A Scenario Study on PWR Spent Characteristics using Updated AMORES Program

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1. Introduction

The operations of commercial PWRs have contributed to the economic growth of our country by providing cheap and stable electricity while they have generated a huge amount of spent fuels. However, our country has no repositories for the spent fuels and the spent fuels are temporarily stored in the spent fuel pool inside the reactor buildings. As a result, it is expected that most of nuclear power plants in our country will face the saturation time in the near future at which the accumulated amount of spent fuels exceed the capacities of the spent fuel pools. Recently, Public Engagement Commission on Spent Nuclear Fuel Management has published a final report in which a permanent repository for spent fuels is recommended to be operated at 2053 after storing them in new interim storage facilities.

In this work, the updated program of the Amores (Automatic multi-batch ORIGEN runner for Evaluation of Spent fuel) program is introduced and it is applied to analyzing the characteristics of spent fuel for three different scenarios of constructions of NPP (Nuclear Power Plants)s and the geological repository.

2. Methods and Results

2.1 Update of the Amores Program

Recently, the authors has updated the Amores program for analyzing the spent fuel characteristics (e.g., radiotoxicities and heat generations) based on the scenarios for the constructions of NPPs and new interim storage facilities or permanent geological repository. Originally, Amores was developed using C++ and C# to generate the source terms of the spent fuels making it possible to automatically generate ORIGEN-S input files and process their output files for a huge number of spent fuel assemblies. Recently, the authors have updated Amores such that it can be used for generating the spent fuel characteristics and source terms based on the scenarios of the construction of NPPs and interim storage facilities or permanent geological repository. As shown in Fig. 1, the analysis starts by reading and processing the spent fuel data which is comprised of a huge number of spent fuel assemblies [4]. Actually, in this work, the realistic data on the spent fuel from KHNP up to 2015 (reference year) are utilized as the initial data in the scenario study. The reference year (i.e., present year) means the year at which the calculation of annual spent fuel generation starts using a simple equation (i.e., Eq.(1)). The schematic calculation flows of the updated Amores are shown in Fig. 1.

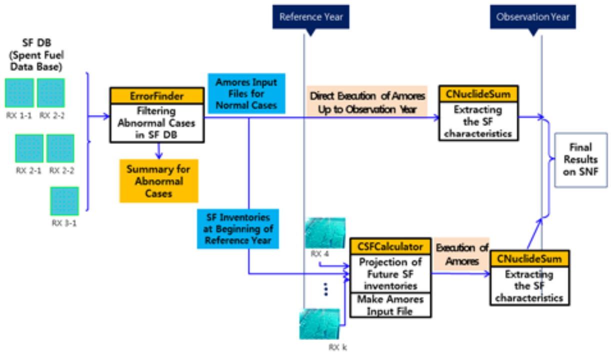

Fig. 1. Schematic calculation flow of updated Amores

The processing of the spent fuel includes the checking errors which may be included in the data and automatic generation of input files for Amores using normal data, and the summary file giving the information which data are wrong. This processing is performed by the ErrorFinder module. Then, there are two path ways in the next steps. The first one is to directly perform ORIGEN-S depletion and decay (or cooling) calculations using Amores up to the observation year which is the year at which we want to know the spent fuel characteristics. The observation year means the year at which the operation of interim storage facilities or geological repository starts. On the other hand, in the second pathway, the Amores calculation is performed only up to the reference year and the spent fuel inventories from the ORIGEN-S output files are utilized in automatically generating a single ORIGEN-S input file which is used to generate the isotopic changes using only decay calculation in the spent fuels at the observation year. This second pathway was considered to reduce the computing time of a huge number of the ORIGEN-S calculations in the first path way. The next step is to estimate the amount of spent fuel generations in the time period from the reference year to the observation year. The following simple equation was used to calculate the annual generation of the spent fuel :

$$SFG = 365.25CF \times NC / (\eta \times BU), \qquad (1)$$

where NC, CF, η, and BU represent the NPP capacity, capacity factor, NPP efficiency, and average discharge burnup of the spent fuels, respectively. It should be noted in Eq.(1) that the amount of spent fuel generation does not only include the actinides but also fission products and the mass defects resulted from fission were neglected [1, 3]. Also, the estimation of the spent fuel inventories strongly depends on the scenario for the

NPP constructions. This estimation of the spent fuel inventories from the reference to the observation year is performed in the CSFCalculator module. This module also automatically generation of input files for Amores for all the representative fuel assemblies of all the considered NPPs. Finally, the amounts of the nuclide-wise inventories estimated from the CSFCalulator module are summed with the results of the Amores calculations with the initial data for the accumulated spent fuels before the reference year in the both pathways. The CNuclideSum module extracts the nuclide wise information such as the radiotoxicities, heat generations, and inventories from the ORIGEN-S output files produced by Amores [4].

2.2 Scenario Analysis

We considered three different scenarios on the NPP constructions including their operations and we assumed that the geological repository is to be operated from 2053. As mentioned in Section 2.1, the reference year is set to 2016 and the PWR spent fuel data from KHNP up to 2015 was used as the initial data. We did not consider the CANDU spent fuel because it was not available to us. The first scenario (SCENARIO A) is based on the national 7th electric power supply schedule. The schedule of new NPPs for the national 7th electric power supply schedule is described in Table I. Based on the national 7th electric power supply schedule, new 13 NPPs will be constructed and operated from 2015. The total electric capacity of these new NPPs is 18.2 GWe [5].

Table I : Description of the national 7th electric power supply schedule

Item	NPP units (Operation Start Year) [MWe]
Schedule is fixed	ShinKori#3 (2016.04) [1400] ShinKori#4 (2016.02) [1400] ShinKori#5 (2021.03) [1400] ShinKori#6 (2022.03) [1400]
	CheonJi#1 (2026.12) [1500] CheonJi#2 (2027.12) [1500]
	ShinHanWol#1 (2017.04) [1400] ShinHanWol#2 (2018.04) [1400] ShinHanWol#3 (2022.12) [1400] ShinHanWol#4 (2023.12) [1400]
	ShinWeolSung#2 (2015.07) [1000]
Not fixed	New NPP#1 (2028.12) [1500] New NPP#2 (2029.12) [1500]

However, the recent situation has becomes unfavorable on the constructions of new NPPs after the Fukushima accident and earth quake in Kyeong Ju. Therefore, the second and third scenarios are considered to reflect this situation. The second scenario (SCENARIO B) assumes that the constructions of ShinHanWol #3 and 4, CheonJi#1 and 2, and New NPP #1 and #2 NPPs are cancelled out. The third scenario (SCENARIO C) is the most limiting case in which the cancellation of the ShinKori #5 and #6 is considered in addition to the cancellations assumed in SCENARIO B. Fig.2 compares the changes of the annual electric capacities for the considered three scenarios from 2015 to 2053. In this work, the reactor lifetime for ShinKORI (#3, #4, #5, #6), ShinHanWol (#1, #2, #3, #4), CheonJi (#1, #2), and New NPP (#1, #2) was assumed to be 60 years while the lifetime of the other NPPs to 40 years. According to the spent fuel data, the burnups are known to be in range of 30,000 to 60,000 MWth·d/MTU. In this work, average burnup and capacity factor was assumed to be 45,000 MWth·d/MTU and 85%, respectively, for all NPPs [1-5].

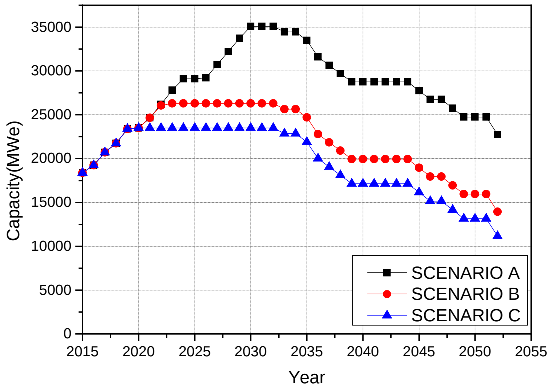

Fig. 2. Comparison of the annual electric capacities for different scenarios

Fig. 3 compares the amounts of annual spent generation with the updated Amores program for the considered scenarios. Actually, the trend of the evolution of the annual spent fuel generation is nearly the same as that of the annual electricity capacity because they are proportional to each other with a single fuel burnup. For the SCENARIO A, the annual spent fuel generation reaches its maximum value of 593 tons at 2030, and decreases and then increases again at 2030 up to 593 tons, and decreases due to no construction of new NPPs. On the other hand, the annual spent fuel generation has its maximum value of 593 tons at 2030~ 2034 and then gradually decreases.

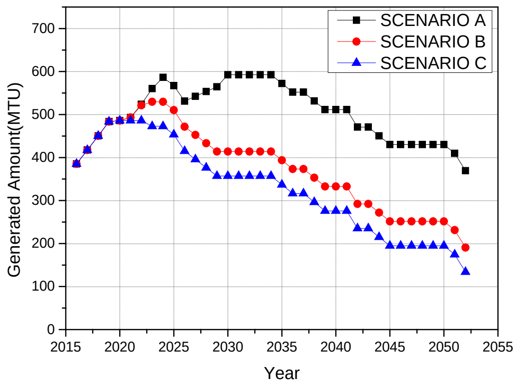

Fig. 3. Comparison of the annual spent fuel generations for different scenarios

The inventories of the accumulated spent fuels estimated with the updated Amores for different scenarios are compared in Fig. 4. The scenarios A, B, and C showed the 26042, 21189, and 19385 tons of spent fuels at 2053, respectively. So, the SCENARIO A has much larger accumulated spent fuel inventory by 34.3% than the SCENARIO C.

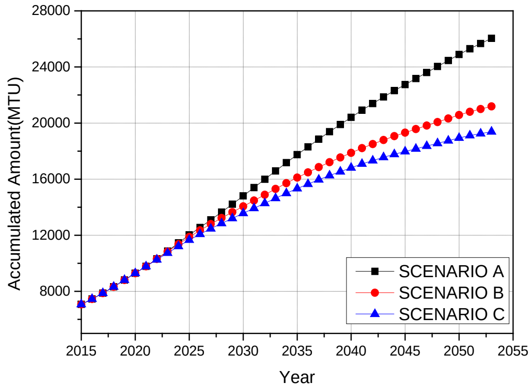

Fig. 4. Comparison of the accumulated amount of spent fuels for different scenarios

Next, the characteristics of the spent fuel inventories such as radiotoxicities and heat generation are evaluated and compared at 2053. The target nuclides that give considerable effects on the spent fuel characterization are selected to simplify the data base of spent fuel. The selected nuclides include all the actinides from thorium to californium and important fission products. These target nuclides are summarized in Table II. The actinides are especially important for waste storage studies due to their long-term radioactivity. The long-lived fission products having half-lives of over 25 years were included in the target nuclides because they have considerable contributions to the spent fuel radiotoxicities. These fission products are ^{135}Cs, ^{137}Cs, ^{129}I, ^{94}Nb, ^{107}Pd, ^{79}Se, ^{151}Sm, ^{126}Sn, ^{90}Sr, ^{99}Tc, and ^{93}Zr. Also, the fission products having half-lives longer than one year (^{113m}Cd, ^{134}Cs, ^{154}Eu, ^{155}Eu, ^{85}Kr, ^{147}Pm, and ^{125}Sb) were included to consider their non-negligible radioactivities [1, 4].

Table II : Target nuclides considered for spent fuel characterization

Nuclides found in the SFD							
Am-239	Cf-249	Cm-248	Np-236	Pd-107	Sb-125	Th-234
Am-240	Cf-250	Cm-249	Np-236m	Pm-147	Se-79	U-230
Am-241	Cf-251	Cm-250	Np-237	Pu-236	Sm-151	U-231
Am-242	Cf-252	Cm-251	Np-238	Pu-237	Sn-126	U-232
Am-242m	Cf-253	Cs-134	Np-239	Pu-238	Sr-90	U-233
Am-243	Cf-254	Cs-135	Np-240	Pu-239	Tc-99	U-234
Am-244	Cf-255	Cs-137	Np-240m	Pu-240	Th-226	U-235
Am-244m	Cm-241	Eu-154	Np-241	Pu-241	Th-227	U-236
Am-245	Cm-242	Eu-155	Pa-231	Pu-242	Th-228	U-237
Am-246	Cm-243	He-4	Pa-232	Pu-243	Th-229	U-238
Bk-249	Cm-244	I-129	Pa-233	Pu-244	Th-230	U-239
Bk-250	Cm-245	Kr-85	Pa-234	Pu-245	Th-231	U-240
Bk-251	Cm-246	Nb-94	Pa-234m	Pu-246	Th-232	U-241
Cd-113m	Cm-247	Np-235	Pa-235	Ru-106	Th-233	Zr-93

The characteristics of the spent fuel inventories at 2053 are compared in Fig. 5. These characteristics include the radioactivity (Curies), heat generation (W), gamma heat generation (W), radiotoxicity in terms of inhalation hazards (m^3 of air at ROG) and radiotoxicity in terms of ingestion hazard (m^3 of water at ROG). From Fig. 5, it can be shown that 1) total radioactivities for SCENARIO A, B, and C are estimated to be 1.07×10^{10}, 7.60×10^{9}, and 6.54×10^{9} curies at 2053, respectively, 2) the thermal heat generations are 38.9MW, 27.8MW, and 23.9MW, respectively, and 3) the radiotoxicities in terms of inhalation hazard are 1.89×10^{22}, 1.49×10^{22}, 1.34×10^{22} m^3 of air at RCG, respectively. So, the SCENARIO C considering the cancellations of the future NPPs shows 25.0%, 38.9%, 38.5%, and 29.1% reductions of the spent fuel inventories, radioactivities, thermal heat generation, and the radiotoxicities, respectively, than the most optimistic scenario of NPPs construction.

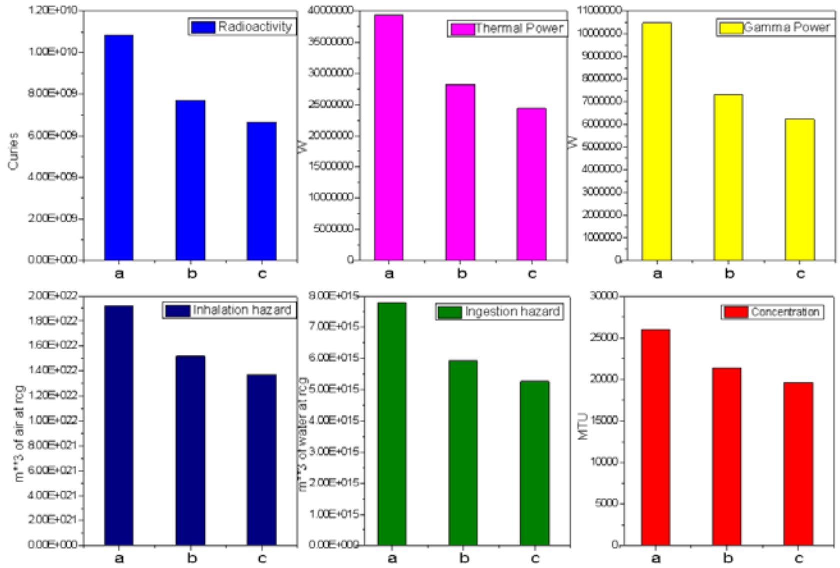

Fig. 5. Comparison of the spent fuel characteristics for different scenarios

The nuclide-wise contributions of the important nuclides to the total thermal heat generation at 2053 are compared in Fig. 6 while the contributions of them to the total radiotoxicities are in Fig. 7. Fig. 6 shows that the nuclide-wise contributions of thermal heat generation are almost same for the considered three scenarios. The largest contributions of ~18% are from ^{238}Pu and ^{241}Am, and the next strong contributors are ^{244}Cm (16%) and ^{134}Cs (14%). On the other hand, it is shown in Fig. 7 that the radiotoxicities are mainly contributed from ^{238}Pu (33%), ^{241}Am (29%), and ^{244}Cm (15%). Also, Fig. 7 shows that there are only minor differences in the nuclide-wise contributions among the different scenarios.

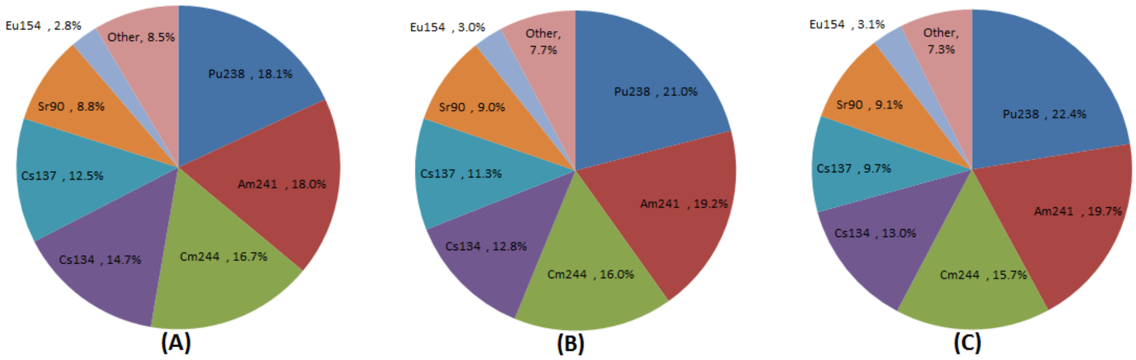

Fig. 6. Comparison of the nuclide-wise contributions to total thermal heat generation

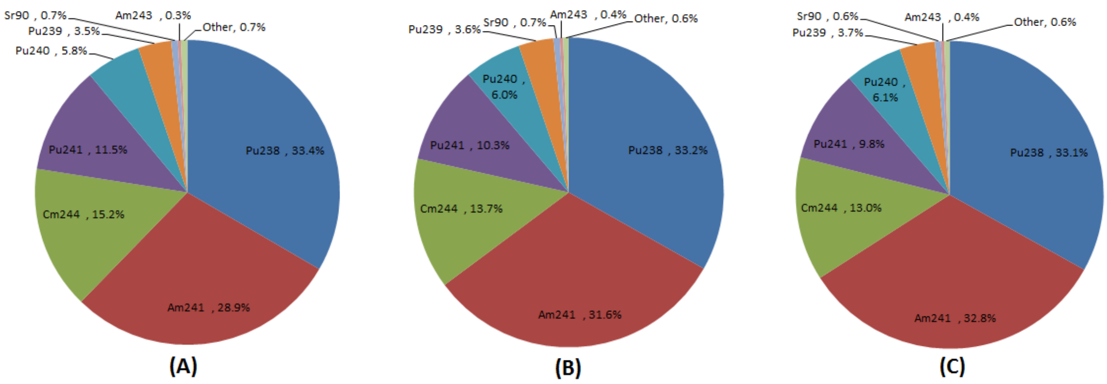

Fig. 7. Comparison of the nuclide-wise contributions to total radiotoxicity

3. Summary and Conclusion

In this work, the update of Amores is reported and this updated version of Amores is applied to analyze characteristics of the spent fuel inventories using three different scenarios on the construction of NPPs up to 2053. The reference scenario is devised on the national 7th electric power supply schedule and the other two scenarios assumed the cancellations of the NPPs scheduled in the future. From the results of the scenario analysis, it was found that the most conservative scenario in NPP constructions produces the reductions of spent fuel inventory by 6,656 tons (i.e., 25.0%), the radioactivity by 4.17x10^9 curies (i.e., 38.9%), the thermal heat generation by 1.50 x10^7 MW (i.e., 38.5%), and the radiotoxicity in terms of inhalation by 5.5x10^{21} m^3 (i.e., 29.1%) at 2053. Also, the nuclide-wise contribution analysis showed that the thermal heat generation are mainly contributed from ^{238}Pu (18%), ^{241}Am (18%), ^{244}Cm (16%), and ^{134}Cs (14%) while the main contributors to the radiotoxicities are from ^{238}Pu (33%), ^{241}Am (29%), and ^{244}Cm (15%).

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