Nuclear Data for Emergency Preparedness of Nuclear Power Plants
—Evaluation of Radioactivity Inventory in PWR using JENDL 3.3—

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The radioactivity inventories in PWR cores, one with UO_2 fuels and the other with 1/4 mixed oxide fuels, which focused on emergency preparedness of nuclear power plants were calculated by ORIGEN2.2 code using the newest nuclear data in Japan, namely JENDL3.3 (neutron cross sections), JENDL FP decay data file 2000 (decay data) and JNDC second version (fission yields). It is seen that these results agree with those for seven cases in which rather older nuclear data and ORIGEN2.1 code have been used. However, in details, these results exceed those by conventional method using ORIGEN2.1 code with its built-in nuclear data from a few % to 7%. It is found that this difference is mainly caused by neutron cross sections, fission yields and calculation codes.

1. Introduction

The purpose of emergency preparedness of nuclear power plants is to protect the public and the employees from radiation exposure and radioactive materials in a severe accident. Therefore, it is necessary to evaluate the accumulation of the radioactivity inventory in a reactor core and the diffusion of radioactive materials to the containment vessel in the accident as precisely as possible. And then, it is required to evaluate their leakage from the containment vessel and their movement to the concerned points inside and outside of the plant accurately. At present, conventional methods using codes such as ORIGEN2.1[(1),(2)] with nuclear data, namely neutron cross sections, decay data and fission yields, which are built-in the code are still often utilized for safety analysis without strict review. Old conventional methods using rather older code and nuclear data are not always inferior to newer ones, but it is advisable to adopt the newest code and nuclear data in which most of the contents are deeply and strictly examined and their uncertainties are also evaluated.

In this work, the radioactivity inventories in PWR cores, one with UO_2 fuels and the other with 1/4 mixed oxide (MOX) and 3/4 UO_2 fuels, have been calculated by a newer burnup code, ORIGEN2.2[(3)], using the newest nuclear data, namely JENDL3.3[(4)] (neutron cross sections), JENDL FP decay data file 2000[(5)] (decay data : it is referred to as JNDC 2000), and JNDC second version[(6)] (fission yields : it is referred as JNDC V2). The results are compared with those for 7 cases in which rather older nuclear data and ORIGEN2.1 have been used. Thereafter, these new radioactivity inventory data are adopted into the database in our employees dose prediction system[(7)] for emergency preparedness of nuclear power plants.

Table 1 Evaluated reactor cores and burnup conditions

	UO_2 Core	MOX Core
Core Composition	UO_2 (17×17 Fuels)	1/4MOX (17×17 Fuels)
Number of Fuel Assemblies	193	157 (UO_2:117) (MOX:40)
Maximum Burn up	55GWd/t	48GWd/t
Burn up Cycle	3 Batches	3 Batches
Average Burn up	36.7GWd/t	30.6GWd/t
Power Ratio	37.6 MW/t	36.7 MW/t

2. Calculated Reactor Cores and Calculation Method

Two cores of PWRs (4 loop plant with UO_2 fuels and 3 loop plant with 1/4 MOX fuels and 3/4 UO_2 fuels) were chosen for evaluation. The conditions of these two cores and fuel burnup are tabulated in Table 1. The burnup calculation was carried out by either ORIGEN2.2 or ORIGEN2.1 to obtain radioactivity inventories and the decay of radioactive nuclides after reactor shutdown was also calculated. We calculated the radioactivity inventories of the UO_2 and MOX cores for 8 cases of the combinations as shown in Table 2. In this table the case 0 is regarded as the basic case in this work. The case 7 is the conventional method which is often used for safety analysis in Japan. The data sets used in the burnup calculation are shown as corresponding neutron cross section libraries in Table 3. Although, the radioactivity inventories were calculated during the burnup and longer time after shutdown, only those at the shutdown and 2, 12 and 24 hours after it are compared and discussed in this work. For the use of emergency preparedness, total amounts of radioactivity, total noble gases (0.5 MeV conversion value) and total iodines (^{131}I equivalent thyroid conversion value of a child) are considered. In order to find the sensitivity of different nuclear data and code to the basic case, we calculated the difference factor *DF* defined as follows,

$$DF = \frac{(C_0 - C_i)}{C_i}$$

where C_0 and C_i are the radioactivity inventories obtained for the basic case and for the case *i*, respectively. The object of the comparison and its purpose are tabulated in Table 4.

Table 2 Combinations of nuclear data, namely neutron cross sections, decay data and fission yields, and calculation code

Case	Radio-activity Inventory	Nuclear Cross Sections	Decay Data	Fission Yields	Calculation Code
0 (Base)	C_0	JENDL 3.3	JNDC2000	JNDC V2	ORIGEN2.2
1	C_1	JENDL 3.2	JNDC2000	JNDC V2	ORIGEN2.2
2	C_2	Built-in ORIGEN	JNDC2000	Built-in ORIGEN	ORIGEN2.2
3	C_3	JENDL 3.3	JNDC V2	JNDC V2	ORIGEN2.2
4	C_4	JENDL 3.3	Built-in ORIGEN	JNDC V2	ORIGEN2.2
5	C_5	JENDL 3.3	JNDC2000	JNDC V2	ORIGEN2.1
6	C_6	JENDL 3.2	JNDC V2	JNDC V2	ORIGEN2.1
7	C_7	Built-in ORIGEN	Built-in ORIGEN	Built-in ORIGEN	ORIGEN2.1

Table 3 Data sets used in burnup calculation

Nuclear Cross Section Library	UO_2 Core	MOX Core	
		UO_2 Fuel	MOX Fuel
JENDL3.3	PWR47J33	PWR41J33	PWRM0205J33
JENDL3.2	PWR47J32	PWR41J32	PWRM0205J32
Built-in ORIGEN	PWR-U50	PWR-U50	PWR-PUPU

Table 4 Object and purpose of comparison and difference factor

Case Number	Object of Comparison		Difference Factor	Purpose
S1	JENDL 3.3(JNDC V2)	JENDL 3.2(JNDC V2)	(*C*0-*C*1)/*C*0	Sensitivity to Nuclear Cross Section and Fission Yields
S2	JENDL 3.3(JNDC V2)	Built-in ORIGEN	(*C*0-*C*2)/*C*0	
S3	JNDC 2000	JNDC V2	(*C*0-*C*3)/*C*0	Sensitivity to Decay Data
S4	JNDC 2000	Built-in ORIGEN	(*C*0-*C*4)/*C*0	
S5	ORIGEN2.2	ORIGEN 2.1	(*C*0-*C*5)/*C*0	Sensitivity to Calculation Code
S6	Newest Version	Previous Version	(*C*0-*C*6)/*C*0	Sensitivity to Nuclear Data and Code
S7	Newest Version	Conventional Calculation	(*C*0-*C*7)/*C*0	

Table 5 Calculated results of total amount, noble gases and iodines

Case	Object of Comparison	Type of Core	Difference Factor (%)											
			Total Amount				Noble Gases				Iodines			
			0 hr	2 hr	12 hr	24 hr	0 hr	2 hr	12 hr	24 hr	0 hr	2 hr	12 hr	24 hr
S1	JENDL 3.3 vs. JENDL3.2	UO_2	0.17%	0.21%	0.25%	0.26%	-0.08%	-0.13%	-0.04%	0.02%	0.10%	0.10%	0.10%	0.10%
		MOX	0.17%	0.22%	0.25%	0.26%	-0.09%	-0.22%	-0.18%	-0.08%	0.11%	0.11%	0.12%	0.12%
S2	JENDL 3.3 vs. Built-in ORIGEN	UO_2	1.55%	1.34%	1.32%	1.28%	2.24%	0.31%	2.93%	2.78%	0.25%	0.30%	0.34%	0.41%
		MOX	1.70%	1.58%	1.61%	1.58%	2.17%	0.96%	3.42%	3.11%	0.38%	0.43%	0.47%	0.54%
S3	JNDC 2000 vs. JNDC V2	UO_2	0.19%	0.48%	0.32%	0.17%	-0.01%	-0.26%	-0.33%	0.21%	0.00%	0.01%	0.01%	0.00%
		MOX	0.18%	0.44%	0.29%	0.16%	-0.01%	-0.25%	-0.26%	0.24%	0.00%	0.00%	0.01%	0.00%
S4	JNDC 2000 vs. Built-in ORIGEN	UO_2	0.23%	0.85%	0.70%	0.56%	-0.20%	1.18%	0.48%	0.01%	-0.02%	0.03%	0.11%	0.18%
		MOX	0.18%	0.83%	0.70%	0.57%	-0.20%	1.21%	0.52%	0.05%	-0.04%	0.00%	0.07%	0.15%
S5	ORIGEN2.2 vs. ORIGEN2.1	UO_2	1.51%	1.33%	1.22%	1.19%	2.48%	2.50%	1.99%	1.83%	1.73%	1.73%	1.71%	1.70%
		MOX	2.50%	2.33%	2.23%	2.20%	2.70%	2.93%	3.36%	3.42%	3.49%	3.49%	3.52%	3.55%
S6	Newest Version vs. Previous Version	UO_2	1.68%	1.81%	1.58%	1.42%	2.31%	2.05%	1.57%	1.99%	1.73%	1.74%	1.73%	1.71%
		MOX	2.77%	2.94%	2.72%	2.57%	2.51%	2.35%	2.82%	3.48%	3.50%	3.51%	3.55%	3.57%
S7	Newest Version vs. Conventional Calculation	UO_2	2.89%	3.21%	2.99%	2.80%	3.23%	2.77%	4.90%	4.29%	1.78%	1.87%	2.01%	2.17%
		MOX	4.06%	4.44%	4.28%	4.09%	4.15%	4.52%	6.85%	6.15%	3.31%	3.40%	3.55%	3.73%

3. Results and Discussion

The calculation results of the difference factors of the total amounts of radioactivity inventories, noble gases and iodines for both cores at the reactor shutdown and after 2, 12 and 24 hours after it are tabulated in Table 5. As a whole, the radioactivity inventories agree with each other within 7% of the difference factor. Sensitivities of each factor of the nuclear data and of the calculation code to the difference factor are shown in Figs. 1~9 with some discussion below.

(1) Neutron cross sections and fission yields

The difference factor of 3 quantities by JENDL3.3 and JENDL3.2 in Table 5 are less than 0.3%, however those by JENDL3.3 and built-in ORIGEN are much larger. The largest difference factors appear for noble gases at 12 and 24 hours after the reactor shutdown, namely 2.93% and 2.78% for 12 and 24 hours for the UO_2 core. This tendency is slightly enhanced for the MOX core. The breakdown of noble gases is shown in Fig. 1, in which large contribution of ^{135}Xe is observed at 12 and 24 hours for both cases. Therefore, the large difference factors of noble gases seen in Table 5 are mainly due to the ^{135}Xe buildup. The neutron fluxes for the cases of 1, 4 and 5 are shown in Fig. 2. As seen in this figure, since the neutron fluxes obtained with built-in ORIGEN are smaller than those calculated with JENDLs (3.3 and 3.2) and with JNDC V2, noble gases, mainly ^{135}Xe, for the former are less than those for the latter.

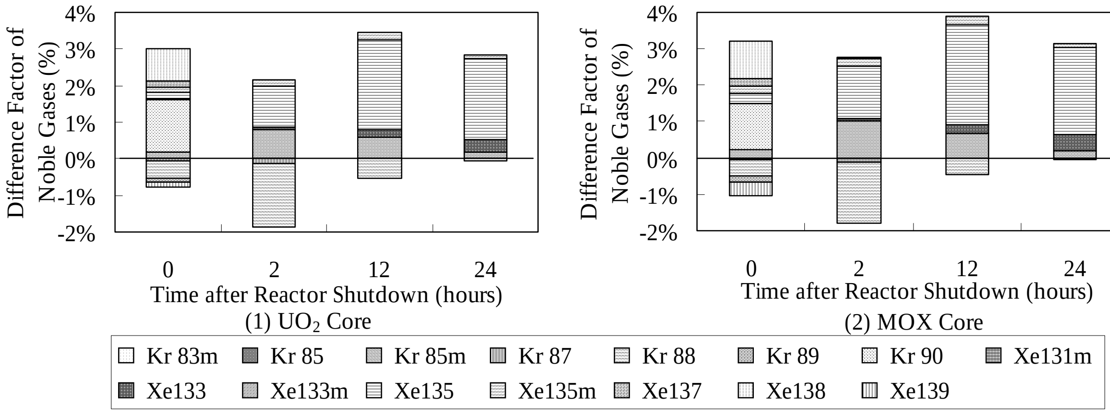


Fig. 1 Breakdown of difference factors between JENDL3.3 and built-in ORIGEN for noble gases.

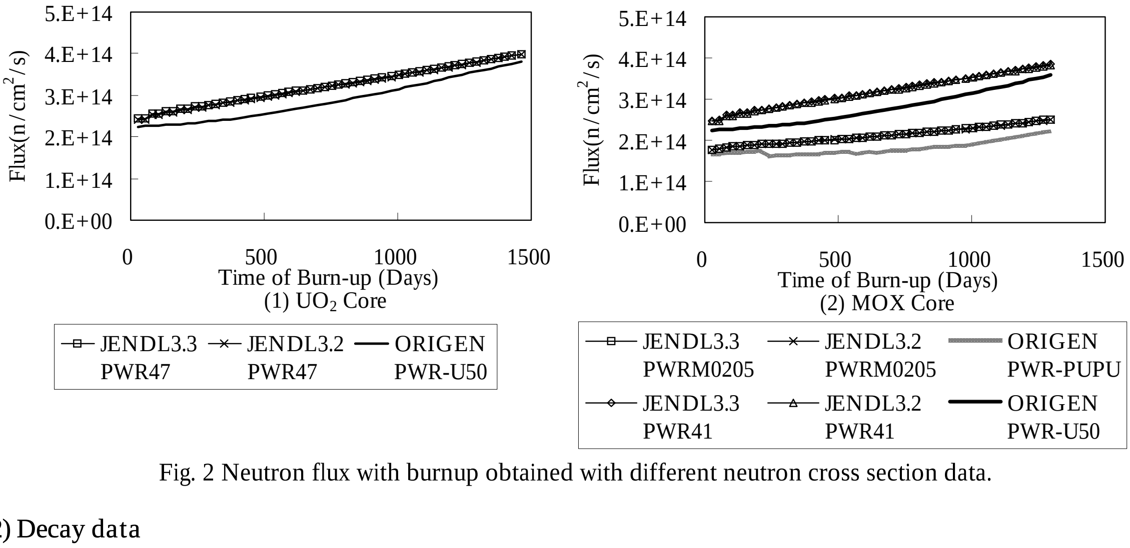


Fig. 2 Neutron flux with burnup obtained with different neutron cross section data.

(2) Decay data

The difference factors of 3 quantities with different decay data (JNDC 2000, JNDC V2 and built-in ORIGEN) are small in general, but those of noble gases for 2 hours with JNDC 2000 and built-in ORIGEN are slightly large as about 1%. The breakdown of noble gases in these cases are shown in Fig. 3. The quantities of ^{88}Kr at 2 hours and those of ^{135m}Xe at 2 and 12 hours calculated with built-in ORIGEN are less than those with JNDC 2000. Therefore, these nuclides would increase the difference factors of noble gases.

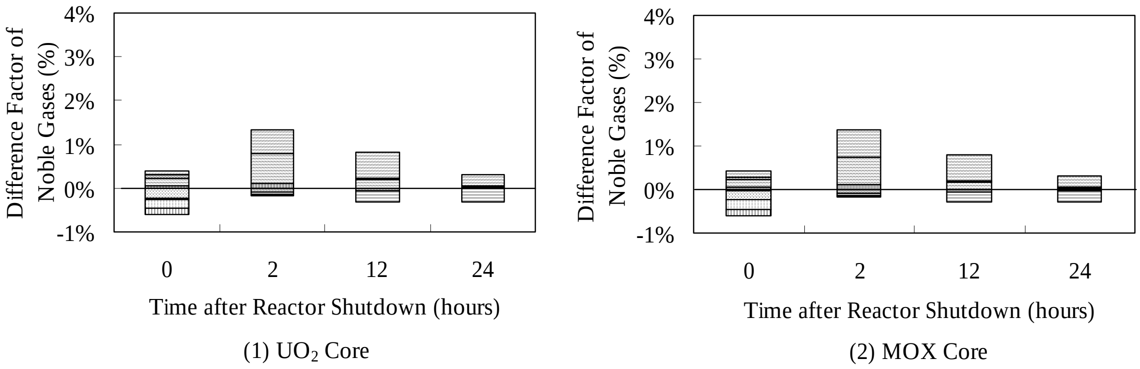


Fig. 3 Breakdown of difference factor between JNDC 2000 and built-in ORIGEN for noble gases. The patterns are as same as those in Fig. 1.

(3) Calculation code

All of the difference factors of 3 quantities between the two calculation codes, ORIGEN2.1 and ORIGEN2.2, show considerably large as from 1.2% to 3.6%. The difference factors for the MOX core are much larger than those for the UO_2 core. The breakdowns of noble gases and iodines are shown in Fig. 4 and Fig. 5, respectively. The quantities of ^{88}Kr, ^{133}Xe, ^{135}Xe, ^{131}I and ^{133}I calculated by ORIGEN2.1 are less than those by ORIGEN2.2. Therefore, these nuclides would increase the difference factors of 3 quantities between the two codes. The noticeably large difference factors for the MOX core are probably caused by defective algorithm calculating total fission rate of the minor actinoides in ORIGEN2.1, which is given in the release note of ORIGEN2.2[1].

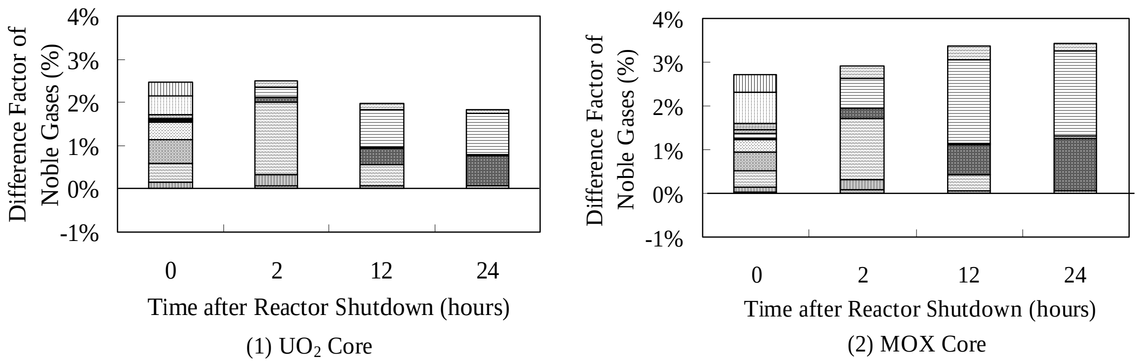


Fig. 4 Breakdown of difference factor between ORIGEN 2.2 and ORIGEN 2.1 for noble gases. The patterns are as same as those in Fig. 1.

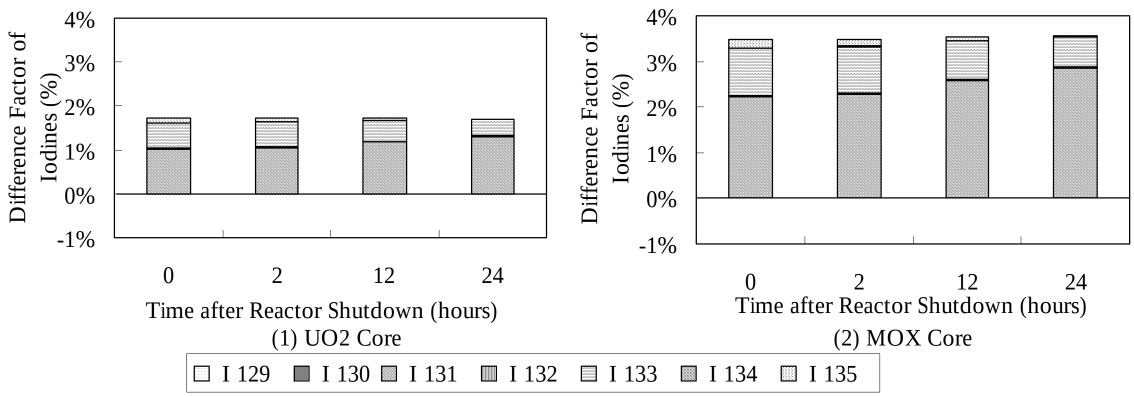
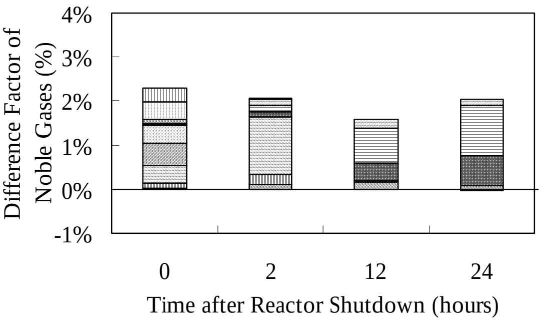


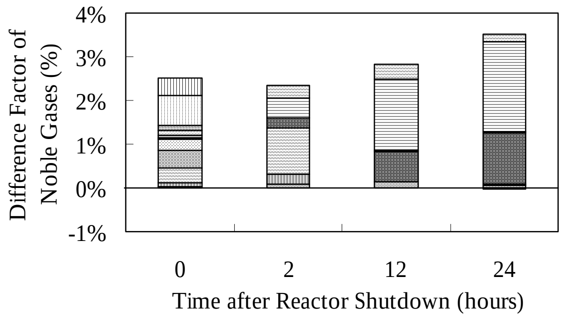
Fig. 5 Breakdown of difference factors between ORIGEN2.2 and ORIGEN2.1 for iodines.

(4) Combination of nuclear data and codes

All of the 3 quantities calculated by the previous version, namely ORIGEN2.1 with JENDL3.2 and JNDC V2, are smaller than those by the new ones, *i.e.* the basic case. This tendency for the MOX core is about twice of the UO_2 core. The breakdowns of noble gases and iodines are shown in Fig. 6 and Fig. 7, respectively. The quantities of ^{88}Kr, ^{133}Xe and ^{135}Xe calculated by the previous version are about 2% for the UO_2 core and about 3% for the MOX core less than those by the new one. The quantities of ^{131}I and ^{133}I obtained by the previous version are also about 2% for the UO_2 core and about 3.5% for the MOX core less than those by the new one. Since the results of comparison of neutron cross section and decay data show less difference factors, the above differences are mainly due to the calculation codes, ORIGEN2.1 and ORIGEN2.2.

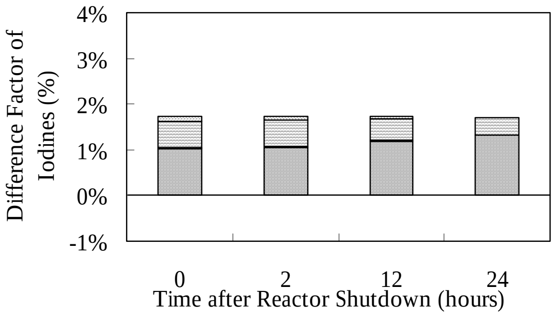


(1) UO_2 Core

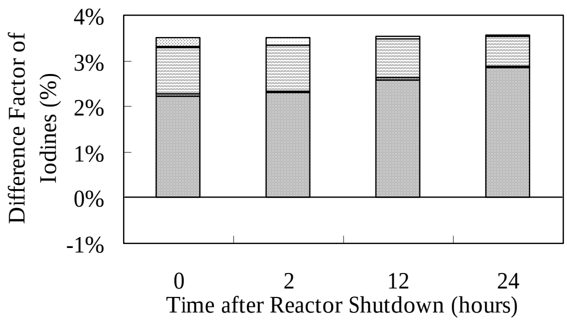


(2) MOX Core

Fig. 6 Breakdown of difference factors between newest version and previous one for noble gases. The patterns are as same as those in Fig. 1.



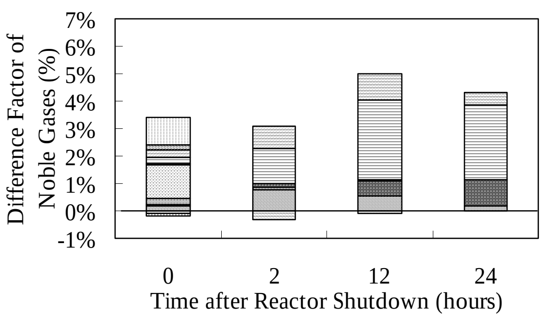
(1) UO_2 Core



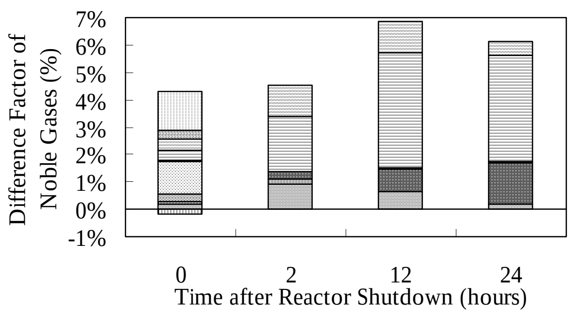
(2) MOX Core

Fig. 7 Breakdown of difference factors between newest version (basic case) and previous one for iodines. The patterns are as same as those in Fig. 5.

All of the 3 quantities obtained by the conventional method are considerably smaller than those for the basic case. This tendency is even enhanced for the MOX core. The breakdown of noble gases is shown in Fig. 8. The maximum difference factors for the sum of the ^{133}Xe and ^{135}Xe by the conventional method are about 4% and 6% for the UO_2 core and the MOX core, respectively. The breakdown of iodines are depicted in Fig. 9. The difference factors for sum of ^{131}I and ^{133}I by the conventional method are about 2% and about 3.5% for the UO_2 core and the MOX core, respectively.



(1) UO_2 Core



(2) MOX Core

Fig. 8 Breakdown of difference factors between newest version (basic case) and conventional method for noble gases. The patterns are as same as those in Fig.1.

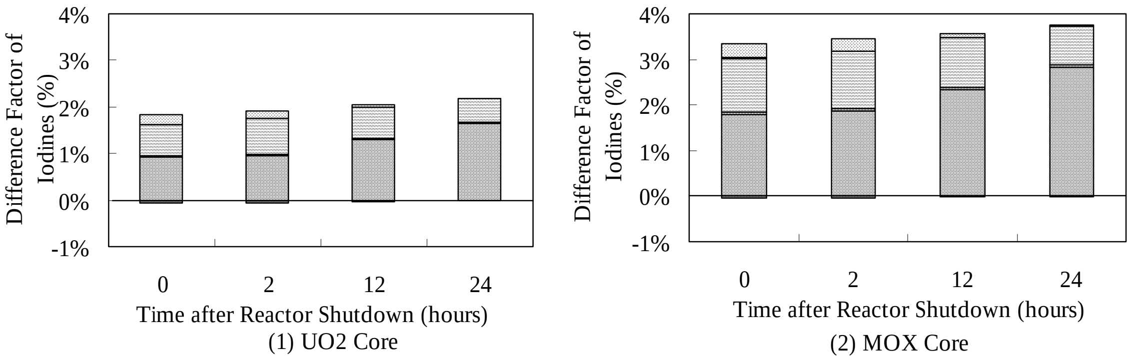


Fig. 9 Breakdown of difference factors between newest version (basic case) and conventional method for iodines. The patterns are as same as those in Fig. 5.

Since the difference factors for different decay data show little values, the difference factors between the conventional method and the basic case are mainly composed of the difference of the neutron cross sections and fission yields between the case 2 and the basic case and the difference of the calculation codes.

4. Conclusions

As a part of the works to construct a prediction system for emergency preparedness of nuclear power plants, the radioactivity inventories in PWR cores, one with UO_2 fuels and the other with 1/4 MOX and 3/4 UO_2 fuels, were calculated by ORIGEN2.2 with the newest nuclear data in Japan (the basic case), and the results were compared with those by the conventional method using ORIGEN2.1 with the built-in nuclear data, and with those for other 6 cases. As a whole, radioactivity inventories agree with each other within 7% of the difference factor. In details, the followings have been pointed out:

(1) Concerning the neutron cross sections, the difference factors by JENDL3.3 and JENDL3.2[8] are small, however those of noble gases at 12 and 24 hours after reactor shutdown between JENDL3.3 and built-in ORIGEN are close to 3% for the UO_2 core, and a little more for the MOX core. This is mainly due to higher buildup of ^{135}Xe which is caused by higher neutron fluxes by JENDL3.3 than those by built-in ORIGEN.

(2) Between 2 calculation codes, ORIGEN2.2 and ORIGEN2.1, there are considerably large difference factors. This tendency is much larger for the MOX core than that for UO_2 core. This difference is considered to be caused by defective algorithm calculating total fission rate of the minor actinoides in ORIGEN2.1.

(3) All of the 3 quantities, *i.e.* total amount, noble gases and iodines, obtained by the conventional method are considerably smaller than those for the basic case. This difference is furthermore enhanced for the MOX core. It is found that this difference is mainly caused by neutron cross sections, fission yields and calculation codes.

Since most of the newest nuclear data have been thoroughly evaluated with the newest experimental data and theoretical models, it is recommended to use them not only for the emergency preparedness of nuclear power plants, but also for their safety analysis in general.

As future subjects, we are planning to investigate the causes of the differences in more details, to make the comparison of the inventories of the major actinoides (U and Pu) and the minor actinoides (Np, Am and Cm), and to make the comparison of the decay heats all together.

References:

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