Update of AMORES Programs for Automatic Criticality Safety Evaluation of the Transport CASK

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1. Introduction

In Korea, it is expected that the storage facilities of SNF (spent nuclear fuel) for each nuclear reactor headquarters will be saturated from 2021 onwards [1]. Demand for transport CASK is expected to increase as the most suitable deep geological disposal is considered. Therefore, accurate evaluation of radiation shielding, heat generation and critical safety of transport CASK is important. As of the end of December 2019, the cumulative storage of SNF at each nuclear reactor is stored in a storage facility at 482,592 assemblies, including 19,268 assemblies of PWRs and 463,324 assemblies of CANDUs [1]. Because evaluating the entire SNF in Korea requires a great deal of time and effort, this study added a criticality safety evaluation module to the AMORES (Automatic Multi-batch Origen Runner for Evaluation of Spent fuel) for automation of criticality safety evaluation. In particular, the criticality safety evaluation of SNF was performed with a specific and accurate operational history to take into account burnup credit. The SNF assemblies was based on a database under a support from KINS. The criticality safety evaluation was performed with KORAD-21 which can transport both WH and CE types.

2. Overview of AMORES and Development Status

Originally, AMORES was developed using C++ and C# to reduce the burden in preparing ORIGEN-S input files, in executing them and in analyzing the results for a large number of SNF assemblies for giving source terms for various analyses [2]. ORIGEN-S (Oak Ridge Isotope Generation in Scale) is the depletion and decay module in the SCALE code system which was developed at Oak Ridge National Laboratory [3]. AMORES performs depletion calculations using the operation and cooling history database for the SNF assemblies of each reactor.

The main functions of the AMORES program can be summarized as follows: 1) Validation of SNF DB information data, 2) Source term evaluation of the selected number of spent nuclear fuel (SNF)s using automatic ORIGEN-S calculation, 3) Radiation shielding of transport and storage casks using Monaco/MAVRIC sequence, 4) Providing user-friendliness GUIs for simulation. In this study, we added a criticality safety evaluation module (hereafter referred to as the criticality module) to AMORES that can efficiently perform criticality safety evaluation for a huge number of SNF to be loaded into the transport CASK. Fig.1 shows the overview of the criticality module.

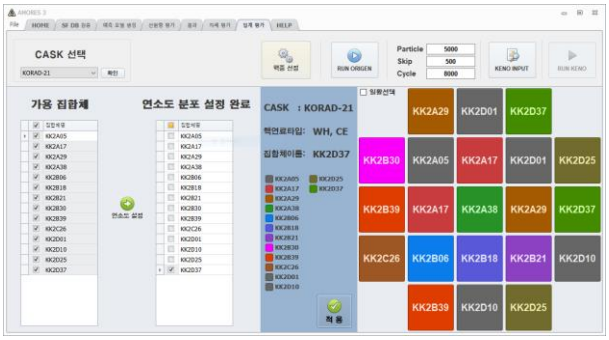

Fig. 1. Overview of AMORES criticality module

3. Development of criticality module

The criticality safety analysis in AMORES is designed to allow the application of burnup credit. STARBUCS (STandardized Analysis of Reactivity for BUrnup Credit using SCALE) module of SCALE6.1 was developed by the Oak Ridge National Laboratory (ORNL) perform and review criticality safety evaluations of transport and storage casks that apply burnup credit [4]. However, STARBUCS assumes that only a single type assembly is loaded and performs critical evaluation. This is not suitable for real conditions. Therefore, AMORES can load different types of assemblies into the CASK and can apply burnup credit. A coupling of the KENO-VI of ORIGEN-S in SCALE6.1 can make it possible to load different assemblies into the CASK. Fig.2 shows the calculation flow in AMORES. This is very similar to the flow in the STARBUCS module sequence, but AMORES can specifically divide the depletion calculations.

BU, DT, CT, M and Enrich in Fig.1 represent burnup, depletion time, cooling time, mass and enrichment of nuclear fuel assembly, respectively. The subscript of each parameter is the index of the assembly. Firstly, AMORES prepares burnup-related input data (burnup, depletion time, cooling time, mass and axial burnup profile) for each assembly to be loaded in the CASK. Each assembly is divided axially into 18 equal parts, and 18 ORIGEN-S inputs are generated and ORIGEN-S is executed for each axial node for each assembly. The atom densities of the major nuclides are extracted from the ORIGEN-S output and entered into the input of KENO-VI, which enables CASK criticality safety analysis. In this process, the user can choose the

assembly types to load in a desired location of the CASK. Finally, KENO-VI is executed to obtain criticality safety analysis and effective multiplication factor of KORAD-21 CASK loaded with SNF assemblies.

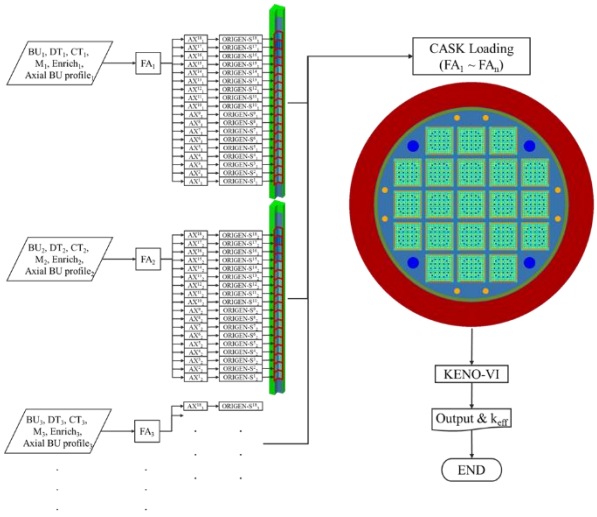

Fig. 2. AMORES criticality module calculation flow

3.1. Detail of Criticality module

The critical evaluation in AMORES can be applied to assemblies completed up to the evaluation of source terms. Also, each assembly is used for criticality safety analysis by applying the operational and cooling history of the PWR nuclear fuel database. At the beginning of the criticality module, the user can select the desired transport CASK. Currently, only KORAD-21 CASK was modelled, but in the near future, KN-18 and KN-12 are also modelled. Thus, the user can edit the set of nuclides for considering burnup credit and the assembly loading pattern without modeling the transport CASK, enabling efficient nuclear criticality evaluation. All CASKs were modelled with the assumption of inundation conditions and the 238 group ENDF/B-VII cross-section library is currently used for criticality calculation. Axial burnup profile is applied to each assembly. Users can easily assign a non-uniform axial burnup profile including uniform one. The average of the burnup profile is perfectly corresponded to the discharge burnup of the assembly in which the source evaluation has been completed. Before generating and executing ORIGEN-S, there are three sets of nuclides that are mainly used in criticality safety evaluation [5]. If there are other nuclides that the user wants to add, the user can add and use them. The user can load assemblies into the CASK as shown on the right side of in Fig.1. The user can load an assembly once or several times. When the execution of ORIGEN-S and loading into CASK are completed, the user set the number of particles, the number of cycles to calculate, and the skip cycles to use in KENO-VI. Then, user can activate the execution of KENO-VI to obtain an effective multiplication factor considering the burnup credit.

4. Comparison with STARBUCS

For verification of AMORES, the comparison calculation with STARBUCS was performed for KORAD-21 CASK. A comparative calculation was performed assuming that a single assembly is loaded into CASK with a burnup axial profile. Table.1 shows the details of a test assembly. The depletion time is 299.525 days and the cooling time is 13357 days. The burnup axial profile was automatically generated when it was divided axially into 18 in STARBUCS [4]. In criticality evaluation, the 10 most conservative nuclides (SET 1 in reference 5) were used to nuclide setting [5].

Table 1. Detail of reference assembly

Characteristic parameters			Value		
Reactor			Kori Unit 2		
Assembly type			WH17x17		
Operation date			1983.07.25.		
Shutdown date			1984.06.07		
Loading date			2021.01.01.		
Enrichment			1.61 wt%		
Mass			407,514 g		
Discharge burnup			11,981 MWd/MTU		
Specific power			40 MW/MTU		
Burnup axial profile					
18	17	16	0.462	0.738	0.971
15	14	13	1.059	1.086	1.095
12	11	10	1.096	1.095	1.094
9	8	7	1.094	1.097	1.102
6	5	4	1.106	1.108	1.103
3	2	1	1.074	0.967	0.652
Set nuclide			Set 1 (10 nuclides)		
Actinide			^{234}U ^{235}U ^{238}U ^{238}Pu ^{239}Pu ^{240}Pu ^{241}Pu ^{242}Pu ^{241}Am		
Other			^{16}O		

The number of particles was 5000, the number of cycles was 8000, and 500 skip cycles were applied to the Monte Carlo calculation for each calculation. Firstly, we compared the nuclides atom densities calculated by ORIGEN-S in the STARBUCS with those obtained with ORIGEN-S in AMORES. Table 2 shows the discrepancies of atom densities between the two codes. The AX^1 and AX^{18} shown in Table.2 represent the lowest and the highest axial nodes, respectively. The comparison results show that the atom densities are almost the same within maximum 0.5% discrepancy. These small discrepancies are resulted by the mismatches in the cooling time divisions between AMORES and STARBUCS.

Table 2. Error of atom density between the AMORES and STARBUCS

Nuclide	Axial position atom density error[1] (%)																	
	AX^1	AX^2	AX^3	AX^4	AX^5	AX^6	AX^7	AX^8	AX^9	AX^{10}	AX^{11}	AX^{12}	AX^{13}	AX^{14}	AX^{15}	AX^{16}	AX^{17}	AX^{18}
^{234}U	-0.05	0.00	-0.18	0.17	0.08	-0.42	0.42	-0.34	0.25	0.25	0.08	-0.17	0.08	0.09	0.09	0.00	0.04	0.00
^{235}U	0.13	0.00	0.00	-0.25	0.13	0.00	-0.32	-0.06	-0.32	-0.32	-0.25	-0.13	-0.25	-0.31	0.06	-0.29	-0.10	0.15
^{238}U	0.04	-0.04	0.09	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.09	0.00	0.13	-0.18
^{238}Pu	0.48	0.08	-0.06	0.15	0.06	0.09	0.06	0.15	0.18	0.18	-0.03	0.06	-0.03	-0.03	-0.13	-0.04	-0.22	0.04
^{239}Pu	0.03	-0.02	-0.04	0.03	-0.01	0.04	-0.04	0.00	-0.01	-0.01	-0.04	0.03	-0.04	0.01	0.01	0.04	0.01	-0.02
^{240}Pu	-0.18	-0.08	0.00	-0.03	0.16	0.00	0.07	-0.13	0.13	0.13	0.03	-0.03	0.03	-0.13	0.10	-0.15	0.26	0.38
^{241}Pu	-0.29	0.15	-0.13	0.13	-0.04	0.13	-0.17	0.00	-0.04	-0.04	-0.17	0.13	-0.17	0.09	0.04	0.05	-0.24	-0.04
^{242}Pu	0.07	0.22	-0.14	0.03	0.22	-0.06	-0.06	0.13	0.16	0.16	-0.06	0.03	-0.06	0.07	-0.04	0.04	0.09	0.19
^{241}Am	-0.02	0.03	0.46	0.45	-0.09	0.09	-0.36	0.27	-0.27	-0.27	-0.36	0.45	-0.36	-0.18	-0.38	-0.03	-0.02	-0.16
^{16}O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

[1]Error=(AMORES-STARBUCS)/AMORES

Next, the atom densities calculated from AMORES and STARBUCS was applied to KENO-VI to obtain the effective multiplication factor. The calculation results are summarized in Table 3. The effective multiplication factor calculated with AMORES is 0.63803 and the STARBUCS is 0.63769, showing a difference of about 24 pcm. This shows that the criticality safety evaluation calculation of AMORES was reasonable.

Table 3. Comparison of k_{eff} calculated with AMORES and STARBUCS

CODE	k_{eff}	Standard deviation
AMORES	0.63803	0.00011
STARBUCS	0.63769	0.00011

5. Conclusion

In this study, criticality safety evaluation was added to AMORES automation module. In AMORES, the atom densities after depletion calculation with ORIGEN-S was entered into KENO-VI to load different assemblies into the transport cask and apply burnup credit. Each assembly is axially divided into 18 equal parts so that the burnup axial profile can be applied and three sets of nuclides can be selected for burnup credit. Currently, only KORAD-21 cask was modelled, but in the near future, KN-18 and KN-12 are also modelled. Thus, the user can easily edit the set of nuclides and manipulate the assembly loading pattern in an efficient way for nuclear criticality evaluation. For verification of AMORES, the comparison calculation with STARBUCS was performed for KORAD-21 CASK. A comparative calculation was performed assuming that one assembly was loaded with the same burn data and burnup axial profile. As a result of the calculation, a maximum discrepancy of 0.5% occurred at atom densities. The discrepancy in k_{eff} with these atomic number densities was just 24 pcm.

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