報文原稿

Effect of ^{140}Ba Fission Yield on Fission Rate Distribution Measurements in UO2-MOX Mixed Core of REBUS Program

Toru YAMAMOTO, Katsuyuki KAWASHIMA, Katsuichiro KAMIMURA

Reactor Core and Fuel Reliability Group, Safety Standard Division

Japan Nuclear Energy Safety Organization (JNES)

Fujita Kanko Toranomon Bldg. 7F, 3-17-1, Toranomon, Minato-ku, Tokyo 105-0001

E-mail: yamamoto-toru@jnes.go.jp

Japan Nuclear Energy Safety Organization (JNES) has been participating in the REBUS international program[4] organized by Belgonucleaire and SCK/CEN and analyzing the experimental data. This paper presents a study of an effect of the ^{140}Ba fission yield on measured fission rate distribution through the analysis of a UO2 - MOX fuel mixed core of the REBUS program.

1. Introduction

In core physics experiments a fission rate distribution is one of the essential data that is used to validate the core analysis methods. The measurements of this parameter have been adopting spectroscopy of specific gamma-rays from fission products, such as 1,596.5 keV gamma-rays from ^{140}Ba ($T_{1/2}$=12.752d) - ^{140}La (T1/2=1.6781d) after short period irradiation of experimental cores. When this method is applied to UO_2 - MOX fuel mixed cores, it is necessary to take into account the difference of the fission yield of ^{140}Ba in the UO_2 and the MOX fuel. For instance, the JNDC Nuclear Data Library of Fission Products[1] shows that the cumulative fission yield of ^{140}Ba is 6.295 % for ^{235}U-thermal fission and 5.545 % for ^{239}Pu-thermal fission.

Recent studies[2, 3] of the UO_2 - MOX fuel mixed cores of VENUS-2 and VIP experimental programs show that the ratios of the analysis result to the measurement result (C/E) of the fission rate tend to be larger than 1.0 in the MOX fuel region and less than 1.0 in the UO_2 fuel region.

Japan Nuclear Energy Safety Organization (JNES) has been participating in the REBUS international program[4] organized by Belgonucleaire and SCK/CEN. The aim of the participation is to obtain measured reactivity change with burn-up of MOX fuel and UO2 fuel and the fission rate and the flux distribution of the cores containing burned MOX and UO2 fuel and to analyze these data in order to validate nuclear core analysis methodologies for burned MOX and UO2 cores. The program partly contains UO2 - MOX mixed cores and a fission rate distribution has been measured with the gamma-ray spectroscopy of 1,596.5 keV gamma-rays from ^{140}La.

This paper presents a study of an effect of the ^{140}Ba fission yield on the measured fission rate distribution through the analysis of a UO2 - MOX fuel mixed core of the REBUS program.

2. Fresh BR3 MOX Core in REBUS Program

Table 1 summarizes core configurations and measurement items of the REBUS (PWR fuel) program. The REBUS cores commonly consist of a 7x7 fuel test bundle in a core center and a driver region of 3.3% (eight lows) and 4.0% (two lows) UO2 rods in the VENUS critical facility of SCK/CEN. A diameter of those fuel rods is about 9.5 mm, an effective fuel length is about 100cm and a fuel rod pitch is 1.26cm. The test region is changed by four different bundles consisting BR3 MOX (fresh and burned) and GKN (a Germany commercial PWR) UO2 (fresh and burned). Fig. 1 shows a schematic diagram of a core configuration consisting of the fresh BR3 MOX (6.8% Puf enrichment) core.

Table 1 Summary of Core Configurations and Measurement Items of REBUS (PWR Fuel)

	Reference Core	BR3 MOX		GKN UO2	
		Fresh	Irradiated	Fresh	Irradiated
Central test bundle configuration	7x7 3.3%VENUS UO2 rods	24 MOX rods 21 Water channels	24 MOX rods (about 20GWd/t) 21 Water channels	5x5 3.8%UO2 20 3.3%VENUS UO2 rods	5x5 3.8%UO2 (about 51GWd/t) 20 3.3%VENUS UO2 rods
Critical height	M	M	M	M	M
Water level reactivity effect	M	M	M	M	M
Fission rate distribution	—	Test bundle Driver region	Driver region	Test bundle Driver region	Driver region
Neutron flux distribution	—	Sc activation	Co activation	Sc activation	Co activation

3. Fission Rate Distribution Measurement

In the measurements of the REBUS program, a relative fission rate of a fuel rod is obtained as:

$$F \propto C/Y \qquad (1)$$

Here, C is a measured count rate of the 1,596.5 keV gamma-ray peak after necessary corrections of decay and gamma-ray self shielding in the fuel rod. Y is an effective cumulative fission yield of ^{140}Ba for the fuel rod that is expressed as:

$$Y = \frac{\sum_i \left(F^{fast} Y^{fast} + F^{th} Y^{th}\right)_i}{\sum_i \left(F^{fast} + F^{th}\right)_i} \qquad (2)$$

Here,

i: nuclides contributing fission such as ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu, ^{241}Pu and ^{242}Pu,

F^{fast}, F^{th}: relative contribution of fast fission and thermal fission for nuclide i,

Y^{fast}, Y^{th}: cumulative fission yields of ^{140}Ba of fast fission and thermal fission for nuclide i.

4. Calculation of Effective Fission Yield

Since Y is not a measured parameter, a core analysis result is used to obtain it. For the effective fission yield of the fuel rods, for which the fission rates were measured in the fresh BR3 MOX core, F^{fast} and F^{th} were calculated as a part of the core analysis using SRAC system[5)] with JENDL-3.2[6)]. Fig. 2 shows the calculated fission rate distribution with the measured one along the Y axis of the core. The figure also shows measurement data that are reported by the organizer (BN) of the REBUS program. Table 2 shows the relative contributions of heavy nuclides to the fast fission (neutron energy: 9.12 keV to 10 MeV) and the thermal fission (0 to 9.12 keV) for several fuel rods. It is seen that the six major nuclides cover more than 99.6% of total fission even for the MOX fuel rod. Table 3 shows the fission yields, Y^{fast} and Y^{th} in JENDL-3.2, ENDF/B-VI and JEF-2.2 for the six major nuclides. The fission yields of Pu isotopes is smaller than U isotopes and the values slightly change depending on the nuclear libraries.

Table 2　Relative Contributions of Heavy Nuclides to Fissions in Fast and Thermal Energy Regions

(X, Y)	MOX (-2, -3)			3.3% UO_2 (-4,-4)			3.3% UO_2 (-7,-7)			3.3% UO_2 (-11,-11)			4.0% UO_2 (-12,-12)		
Nuclide	Fast	Th	Total	Fast	Th	Total	Fast	Th	Total	Fast	Th	Total	Fast	Th	Total
U-234	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
U-235	0.1	2.2	2.4	1.4	93.5	95.0	1.3	94.0	95.3	1.3	94.0	95.3	1.9	92.6	94.6
U-236	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
U-238	6.1	0.0	6.1	5.0	0.0	5.0	4.7	0.0	4.7	4.7	0.0	4.7	5.4	0.0	5.4
Pu-238	0.1	0.1	0.1												
Pu-239	3.8	79.6	83.3												
Pu-240	0.8	0.0	0.8												
Pu-241	0.3	6.6	6.9												
Pu-242	0.1	0.0	0.1												
Am-241	0.2	0.1	0.2												
Total	11.4	88.6	100.0	6.5	93.5	100.0	6.0	94.0	100.0	6.0	94.0	100.0	7.4	92.6	100.0
6 Nucl	11.2	88.5	99.6	6.4	93.5	100.0	6.0	94.0	100.0	6.0	94.0	100.0	7.3	92.6	100.0

Fast: 9.12keV～10MeV, Th (Thermal): 0～9.12keV,　 6 Nucl (Nuclides): U-235, U-238, Pu-239, Pu-240, Pu-241, Pu-242

Table 3　Cumulative Fission Yields of ^{140}Ba for Six Major Nuclides in Three Nuclear Libraries

Library	JENDL-3.2		ENDF/B-VI		JEF-2.2	
Nuclide	Fast	Th	Fast	Th	Fast	Th
U-235	6.119	6.295	5.978	6.215	5.782	6.276
U-238	5.988		5.815		5.743	
Pu-239	5.317	5.545	5.323	5.355	5.119	5.285
Pu-240	5.110		5.502	5.701	5.462	
Pu-241	5.378	6.215	5.306	5.766	5.395	5.743
Pu-242	5.005		5.449	6.022	5.682	5.462

Table 4　Effective fission Yields of ^{140}Ba for MOX and UO_2 fuel rods

	JENDL-3.2	ENDF/B-VI	JEF-2.2
MOX (-2, -3)	5.621 (1.0)	5.430 (1.0)	5.362 (1.0)
3.3% UO_2 (-4,-4)	6.277 (1.117)	6.191 (1.140)	6.242 (1.164)
3.3% UO_2 (-7,-7)	6.278 (1.117)	6.193 (1.141)	6.245 (1.165)
3.3% UO_2 (-11,-11)	6.278 (1.117)	6.193 (1.141)	6.245 (1.165)
4.0% UO_2 (-12,-12)	6.267 (1.115)	6.178 (1.138)	6.223 (1.161)

From these data, the effective fission yields, Y, were evaluated based on the relative contributions of the six major nuclides in Table 2 and shown in Table 4. The Table also shows ratios of the effective fission yield of UO_2 rods to that of the MOX fuel rod in brackets for each library. The ratios of 3.3% UO_2 to MOX are 1.117 for JENDL-3.2, 1.140 for ENDF/B-VI and 1.165 for JEF-2.2.

The organizer (BN) of the REBUS program have evaluated and used 1.123 ± 0.012 for 3.3UO_2/MOX to the measured radial fission rate distribution, which is 0.6 % larger than that of this study with JENDL-3.2.

Those effective fission yields were applied to the measured fission rates and comparison between the SRAC analysis (C) and the measured fission rates (E) were shown in Fig. 3.

5. Discussion and Conclusion

The ratio of the measured fission rates of MOX fuel rods to UO_2 fuel rods is expressed as:

$$\frac{F_M}{F_U} \propto \frac{C_M}{C_U}\frac{Y_U}{Y_M} \qquad (3)$$

Here, the suffix, M, means MOX fuel rods and U UO_2 fuel rods. Generally the change of Y_U is negligible small among the UO_2 fuel rods and also among the MOX rods. The uncertainty of Y_U/Y_M directly influences on the ratios of the measured fission rates of the MOX fuel rods to the UO_2 fuel rods so that the ratios depend on the nuclear data library adopted in the measurements. Some difference in the cumulative fission yield of ^{140}Ba is seen for the Pu isotopes as shown in Table 3. Table 5 shows a comparison of the fission yields among the libraries for the thermal fission of ^{235}U and ^{239}Pu and their ratio of ^{235}U to ^{239}Pu. The ratio of ^{235}U to ^{239}Pu is a major part of Y_U/Y_M and therefore F_M/F_U. It is seen that the F_M/F_U change up to 4 % depending on the nuclear library.

When the Y_U/Y_M of this study with JENDL-3.2 is used in place of the REBUS organizer (BN), the F_M/F_U will decrease by 0.6 % and then the C/E is almost increase by 0.6 % in the MOX test bundle as shown in Fig. 3, which is not significant. However, when the Y_U/Y_M in this study with ENDF/B-VI or JEF-2.2 is used, the F_M/F_U will increase by 1.5 % or 3.7 % and then the C/E is almost decrease by about 1.5 % or about 3.7 % in the MOX test bundle.

Table 5 Comparison of Cumulative Fission Yields (%) of ^{140}Ba for Thermal Fission of ^{235}U and ^{239}Pu

	JENDL-3.2	ENDF/B-VI	JEF-2.2
U-235	6.295 (1.0)	6.215±1.0% (0.987)	6.276±1.2% (0.998)
Pu-239	5.545 (1.0)	5.355±1.4% (0.966)	5.285±1.0% (0.953)
U-235/Pu-239	1.135 (1.0)	1.161±1.7% (1.022)	1.188±1.6% (1.046)

For conclusions: (1) The ratios of fission rates of the MOX and the UO_2 fuel rods depend on the cumulative fission yields of ^{140}Ba that is used in the process of the experimental data, (2) The difference in the ^{140}Ba fission yield for the ^{239}Pu thermal fission among the libraries is up to 5 % and not negligible. (3) The fission yield data of ^{140}Ba used in the process of the experimental data should be precisely reviewed in order to evaluate the calculation errors for the ratio of the fission rate of the MOX and the UO_2 fuel rods in the UO2 - MOX mixed cores, (4) The Effort to decrease uncertainty of the fission yield data of ^{140}Ba for ^{239}Pu (Thermal fission) is requested for the precise evaluation of the calculation errors of fission rate distribution in the UO2 - MOX mixed cores.

References

1) K. Tasaka *et al.*, " JNDC Nuclear Data Library of Fission Products - Second Version -," JAERI 1320 (1990).

2) Y. Nagaya, K. Okumura and T. Mori, "Analysis of VENUS-2 MOX Core Measurements with a Monte Carlo Code MVP," Proc. Int. Conf. PHYSOR 2002, Seoul, Korea, October 7-10, 2002.

3) T. Shiraki, H. Matsumoto and M. Nakano, "Analysis of MOX Critical Experiments with JENDL-3.3," Proc. the 2004 Symposium on Nuclear Data, Nov. 11-12, 2004, JAERI, Tokai, Japan, JAERI-Conf, 2005-3 (2005).

4) P. Baeten *et al.*, "The REBUS Experimental Programme for Burn-up Credit," Proc. Int. Conf. on Nuclear Critical Safety (ICNC 2003), Oct. 20-24, 2003, Tokai, Japan (2003).

5) K. Tsuchihashi, Y. Ishiguro, K. Kaneko, M. Ido, Revised SRAC Code System, JAERI-1302, Japan Atomic Energy Research Institute (JAERI), (1986).

6) T. Nakagawa, K. Shibata, S. Chiba, *et al.*, "Japanese Evaluated Nuclear Data Library Version 3 Revision-2," J. Nucl. Sci. Technol., 32, 1259 (1995).

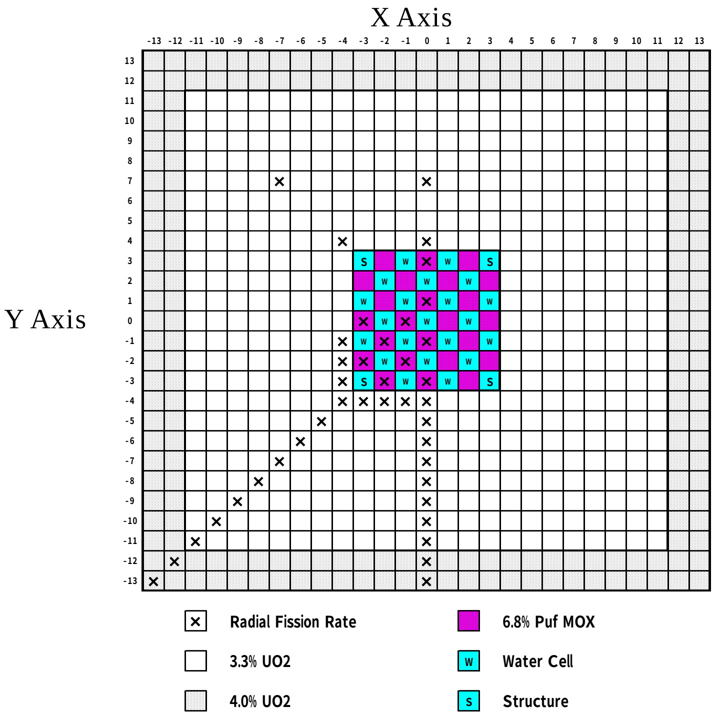

Fig. 1　Schematic Radial Core Configuration of Fresh BR3 MOX Core in REBUS Program

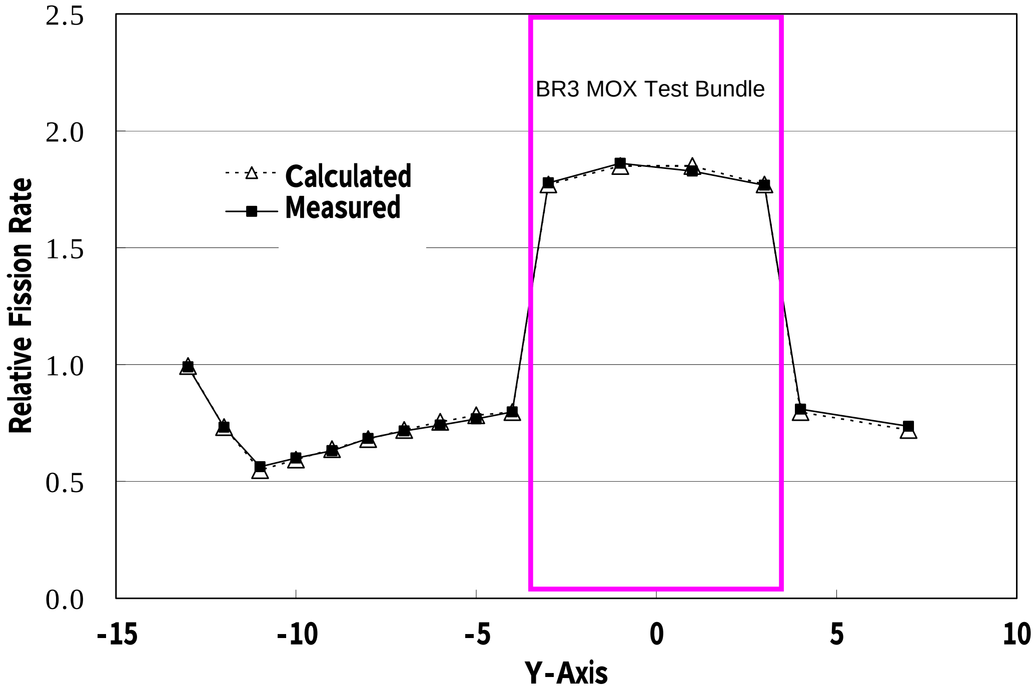

Fig. 2 Relative Fission Rate Distribution along Y Axis and Difference between Calculation and Measured Values for Fresh BR3 MOX Core in REBUS Program

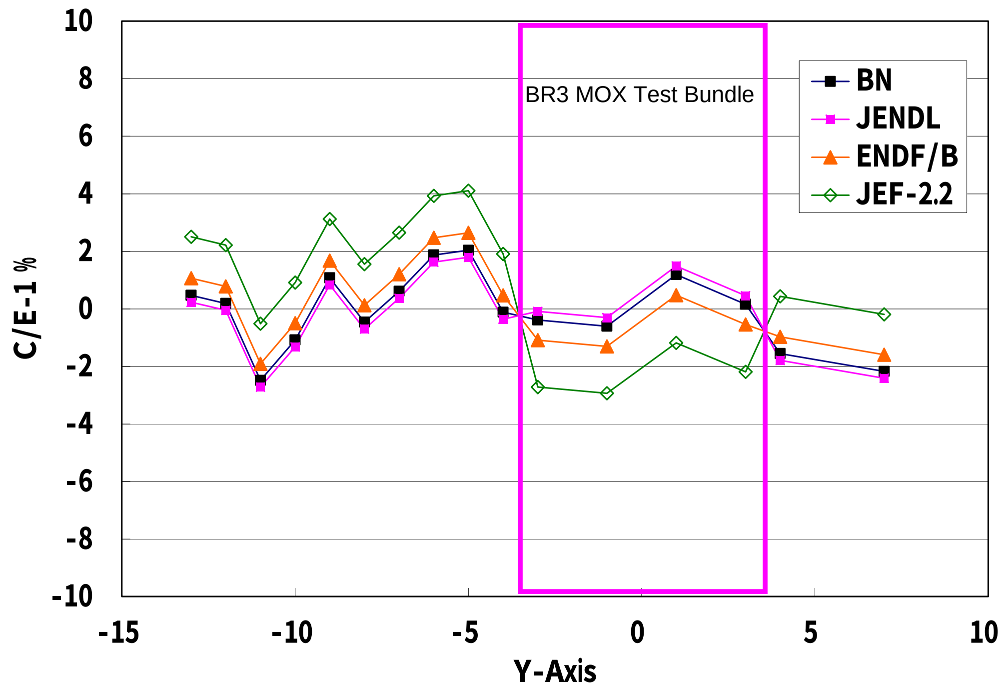

Fig. 3 Comparison between the SRAC analysis (C) and the measured fission rates (E) with effective fission yields by the different nuclear libraries