Optimization of Spent Nuclear Fuel Assemblies per Canister Based on Decay Heat to Improve the Disposal Efficiency

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1. Introduction

In Korea, various kinds of spent fuels are being generated from nuclear power plants. They are being temporarily stored in spent nuclear fuel (SNF) storage pools and will be disposed into a deep geological repository. According to the conceptual design for the disposal of SNFs, four SNF assemblies will be emplaced into a canister and then canisters will be disposed into disposal boreholes.

In general, disposal areas of a repository are determined through thermal analyses using the decay heat of a reference SNF. The decay heat of a reference SNF is relatively high for conservatism. However, the decay heat of each SNF can be reduced remarkably, if the optimization of SNF assemblies per canister based on the decay heat estimated using the characteristics data of each SNF assembly such as burnup, discharge time, cooling time, and disposal schedule is made. Therefore, we can reduce the disposal areas of a repository by reducing spacings between disposal holes and disposal tunnels through this optimization procedure.

In this study, we develop a computer program for the combination of SNF assemblies per canister based on decay heat. We check the applicability of this program by implementing the combination of SNF assemblies per canister for the disposal scenarios suggested in the conceptual design for the disposal of spent fuels [1].

2. Methods and Results

2.1 Database for spent fuel

Spent nuclear fuels that will be disposed into a deep geological repository have diverse fuel type, physical data, initial enrichment, cooling time, and burnup. In addition, each SNF have different cooling time depending on the discharge time from reactor and disposal time based on the disposal scenario. We obtained SNF generation data based on the 8th basic plan for electric power demand and supply [2]. We develop a SNF database considering characteristics data for each spent fuel. Each record in the database consists of fields such as ID, Type, Initial_Enrichment wt %), Initial_U_Mass (g), Burnup (MWD/MtU), Discharge_Time, and Storage_Location. ID is an identification number for each SNF, Type is a SNF type such as KSFA and PLUS7, Initial_Enrichment wt %) is an initial uranium enrichment ratio, Initial_U_Mass (g) is an initial uranium mass, Burnup (MWD/MtU) is a burnup at the time of discharge from a reactor, Discharge_Time is a discharge time from a reactor, and Storage_Location is a power plant name that discharged SNF is stored temporarily. As an example of a database, a part of spent fuel data of Kori 1 Unit is shown in Fig. 1.

	A	B	C	D	E	F	G
1	ID	Type	Initial_Enrichment	Initial_U_Mass	Burnup	Discharge_Time	Storage_Location
2	KK1A01	14_SFA	2.1	401,525	24,241	1983-04-21	Kori_3
3	KK1A02	14_SFA	2.1	400,564	24,286	1983-04-21	Kori_3
4	KK1A03	14_SFA	2.1	400,088	16,837	1979-11-16	Kori_3
5	KK1A04	14_SFA	2.1	400,018	16,966	1979-11-16	Kori_3
6	KK1A05	14_SFA	2.1	399,039	24,170	1981-02-18	Kori_3
7	KK1A06	14_SFA	2.1	399,542	25,588	1982-05-03	Kori_3
8	KK1A07	14_SFA	2.1	399,595	25,700	1982-05-03	Kori_3
9	KK1A08	14_SFA	2.1	399,973	16,806	1979-11-16	Kori_3
10	KK1A09	14_SFA	2.1	399,859	23,902	1981-02-18	Kori_3

Fig. 1. An example screenshot of a spent fuel database.

2.2 Decay Heat of Spent Fuels

The decay heat of SNF is the heat released as a result of radioactive decay of fission products and activation products in SNFs. In general, decay heat decrease exponentially with time after released from the reactor. Decay heats from SNFs are usually estimated using a regression equation because they are nearly impossible to calculate or measure directly. In this study, we use a regression equation suggested by Cho et al. for the estimation of decay heat [3]. The regression equation and constants are summarized in Table 1.

Table I: Regression Equation for Decay Heat

	Category	Time (yr)	Equation	Constant
α	Fitting	1~30	$\alpha = y_0 + A_1 \cdot e^{-\left(\frac{x}{t_1}\right)} + A_2 \cdot e^{-\left(\frac{x}{t_2}\right)} + A_3 \cdot e^{-\left(\frac{x}{t_3}\right)}$	y0=4.908966E+02, A1=7.679070E+03, t1=1.797920E+02 A2=1.045528E+03, t2=2.488088E+01 A3=1.322184E+04, t3=8.543600E+01
		30~300	$\alpha = y_0 + A_1 \cdot e^{-\left(\frac{x}{t_1}\right)} + A_2 \cdot e^{-\left(\frac{x}{t_2}\right)}$	y0=4.490509E+01, A1=1.132256E+03, t1=4.379002E+01 A2=2.034482E+02, t2=3.939357E+02
		300~10^6	$\alpha = a \cdot x^b$	a=8.533352E+03, b=-7.193700E-01
β	Weighting	1~30	$\beta = y_0 + A_1 \cdot e^{-\left(\frac{x-x_0}{t_1}\right)} + A_2 \cdot e^{-\left(\frac{x-x_0}{t_2}\right)} + A_3 \cdot e^{-\left(\frac{x-x_0}{t_3}\right)}$	y0= 17.23509, x0= 0.23599 A1= 1102.09085, t1= 1.29539 A2= 298.05839, t2= 4.41315 A3= 204.66334, t3= 54.00279
		3x10^2 ~ 3x10^4		y0= 0.27076 , x0= -2511.04593 A1= -733.76391, t1= 3622.04249 A2= 2784.07004 t2= 552.36651 A3= 728.61222, t3= 3663.67428
		3x10^4 ~ 10^6	$\beta = a \cdot x^b$	a= 308.48779, b= -0.68194
γ	Burnup	all range	$\gamma = (Burnup - 35)/5$	
Input variable: [year], Burnup [GWD/MtU] Final Output: Decay Heat = $\alpha + \beta \times \gamma$, (Watt/MtU)				

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2.3 Program for the Combination of SNF assemblies per Canister Based on Decay Heat

We develop an algorithm for the optimum combination of SNF assemblies per canister based on decay heat, which is shown in Fig.2. Based on the number of total SNF assemblies to be disposed, the number of SNF assemblies per canister, and the number of canisters to be disposed per day, overall disposal schedule is set up with blank canisters. Then, all SNF assemblies are randomly assigned to canisters. For the optimization, the assembly having the maximum decay heat in the canister having the maximum decay heat and the assembly having the minimum decay heat in the canister having the minimum decay heat are exchanged, and the decay heats for both canisters are recalculated considering the changed disposal schedule. This optimization process is iterated until a user-defined criteria is met.

According to the general procedure of emplacing four SNF assemblies into a canister, SNF assemblies generated from the same nuclear power plant will be emplaced into a canister. If SNFs are stored temporarily in the wet interim storage facility before disposing them into a deep geological repository, however, any SNF assembly can be assigned to a canister regardless of which reactor was generated. In this study, therefore, we develop a computer program using MATLAB for the optimum combination of SNF assemblies per canister based on decay heat without considering the source of the SNF.

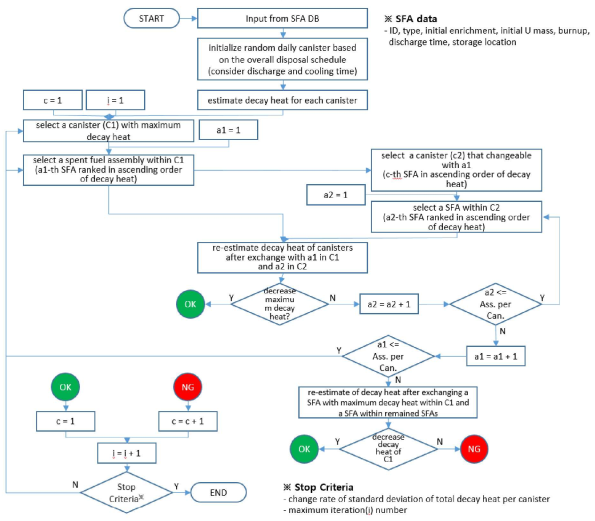

Fig. 2. An algorithm for the optimum combination of SNF assemblies per canister based on decay heat.

2.4 Analysis of combination of decay heat per canister

We applied the program for the optimum combination of SNF assemblies per canister based on decay heat considering all SNF assemblies simultaneously. We assumed that the emplacement of four SNF assemblies into a canister will start in 2063 and emplacement will occur only on working days. Therefore, about 250 canisters will be made per year. We also assume that the minimum cooling time is 30 years. We assigned 1,700 W for the design target value for the decay heat in the conceptual design of a repository for spent fuels.

As a result, Fig.3 shows the optimized distribution of decay heats per canister during the total disposal schedule. Here, four different color bars, which indicate the decay heats from four assemblies in a canister, for each day are stacked, and thus the sum of the decay heats become the decay heat of the canister. In the figure, MAX means the maximum decay heat per canister, MIN means the minimum decay heat per canister, AVG means the average of decay heats per canister, SD means the standard deviation of decay heats per canister, and Iteration means the number of iterations for the optimization. The number in parenthesis after the iteration number means the number of canisters whose decay heats exceed the design target, 1,700 W. As shown in Fig.3, there is no canister that exceeds the design target value of decay heat. The distribution of decay heat per canister shows relatively even distribution. Therefore, we found that this program could be used for the optimum combination of SNF assemblies per canister based on decay heat.

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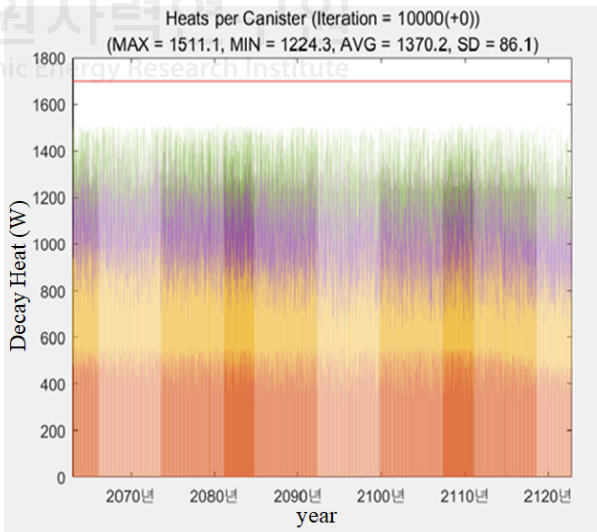

Fig. 3. Simulation result of combination of SNF assemblies per canister based on decay heat.

We simulate 10 times with the same iteration number to check the stability of the program. The results are shown in Fig. 4. As shown in this figure, the variations of each values of MAX, MIN, AVG, and SD are very small. Therefore, we find that the computer program developed in this study is very stable.

According to a research for the design improvement of a repository for the disposal of spent fuels, SNFs in Korea are classified into two types according to their length [4]. The one is R-SF (Regular-Spent Fuel) whose

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length is 406 cm and the other is S-SF (Short-Spent Fuel) whose length is 453 cm. In addition, they suggested a disposal scenario that the disposal of S-SF will start in 2063 and that of R-SF will start in 2078. Therefore, we simulated the combination of SNF assemblies per canister based on decay heat for this disposal scenario. The results for the disposal scenarios of S-SF and R-SF are plotted in Figs. 5 and 6.

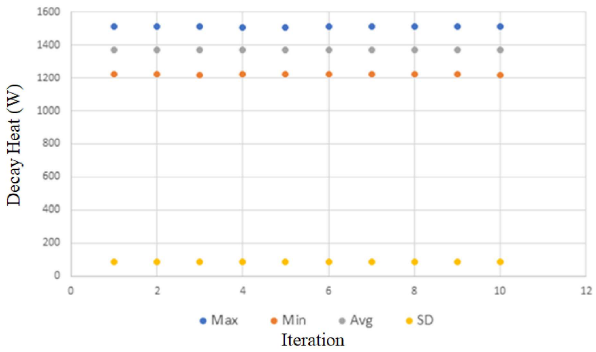

Fig. 4. Simulation results for 10 times with the same iteration number.

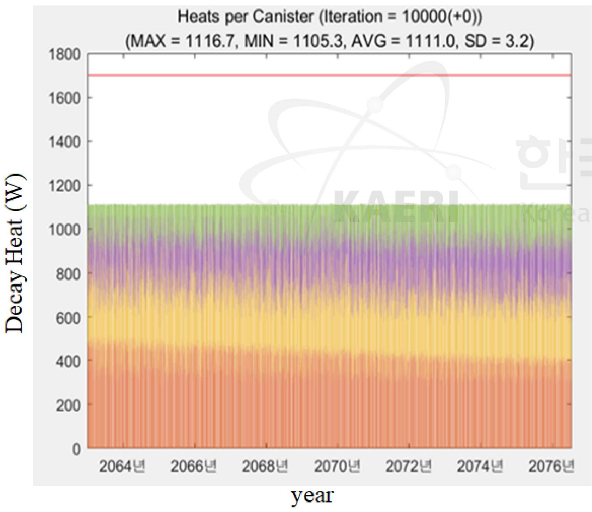

Fig. 5. Simulation result for the disposal of S-SF.

As shown in Fig.5, the maximum decay heat of a canister is 1116.7 W, which is much lower than the design target value of decay heat, 1,700 W. In addition, the distribution of decay per canister is uniform. This may be because S-SFs have longer cooling time and low burnup comparing with R-SF. As shown in Fig.6, the maximum value of decay heat per canister for R-SFs is also lower than the design target value of decay heat, and the distribution of decay shows relatively even distribution. Therefore, the computer program for the combination of SNF assemblies per canister based on decay heat can be used for any kind of combination of spent fuels for the disposal.

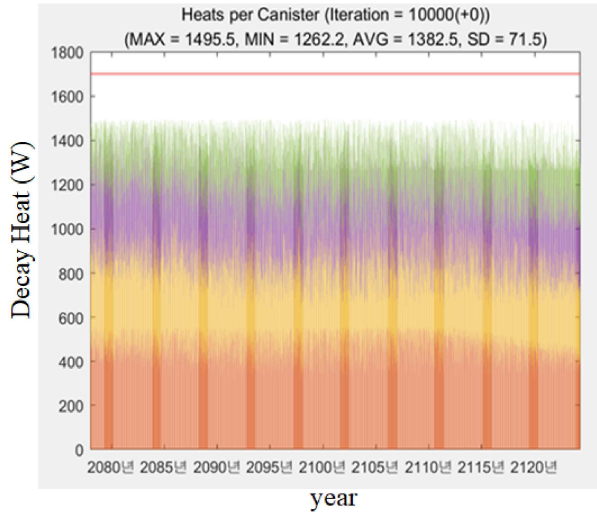

Fig. 6. Simulation result for the disposal of R-SF.

3. Conclusions

We develop a computer program for the optimum combination of SNF assemblies per canister based on decay heat. In addition, we check the stability of the program by simulating 10 times with the same iteration number. We apply the program for the disposal scenario suggested during the design improvement study for the disposal of spent fuels into a deep geological repository. We can obtain relatively even distribution of decay heat per canister using this program. Therefore, this program can be used for the optimum design of a deep geological disposal system for spent fuels because we can secure relatively even distribution of decay heat per canister. This program can also be used for the optimum combination of decay heat per canister for the transport and interim storage of spent fuels if we modify the input data such as the number of SNF assemblies per canister and an emplacement schedule.

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