table I, each proposed canister design satisfies the design limit of the safety factor for each load condition. Yield strength was assumed to be 235 MPa for the nodular cast iron.

Table I. Specifications and performance parameters of each model

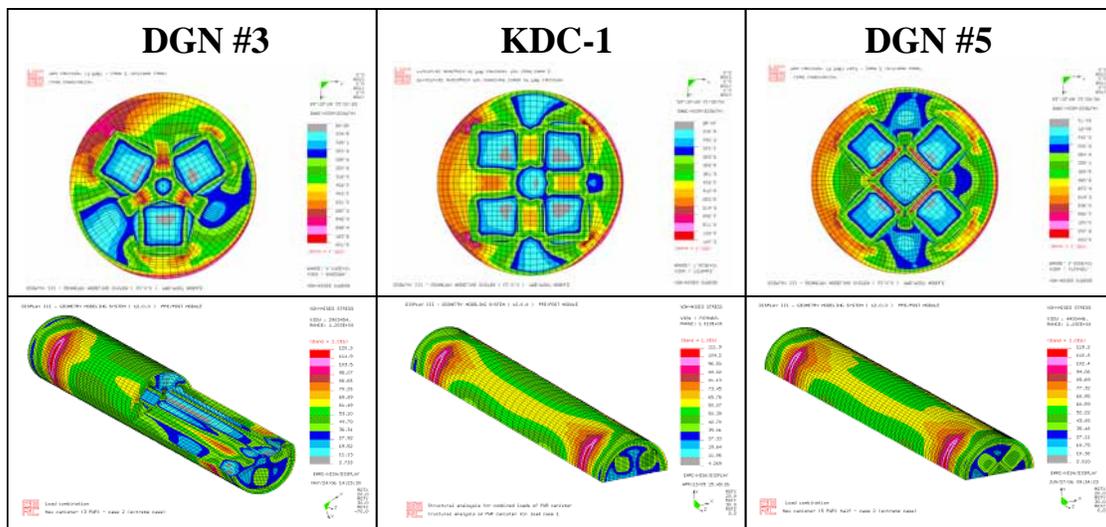|		DGN #3	KDC-1	DGN #5
No. of fuel assemblies in canister		3	4	5
Outer diameter (cm)		102	102	95
Normal Case	Max. von-Mises stress (safety factor)	84.7 MPa (2.77)	74.9 MPa (3.13)	99.5 (2.36)
	Max. deformation (mm)	2.56	2.54	2.52
Extreme Case	Max. von-Mises stress (safety factor)	120.3 MPa (1.95)	111.9 MPa (2.10)	119.2 (1.97)
	Max. deformation (mm)	2.66	2.64	2.63
Absorbed dose (Gy/hr)		< 0.5	< 0.5	< 0.5
Criticality		< 0.95	< 0.95	-

Figure 2. Von Mises stress distribution for an abnormal case

Shielding analysis was implemented to check that the proposed design satisfies the absorbed dose limit. Dose of 0.5 Gy/hr at the surface of a canister was considered as the design limit value to restrain a radiolysis and subsequent corrosion of a canister. The gamma intensity and spectra was estimated by ORIGEN-ARP with the built-in 17×17 Westinghouse fuel type library. The shielding calculation was carried out by MCNP4c2[8] with the MCPLIB02 library.

As a result, it was shown that the thickness required for a radiation shielding is less than that needed to maintain the structural integrity for all the cases. And, each design can accept 60 GWD/MtU within the dose limit.

Criticality was also checked under the optimum moderation condition. Detailed analysis was not undertaken because the KDC-1 canister was already confirmed from a criticality safety aspect[9]. It is clear that DGN #3 assures a criticality safety, because it contains lesser fuel assemblies than the KDC-1. A criticality analysis for DGN #5, however, is needed. The reason that this analysis was not done will be explained later.

Calculation of the Tunnel and Hole Spacings

Thermal analysis was carried out to propose the optimized disposal system for different burnups, namely, different thermal loads. The disposal hole and tunnel spacings for satisfying the maximum buffer temperature limit, 100 °C, as a function of the thermal load were calculated by NISA. The vertical disposal hole concept, as shown in Figure 1, was considered. Top and bottom boundary conditions to calculate the temperature profile were set at ground surface and 500 m below the surface. It was assumed that the surface temperature is maintained at 20 °C and the temperature increased by 3 °C every 100 m in depth.

Tunnel spacing and the corresponding hole spacing for the canister containing 4 spent fuels as a function of the thermal load is illustrated in Figure 3. From this data, the correlation between the tunnel spacing, hole spacing, and surface heat flux can be expressed by Eq. (5) for the KDC-1 disposal container.

$$P = 0.00463 \, EXP(q/17.79) + 11.3 \, EXP(-y/16.27) + 3.26 \qquad (5)$$

where, P = hole spacing in unit of meter,
$\quad\quad q$ = surface heat flux in unit of W/m^2,
$\quad\quad y$ = tunnel spacing in unit of meter.

A correlation was developed for each proposed canister model. Finally the tunnel and hole spacings as the thermal load increases were calculated through each regression formula.
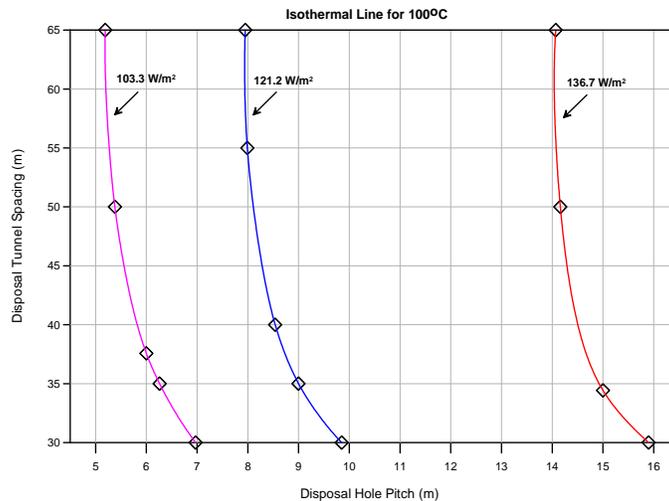

Figure 3. Hole and tunnel spacings for the thermal load of KDC-1

Results and Discussions

Comparison was implemented for each spent fuel inventory which was inevitably discharged to produce an equivalent amount of electricity, 1TWa. On the basis of the tunnel and hole spacings calculated from the each regression formula described above, the tunnel length, excavation volume, and the raw materials for a cast insert, copper bentonite, and backfill, needed to constitute a disposal system, were analyzed by a separate program. The reference repository concept is described in Figure 1. At first, the spent fuel inventory and the number of canisters needed were calculated as the burnup increased. And then, the hole and tunnel spacings as a function of the burnup for each proposed design were calculated as a basis. It was confirmed that the hole spacing increased, as the burnup increased and the tunnel spacing decreased.

The results from this comprehensive study are as follows. For the DGN #3 canister containing three fuel assemblies, it was shown that the total disposal tunnel length can be shortened by increasing the tunnel spacing up to 50 GWD/MtU. However, it should be noted that the repository area widens when the tunnel spacing increases. The reason that the tunnel length is decreasing up to 50 GWD/MtU is because of the effect induced by a decrease in the waste inventory which is superior to that caused by an increase in the hole spacing. For the cases using KDC-1 and DGN #5, it was shown that the total disposal tunnel length continuously increased as the burnup increased.

Figure 4 describes the excavation volume as a function of the burnup when the tunnel spacing is 40 m. The width and height of the disposal tunnel were assumed to be 6 m and 7 m, respectively. It should be noted that the excavation volume increases considerably with an increasing burnup if a container accommodating 4 or 5 spent fuels is used. This attribute can be alleviated by using a canister with 3 spent fuels, as shown in Figure 4. This means that it is advantageous to use a disposal canister containing a lesser number of spent fuels for a higher burnup fuel. This tendency was shown to be the same for the total disposal tunnel length and the backfill material needed. This is the reason that a criticality analysis for DGN #5 was not performed.

For the entire weight of the canisters which will be emplaced in a repository, a decreasing trend was observed because the spent fuel inventory required for the same amount of energy decreases as the burnup increases. The same trend was seen for the amount of cast insert, copper, and bentonite.

Based on the above results, the tendencies were summarized as follows: As the burnup increases, (i) the disposal tunnel length increases, even if the spent fuel inventory decreases (ii) the excavation volume and backfill material increases (iii) the total weight of the canisters decreases, which can offset an increase in the construction cost. As a whole, it can be concluded that it is reasonable to use a container like KDC-1 containing 4 spent fuels up to 50 GWD/MtU, and to use a canister containing 3 spent fuels beyond 50 GWD/MtU.
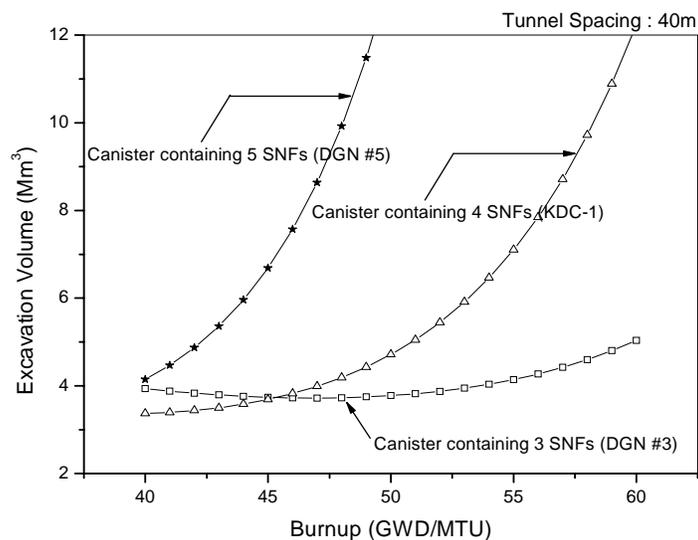

Figure 4. Excavation volume for each canister design

Table 2 quantitatively compares the design parameters to accommodate the spent fuels with a burnup of 40, 50, and 60 GWD/MtU. It was assumed that the most competitive canister design was used for each burnup during a comparison, namely, KDC-1 for a spent fuel with 40 GWD/MtU and DGN #3 for spent fuel with 50 and 60 GWD/MtU. In the case where the burnup increases from 40 to 50 GWD/MtU, a disadvantage was not perceived. However, in the case where the burnup increases from 50 to 60 GWD/MtU, a remarkable increase, 33% in tunnel length and 30 % in excavation volume, was observed in Table 2. This advantage can be offset by a reduction of the raw materials in the canister components and bentonite, as shown in Table II. The cost for the above and underground facilities, the cost for the

disposal canister fabrication, and the cost for a repository construction have approximately the same portion in total cost for a spent fuel disposal. Because a cost decrease in a canister fabrication can offset an increased construction cost, it can be concluded that a burnup increase of the spent fuel with time is not a critical concern for a deep geological disposal of a spent fuel.

Table II. Comparison of disposal system parameters for spent fuels

		Discharge burnup (GWD/MtU)			Diff.(%) (b-a)/a×100	Diff.(%) (c-b)/b×100
		40[a]	50[b]	60[c]		
Candidate canister design		KDC-1	DGN #3	DGN #3		
SNF Inventory (MtU/TWa)		27,652	22,121	18,434	6.7	-16.7
No. of canisters		14,995	15,995	13,329	-20.0	-16.7
Tunnel spacing (m)/Hole spacing (m)		40/5.34	40/5.62	40/9.00	5.2	60.1
Total disposal tunnel length (km)		84	95	126	12.2	33.4
Canister	Cast insert (ton)	2.37E+5	2.27E+5	1.89E+5	-4.3	-16.7
	Cu outer shell (ton)	1.08E+5	1.07E+5	8.90E+4	-1.5	-16.7
Backfill	volume (m^3)	3.37E+6	3.77E+6	5.04E+6	-3.5	33.5
Bentonite	volume (m^3)	3.17E+5	3.19E+5	2.66E+5	0.7	-16.7
Excavation volume (m^3)		3.74E+6	4.15E+6	5.35E+6	10.8	29.0

CONCLUSIONS

The characteristics of a geological disposal system with an increasing burnup of spent fuel were assessed in this study. Impact of a burnup increase on the criticality safety and radiation shielding concern was shown to be negligible. The disposal hole spacing, however, is affected considerably relative to the increase of a thermal load. Therefore, a thermal design to mitigate this negative effect is important. The tunnel length, excavation volume, and the raw materials for a cast insert, copper bentonite, and backfill needed to constitute a disposal system were analyzed based on the spent fuel inventory to generate 1TWa. Through a comprehensive analysis, it was concluded that it is reasonable to use a container like KDC-1 containing 4 spent fuels up to 50 GWD/MtU, and to use a canister containing 3 spent fuels beyond 50 GWD/MtU. And, although a remarkable increase, 33% in tunnel length and 30 % in excavation volume, was observed as the burnup increased from 50 to 60 GWD/MtU, because a cost decrease in a canister fabrication can offset an increased construction cost, it can be concluded that a burnup increase of a spent fuel is not a critical concern for a deep geological disposal of a spent fuel.

ACKNOWLOGEMENTS

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