Analysis of Detailed Operational History Effects on the Spent Fuel Characteristics for Hanbit Unit 3

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1. Introduction

Active research on the safety analysis of spent fuel and the back-end nuclear cycle facility is ongoing based on the permanent shut down of Kori unit 1. Therefore, the efficient evaluation of source terms is increasingly required for safety analysis of the spent fuel storage facilities. The authors have developed the AMORES (Automatic Multiple ORIGEN Runner for Evaluation of Source Terms) which can automatically estimate the characteristics of a huge amount of spent fuels coupled with ORIGEN-S and a given scenario on the projection of future nuclear power plant construction and operation. Originally, the AMORES assumed a single value of specific power of 40 MW/MTU for PWRs because it is expected that this high specific power leads to the conservative estimation of radiation source terms [1]. On the other hand, our recent previous work considered a more realistic irradiation histories of spent fuels provided by KHNP for the representative patterns of irradiation histories, which showed that some irradiation patterns can lead to more conservative estimation of radioactivity and heat generation than the simple irradiation using a single continuous depletion with a single specific power of 40 MW/MTU. However, in the previous work, the shutdown time between successive cycles and accurate consideration of capacity factor were not considered due to the lack of the data on the detailed operational history of nuclear power plants [2].

The objective of this work is to analyze the difference in the spent fuel characteristics such as radioactivity, heat generation, and radiotoxicities between the use of updated realistic irradiation histories and the simple irradiation using a single specific power of 40MW/MTU. Actually, this work is an extension of our recent previous with more realistic irradiation histories. In this work, we did not only consider the shutdown time between successive cycles but also the realistic capacity factor or the cycle lengths in term s of effective full power days (EFPD).

2. Methods and Results

To start the analysis with the realistic irradiation and cooling histories of spent fuels, we first analyzed the distinct patterns of irradiation and cooling for the spent fuels included in the spent fuel data base for Hanbit Unit 3 provided by KHNP. The spent fuel data base includes the detailed information such as the initial uranium enrichment, the number of irradiation cycles, the irradiation cycle numbers, and the cumulative burnups up to the irradiation cycles for each spent fuel assembly. In addition to these spent fuel assembly specific data, the spent fuel database includes the cycle specific data such as the starting date of critical operation, the shutdown date, cycle length in terms of EFPDs and the date of fuel unloading. From the analysis of the patterns, we selected the representative six patterns (Cases A ~ F) that are used in the detailed analysis. The selected patterns of the irradiation and cooling histories are shown in Fig. 1. As shown in Fig. 1, for example, the Case B represents that the fuel assembly is irradiated during the first and second cycles, cooled down over the next five cycles followed by the one cycle irradiation and then discharged from the reactor while the first case (i.e., Case A) represents a simple pattern in which the fuel assembly is irradiated only over the first one cycle and then discharged from reactor. In Fig. 1, it should be noted that the shutdown times (yellow bar) during refueling are considered, which was not considered in our previous work.

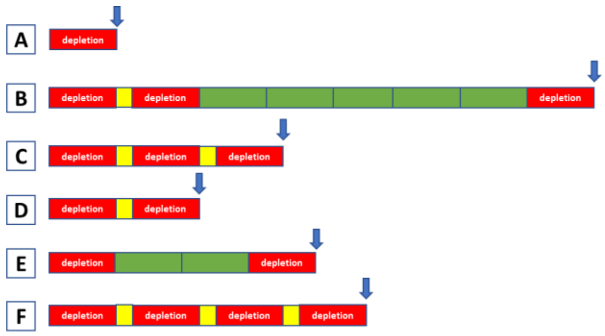

Fig. 1. Representative Spent Nuclear Fuel Assemblies according to irradiation history of Hanbit#3

Table I summarizes the specifications of the considered spent fuel assemblies corresponding to the representative irradiation and cooling history patterns given in Fig. 1. Because the realistic irradiation histories of each cycle are available, it is possible to consider the different specific powers for each cycle. The ORIGEN-S calculation requires the initial heavy metal loading, specific power, and irradiation and cooling times. In this work, the irradiation time interval for each cycle was estimated using the difference date of loading and discharged. The specific power for each cycle was calculated by dividing the cycle burnup with the operational time (i.e., time interval between the starting date of criticality completion and the shutdown date for each cycle). The time interval between the final discharge date and observation date was used as the cooling time after the final discharge. Also, we considered the shutdown time between the successive cycles as a cooling time in ORIGEN-S calculations.

Table I: Specification of the considered spent fuel assemblies corresponding to the representative patterns of irradiation and cooling

ID	Pattern type	Initial Enrichment [wt% ^{235}U]	Initial Uranium Mass [g]	Discharge Burnup [MWD/MTU]	Number of Cycle	1st Cycle	2nd Cycle	3rd Cycle	4th Cycle	Discharge Date
KY3A034	A	1.3	431,528	12,259	3	1				1996-02-26
KY3B009	B	2.36	432,351	32,171	3	1	2	8		2004-10-13
KY3B001	C	2.37	432,384	25,684	2	1	2	3		1998-04-14
KY3Q401	D	4.5	429,707	41,780	2	13	14			2012-10-26
KY3B103	E	2.35	430,441	25,617	3	1	4			1999-06-17
KY3E003	F	4.09	431,826	42,434	4	2	3	4	5	2000-10-12

In this work, we used the 'CE 16x16' one group cross section libraries provided by SCALE 6.1 were used for all the ORIGEN-S calculations [3]. Table II summarizes not only the specific powers and the irradiation time interval (i.e., depletion time) estimated with the method describe above but also the representative spent fuel characteristics estimated at 2035.01.01 (i.e., observation date) with the irradiation and cooling histories given in Table I. The numbers given in the parenthesis represent the percentages of the discrepancies between the values estimated with a single specific power of 40 MW/MTU and with the realistic irradiation (and cooling) histories. The specific powers given in Table II represent the average ones of the specific powers over all the cycles. For example, the Case A spent fuel assembly has 25.83MW/MTU specific power, and 40MW/MTU has much higher specific power by 54.83% than realistic irradiation histories. From Table II, it is shown that the Cases B and E which has long cooling times between the irradiation cycles give higher radioactivities and gamma powers for 40MW/MTU than the ones for the realistic irradiation histories. Also, it is noted that the consideration of realistic irradiation histories gives higher (i.e., conservative) the inhalation and ingestion hazards than the ones using 40MW/MTU for all the cases except for the Case F.

Table II: Comparison of Spent Nuclear Fuel Characteristics

Characteristic parameters	[a]Case A	Case B	Case C	Case D	Case E	Case F
Specific power	25.83	28.09	23.29	46.06	29.68	28.50
[MW/MTU]	(54.83%)	(42.39%)	(71.72%)	(-13.16%)	(34.79%)	(40.33%)
Irradiation day	474.5	1220	1123	911.5	856.25	1472.5
[Day]	(-35.41%)	(-34.08%)	(-42.82%)	(14.59%)	(-25.21%)	(-27.96%)
Cooling time	14189.3	13457.8	13552.3	8132.75	13818.5	12640.3
[Day]	(0.00%)	(-17.99%)	(-1.05%)	(-0.39%)	(-6.06%)	(-1.12%)
Inventory	431,489	432,370	432,410	429,680	430,430	431,830
[g]	(0.02%)	(0.00%)	(0.00%)	(0.00%)	(0.00%)	(0.00%)
Radioactivity	29,025	83,910	61,660	148,110	61,420	106,760
[Curies]	(-1.34%)	(7.62%)	(0.91%)	(-0.20%)	(3.74%)	(1.00%)
Thermal power	104.29	321.8	223.79	476.9	227.19	396.3
[W]	(-2.15%)	(-1.21%)	(0.06%)	(-0.10%)	(3.94%)	(0.53%)
Gamma power	23.96	70.49	52.15	121.19	51.86	90.59
[W]	(-0.05%)	(9.32%)	(1.24%)	(-0.16%)	(3.94%)	(1.00%)
Inhalation hazard	8.03E+16	2.65E+17	1.63E+17	2.77E+17	1.72E+17	2.81E+17
[m^3 of air at RCG]	(-5.98%)	(-17.05%)	(-2.26%)	(0.29%)	(-7.54%)	(-0.70%)
Ingestion hazard	2.75E+10	8.46E+10	5.77E+10	1.17E+11	5.91E+10	1.01E+11
[m^3 of water at RCG]	(-3.06%)	(-5.77%)	(-0.61%)	(-0.02%)	(-2.17%)	(0.15%)

[a] (Value obtained with 40 MW/MTU – Value obtained with realistic irradiation histories) / Value obtained with realistic irradiation histories

The better understand these trends, we analyzed the nuclide-wise contributions to radioactivity (Ci), thermal power (W), and radiotoxicity (i.e., inhalation hazard) for the Case B giving the largest discrepancies. We considered only ten nuclides giving the significant contributions. For radioactivity, the largest contribution is from ^{137}Cs and the next significant contributions are from ^{137m}Ba, ^{241}Pu, ^{90}Y, and ^{90}Sr in the order of magnitude. The contribution from these five nuclides to radioactivity is ~95% of the total radioactivity. As mentioned above, for Case B, the calculation using 40 MW/MTU give higher radioactivity than the one using realistic irradiation histories. This is due to the fact that the depletion of fuels for the case considering 40MW/MTU occurs during the time intervals nearer the discharge date and so the cooling time is shorter than the case considering realistic irradiation histories because the discharge dates are the same for the both cases. For thermal power, the largest contribution is from ^{137m}Ba and the next significant contributions are from ^{90}Y, ^{241}Am, ^{238}Pu, and ^{137}Cs. The contribution from these five nuclides to radioactivity is ~82% of the total radioactivity. And the next contributions are from ^{241}Am, ^{238}Pu, ^{241}Pu, ^{244}Cm, and ^{240}Pu in the order of magnitude and their contributions are ~94% of the total radiotoxicity. The difference in thermal power between the both cases is not so large.

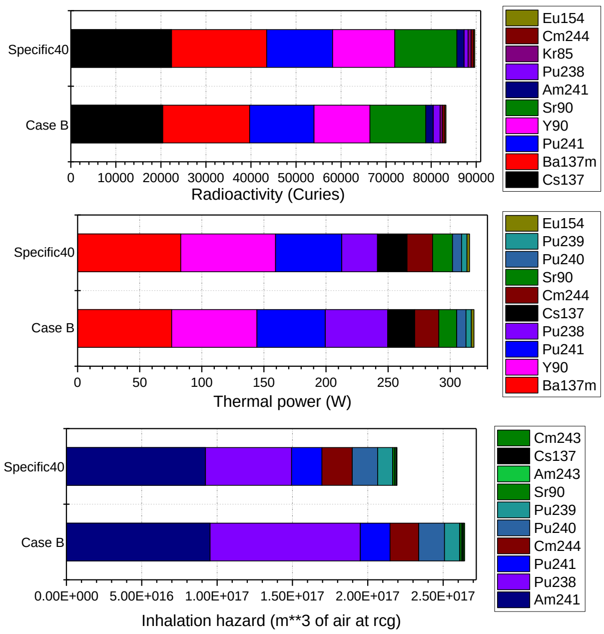

Fig. 2. Nuclide-wise contribution analysis results of Case B

In particular, ^{238}Pu gives a small contribution (i.e., 7th largest contribution) to the radioactivity and the discrepancy between the cases using 40MW/MTU and the realistic irradiation histories is largest (~74.7%), which is actually due to the discrepancy in ^{238}Pu inventories. The large discrepancy in ^{238}Pu inventories is due to the fact that ^{238}Pu is generated by α decay of ^{242}Cm during the long cooling time between the 2nd and 8th cycles for Case B (note that ^{242}Cm has relatively a short half-life of 162 days). In thermal power, it is very interesting to note that the discrepancy mainly comes from the large discrepancy in ^{238}Pu inventories. The large discrepancy in ^{238}Pu also explains the reason why the case using realistic irradiation histories give higher radiotoxicity than the case using 40MW/MTU.

Next, we analyzed the spent fuel characteristics of total spent fuel assemblies (i.e., 1,004 fuel assemblies) discharged from Hanbit Unit 3 evaluated with the consideration of irradiation and cooling histories with the method describe above. Before updating the AMORES program, we wrote an in-house program which automatically generates ORIGEN-S input files with consideration of realistic irradiation and cooling histories. This program also automatically prepares a batch file for automatic multiple ORIGEN-S and extracts the spent fuel characteristics from the generated ORIGEN-S outputs. We applied this in-house program to analyze the spent fuel characteristics of all spent fuel assemblies discharged from Hanbit Unit 3. We considered two different observation dates: 1) 2017.01.01 and 2) 2035.01.01. Table III compares the results of the analyzed spent fuel characteristics both at 2017.01.01 and 2035.01.01. At the observation date of 2017.01.01, the case using 40 MW/MTU gives higher radioactivity by 19.3%, higher thermal power by 20.1%, higher gamma power by 23.0%, higher radiotoxicity by ingestion hazard by 6.5% but slightly smaller radiotoxicity by inhalation hazard by 0.8% than the one using the realistic irradiation and cooling histories. On the other hand, there are only small differences of these quantities at the observation date of 2035.01.01.

Table III: Comparison of Spent Nuclear Fuel Characteristics of Hanbit#3

Characteristic parameters	2017			2035		
	Reference (40MW/MTU)	Realistic History	Discrepancy	Reference (40MW/MTU)	Realistic History	Discrepancy
Inventory [Ton]	432.427	432.423	0.004 (0.0%)	432.427	432.423	0.004 (0.0%)
Radioactivity [Curies]	5.20E+08	4.19E+08	1.00E+08 (19.3%)	1.27E+08	1.24E+08	2.26E+06 (1.8%)
Thermal power [W]	1,934,040	1,544,387	3.90E+05 (20.1%)	439,839	436,723	3,116 (0.7%)
Gamma power [W]	711,597	548,041	163,556 (23.0%)	105,846	104,284	1,562 (1.5%)
Inhalation hazard [m^3 of air at RCG]	3.24E+20	3.27E+20	-2.59E+18 (-0.8%)	2.85E+20	2.87E+20	-2.38E+18 (-0.8%)
Ingestion hazard [m^3 of water at RCG]	1.90E+14	1.78E+14	1.24E+13 (6.5%)	1.09E+14	1.09E+14	3.72E+11 (0.3%)

Fig. 3 and Fig. 4 show nuclide-wise contributions to radioactivity (Ci), thermal power (W), and radiotoxicity (i.e., inhalation hazard) for the total spent fuel assemblies discharged from Hanbit Unit 3 at 2017.01.01 and 2035.01.01, respectively. Fig. 3 shows that the discrepancy between the cases using 40MW/MTU and realistic irradiation and cooling histories in the radioactivity at 2017.01.01 comes from the large discrepancies of ^{144}Pr and ^{144}Ce which have large contributions to the total radioactivity at this observation date. On the other hand, there was no large discrepancy in ^{241}Pu that has the largest contribution to the total radioactivity. For thermal power, the fact that the case using 40MW/MTU gives higher value than the one using realistic irradiation and cooling is contributed from the discrepancies in ^{144}Pr,^{106}Rh, and ^{95}Nb that have large contributions to the total thermal power.

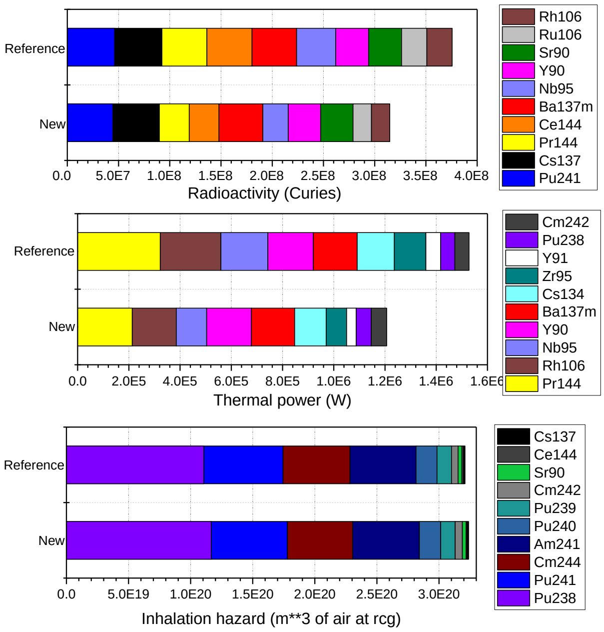

Fig. 3. Nuclide-wise contribution analysis results of Hanbit#3 at 2017

It is noted that the orders of the nuclides' contribution at 2035.01.01 is quite different from the ones at 2017.01.01. For radioactivity, ^{137}Cs has the largest contribution and ^{137m}Ba has the next large contribution but their discrepancies between the cases using 40MW/MTU and realistic irradiation and cooling histories are much smaller than those at 2017.01.01. For thermal power, the large contributions come from ^{90}Y, ^{137m}Ba, ^{241}Am, and ^{238}Pu, but their discrepancies between two calculation options are quite small. For radiotoxicity by inhalation hazard, the large contributions come from ^{241}Am, ^{238}Pu, ^{244}Cm, and ^{241}Pu in the order of magnitude and their discrepancies between two calculation options are also small.

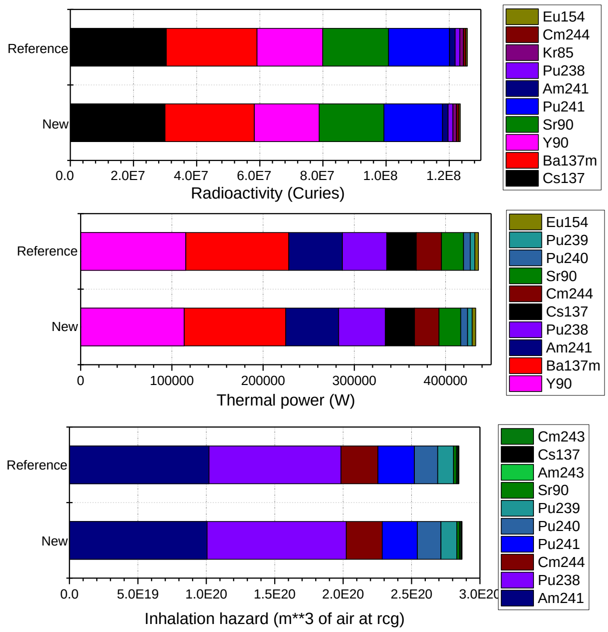

Fig. 4. Nuclide-wise contribution analysis results of Hanbit#3 at 2035

3. Conclusions

In this work, a detailed analysis of the effect of the realistic irradiation and cooling histories was performed for the spent fuels discharged from Hanbit Unit 3. This analysis was conducted using a recent spent fuel database which contains the number of irradiation cycles, the irradiation cycles, cumulative burnups for each irradiation cycle, and so on for Hanbit Unit 3 provided KHNP. The analysis of the spent fuel characteristics for the distinct six patterns of irradiation and cooling showed that the Cases which has long cooling times between the irradiation cycles give higher radioactivities and gamma powers but smaller thermal power and radiotoxicities for 40MW/MTU than the ones for the realistic irradiation histories. From the additional nuclide-wise analysis for these special cases, it was shown that the discrepancy in thermal power and radiotoxicities mainly come from the large discrepancy in ^{238}Pu inventories. On the other hand, the analysis of the spent fuel characteristics of total discharged spent fuel assemblies of Hanbit Unit 3 showed that at the observation date of 2017.01.01, the case using 40 MW/MTU gives higher radioactivity by 19.3%, higher thermal power by 20.1%, higher gamma power by 23.0%, higher radiotoxicity by ingestion hazard by 6.5% but slightly smaller radiotoxicity by inhalation hazard by 0.8% than the one using the realistic irradiation and cooling histories. On the other hand, there are only small differences of these quantities at the observation date of 2035.01.01.

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