Design of MA-loaded Core Experiments using J-PARC

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Uncertainties of the current minor actinide (MA) nuclear data are larger than those of other major nuclides. Therefore, analyzed neutronic properties of MA-loaded fast reactor (FR) and accelerator driven system (ADS) have much larger design margins in comparison with those of conventional FR. To improve the reliability, safety and economical efficiency of these systems, it is required to increase the accuracy of the nuclear data of MA by the experimental data taken by adequate experimental conditions.

In this study, error analyses were performed to estimate "How much would the error caused by the MA nuclear data decrease if the MA-loaded core experiments were performed". TEF-P (Transmutation Physics Experimental Facility), which is being planned to carry out basic experiments for MA-loaded systems in JAEA, was employed to simulate hypothetical MA-loaded core experiments. For the estimation, the cross section adjustment procedure was employed.

These analysis results showed that the errors caused by the nuclear data were improved by considering existing 233 integral data and 7 hypothetical results simulating TEF-P experiments. As a typical result, the errors (the confidence level is 1σ) for the coolant void reactivity were improved from 2.4% to 1.4% for MA-loaded FR and from 5.8% to 3.0% for ADS designed by JAEA.

1. Introduction

Research and development (R&D) for minor actinide (MA) transmutation technologies by using Fast Reactor (FR) and Accelerator Driven System (ADS) have been performed at Japan Atomic Energy Agency (JAEA). Improvement on the neutronic design accuracy of the MA-loaded core is one of the most important issues in the MA transmutation technology. Uncertainties of the current MA nuclear data are larger than those of other major nuclides. Therefore, analyzed neutronic properties of MA-loaded FR and ADS have much larger design margins in comparison with those of conventional FR. To improve the reliability, safety and economical efficiency of these systems, it is required to increase the accuracy of the nuclear data of MA by the experimental data taken by adequate experimental conditions.

JAEA plans a construction of "TEF-P" (Transmutation Physics Experimental Facility) in the second phase of the “J-PARC” (Japan Proton Accelerator Research Complex) project. TEF-P is a plate-type fuelled critical assembly which is able to accept a proton beam (400MeV, 10W) delivered from a LINAC of J-PARC. Various experiments are available in a critical condition or a sub-critical state driven by spallation neutrons. Furthermore, the experiments using pin-type MA fuel, which must be handled with remote devices, are planned to simulate the MA-loaded systems.

In this study, error analyses were performed to estimate “How much would the error caused by the MA nuclear data decrease if the MA-loaded core experiments at TEF-P were performed”. In this estimation, the cross-section adjustment procedure was employed.

2. Procedure to estimate Errors caused by Nuclear Data

The error analyses were performed by the cross-section adjustment procedure [1]. This procedure adjusts the nuclear data to reduce the errors caused by the nuclear data and makes it possible to estimate the errors quantitatively. Figure 1 shows a simplified schematic of this procedure (details are described in the reference [1]). Existing nuclear data (cross section **T** and covariance data **M**) such as JENDL-3.3 are adjusted by the Bayesian theorem by using sensitivity **G**, analytical modeling error $\mathbf{V_m}$ and experimental error $\mathbf{V_e}$ for 233 integral data [1]. The adjusted nuclear data **T’** and **M’** are calculated as an output.

In this theory, the errors caused by the nuclear data are defined as $\mathbf{GMG^t}$ (t means a transpose). So, it is available to compare the errors before the adjustment ($\mathbf{GMG^t}$) and after the adjustment by the 233 integral data ($\mathbf{GM'G^t}$). This procedure also enables to assess the effect of hypothetical experiments. In this study, seven hypothetical MA experiment data at TEF-P were added to the 233 integral data to estimate “How much would the error caused by the MA nuclear data decrease”. New adjusted nuclear data **T”** and **M”** were calculated and the error caused by the new data ($\mathbf{GM''G^t}$) was estimated.

3. Calculation Conditions

(1) Hypothetical MA experiments

To simulate hypothetical MA experiments, the FCA XVII-1 core [2] which was a mock-up of a MOX fueled fast reactor was referred. Figure 2 shows the RZ calculation model of the TEF-P core. The characteristic and difference against the FCA core of the TEF-P are that it is available to treat the pin-type MA fuel. The MA fuel pin was loaded in the TEST region. In this study, a MA-loaded FR and an ADS were treated for the error analyses. For the FR analysis, U/Pu/MA(=77.4/17.6/5.0 wt%) oxide fuel pin surrounded by Na was set to the TEST region. Pu/MA(31/69 wt%) nitride fuel surrounded by Pb-Bi was set to the TEST region for the ADS analysis. The composition of MAs was Np-237/Am-241/Am-243/Cm-244 = 11.1/44.4/22.2/22.2 wt% through this study.

In these calculations, the sensitivity was calculated by the SAGEP code [3] with 18 energy group structure. Seven calculation cases shown in Table 1 were performed; for a criticality, for a coolant void reactivity and a Doppler reactivity. The analytical modeling error and the experimental errors were determined based on the FCA XVII-1 experiments described in the reference [1].

(2) Object of estimation

In this study, the errors included in neutronic designs of the MA-loaded FR and the ADS were estimated. The 1600MWt sodium cooled FR core studied in the feasibility study [4] was employed as a typical FR. Figure 3 shows the RZ calculation model of the FR core. 5 wt% MAs were added to the inner and outer core region. The 800MWt LBE (lead bismuth eutectic) cooled ADS designed by JAEA [5] was employed as a typical ADS core (Fig. 4). The sensitivities for the criticality, the coolant void reactivity (coolant volume fraction at the driver region was changed to 0%) and the Doppler reactivity (Δ T=500K at the driver region) were calculated for both cores by SAGEP code.

(3) Nuclides and reactions for adjustment

In this study, nuclides and reactions whose covariance data were prepared in JENDL-3.3 were treated for the adjustment. Table 2 and Table 3 show the nuclides and reactions which were adjusted for the FR and the ADS, respectively. As shown in these tables, covariance data for elastic and inelastic reactions of MAs are not prepared in JENDL-3.3. Additionally, many covariance data which are important to analyze the errors of the ADS are not prepared; such as capture and elastic reactions for Pb isotopes and Bi-209, capture and inelastic reactions for N-15. In the present study, these nuclides and reactions which were not prepared in JENDL-3.3 were not considered; in other words, errors caused by these nuclides and reactions were not included in present results.

4. Results and Discussion

The errors caused by the nuclear data are summarized in Table 4 for the FR and Table 5 for the ADS. Figure 5-10 show the contributions of the nuclides and the reactions to the errors caused by the nuclear data for each case. For the FR, the effect of the TEF-P experiments was shown as the improvement of the error for Am-241 and Cm-244 capture reaction mainly though the changes (from 233 to 240) of the total error were small for all cases.

For the ADS, the total error was decreased by the TEF-P experiments from 0.74% to 0.68% (from 233 to 240) for the criticality, from 3.8% to 3.0 for the coolant void reactivity and from 4.0% to 2.8% for the Doppler reactivity. For the criticality, the changes of the errors for Am-241 capture reaction, N-15 elastic reaction and inelastic reactions of the Pb isotopes and Bi-209 were prominent (Fig. 6). For the coolant void, the changes of the errors for Am-241 and Am-243 capture reactions, N-15 elastic reaction and inelastic reactions of the Pb isotopes and Bi-209 were significant (Fig. 8). For the Doppler reactivity, the changes of the errors for Am-241 and Am-243 capture reactions, N-15 elastic reaction and capture reactions of Fe and Zr-40 were impressive (Fig. 10).

However, the results for the ADS are not exact since the covariance data of many nuclides and reactions, such as elastic and inelastic reactions for MAs, capture and elastic reactions for the Pb isotopes and Bi-209 and capture and inelastic reactions for N-15 (Table 3), are not prepared as described above. To perform more correct estimations, more experiments and estimations for MAs and other nuclides should be carried out and an expansion of the covariance data is important.

5. Conclusion

The error analyses were performed to estimate "How much would the error caused by the MA nuclear data decrease if the MA-loaded core experiments at TEF-P were performed". In this estimation, the cross-section adjustment procedure was employed for the FR and the ADS. The seven hypothetical TEF-P experiments were calculated and the sensitivities were used in the cross-section adjustment procedure.

These results showed that the TEF-P experiments with MA fuel were effective to improve the accuracy of the neutronic design for MA-loaded systems. For the ADS, the errors caused by the nuclear data were changed from 0.74% to 0.68% for the criticality, from 3.8% to 3.0% for the coolant void reactivity and from 4.0% to 2.8% for the Doppler reactivity (from 233 to 240 int. data). On the other hand, these results were unable to reduce the margins in the neutronic designs for the MA-loaded systems since the covariance data for elastic and inelastic reactions for MAs were not considered. For the present ADS design, the covariance data for capture and elastic reactions of Pb isotopes and Bi-209, capture and inelastic reactions of N-15 and all reactions for Zr isotopes were also required since the quantities of these nuclides were very large in the present design. More experiments for MAs and other nuclides are important, and the expansion of the covariance data is also necessary.

References

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Table 1: Calculation cases for hypothetical MA experiments at TEF-P

Cases	Analytical modeling error **V'm**[%]	Experimental error **V'e**[%]
Criticality	0.04	0.2
Void reactivity (1-3z)	1.0	5.0
Void reactivity (1-6z)	2.0	5.0
Void reactivity (1-9z)	3.0	10.0
Doppler reactivity (573K)	3.0	3.5
Doppler reactivity (823K)	3.0	4.0
Doppler reactivity (1073K)	3.0	4.5

Table 2:Nuclides and reactions for adjustment (FR)

Nuclide	Capture	Fission	ν	Elastic	Inelastic	χ	μ -bar
U-235	○	○	○	○	○	○	○
U-238	○	○	○	○	○	○	○
Pu-238	○	○					
Pu-239	○	○	○	○	○	○	○
Pu-240	○	○	○	○	○	○	○
Pu-241	○	○	○	○	○		○
Pu-242	○	○					
Np-237	○	○	○				
Am-241	○	○	○				
Am-243	○	○	○				
Cm-244	○	○					
O	○	-	-	○	○	-	○
Fe	○	-	-	○	○	-	○
Cr	○	-	-	○	○	-	○
Ni	○	-	-	○	○	-	○
Na	○	-	-	○	○	-	○

Table 3: Nuclides and reactions for adjustment (ADS)

Nuclide	Capture	Fission	ν	Elastic	Inelastic	χ	μ -bar
Pu-238	○	○					
Pu-239	○	○	○	○	○	○	○
Pu-240	○	○	○	○	○	○	○
Pu-241	○	○	○	○	○		○
Pu-242	○	○					
Np-237	○	○	○				
Am-241	○	○	○				
Am-242m	○	○					
Am-243	○	○	○				
Cm-244	○	○					
N-15		-	-	○		-	
Fe	○	-	-	○	○	-	○
Cr	○	-	-	○	○	-	○
Ni	○	-	-	○	○	-	○
Zr-40	○	-	-		○	-	
Pb-206		-	-		○	-	
Pb-207		-	-		○	-	
Pb-208		-	-		○	-	
Bi-209		-	-		○	-	

Table 4: Errors caused by nuclear data (FR)

unit [%]	Before Adjustment	After Adjustment by 233 int. data	After Adjustment by 240 (233+TEF-P) int. data
Criticality	1.06	0.30	0.27
Coolant Void Reactivity	2.43	1.57	1.36
Doppler Reactivity	3.76	2.16	1.71

Table 5: Errors caused by nuclear data (ADS)

unit [%]	Before Adjustment	After Adjustment by 233 int. data	After Adjustment by 240 (233+TEF-P) int. data
Criticality	1.08	0.74	0.68
Coolant Void Reactivity	5.80	3.82	2.98
Doppler Reactivity	4.92	3.99	2.77

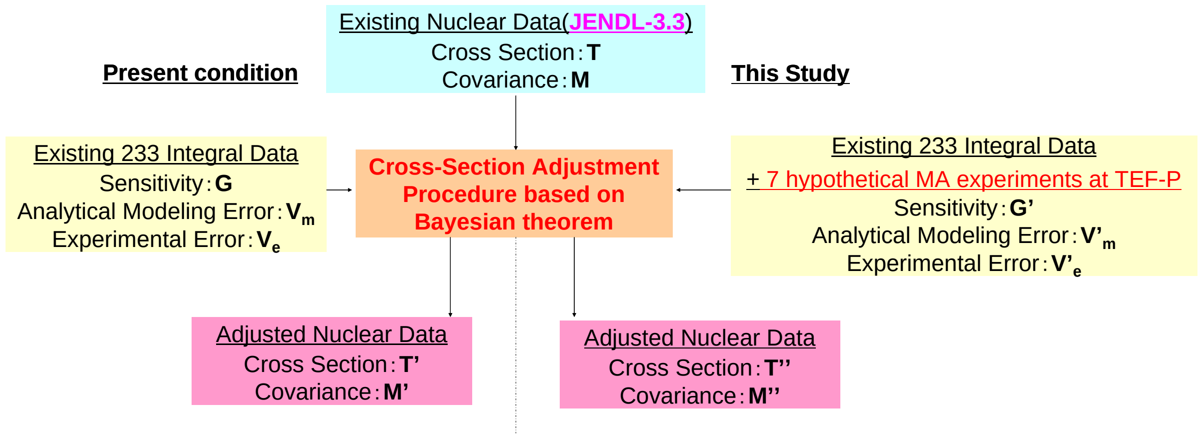

Fig. 1: Procedure to estimate errors caused by nuclear data

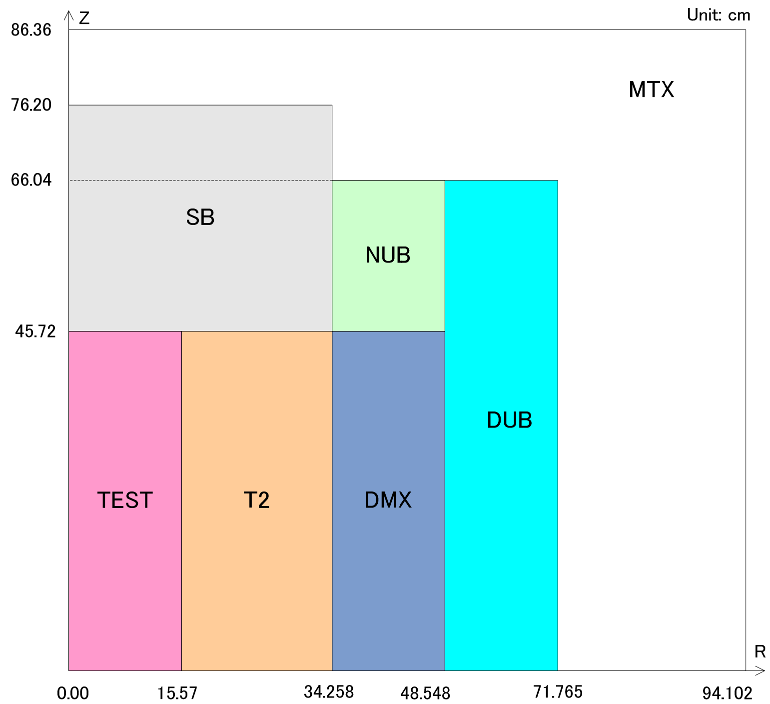

Fig. 2: RZ model of TEF-P core

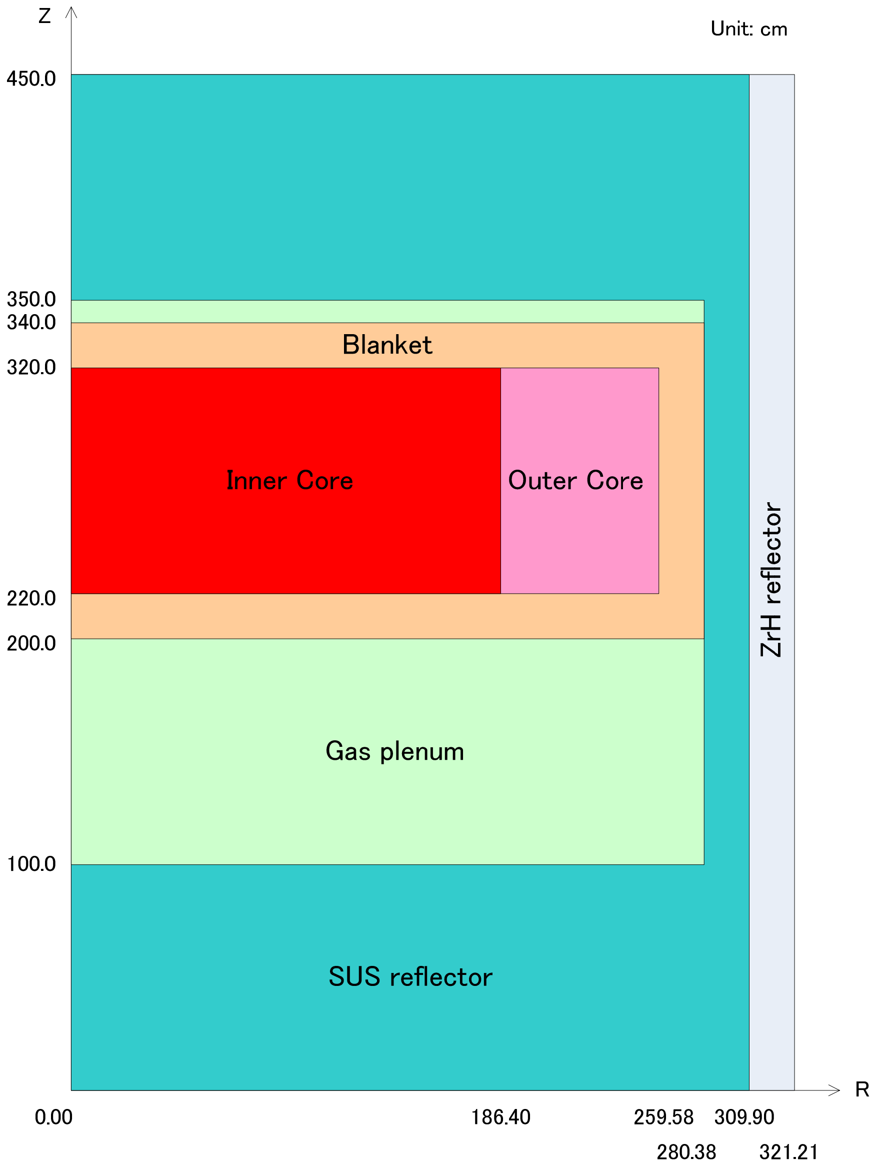

Fig. 3: RZ model of FR core

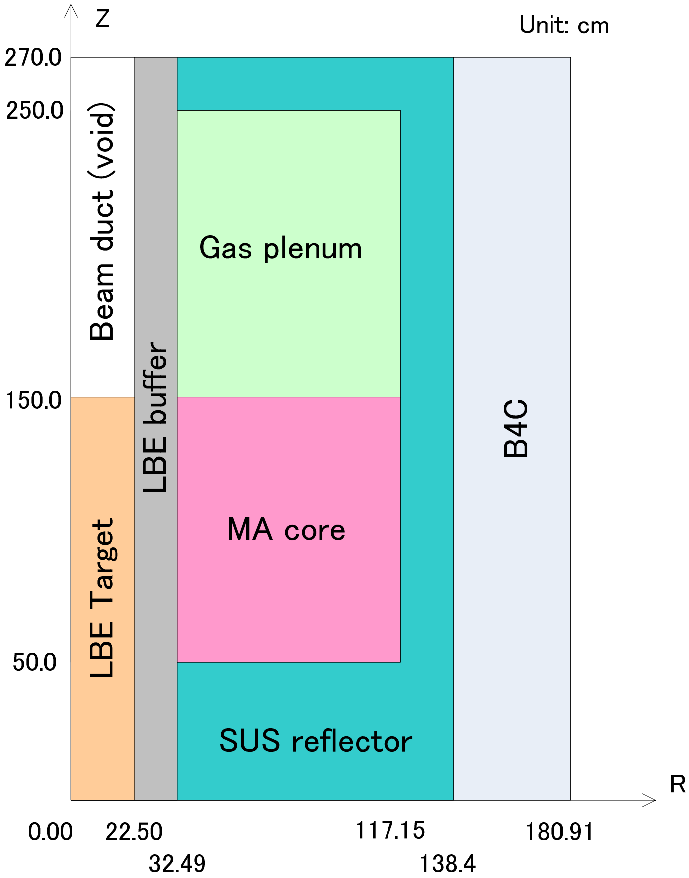

Fig. 4: RZ model of ADS core

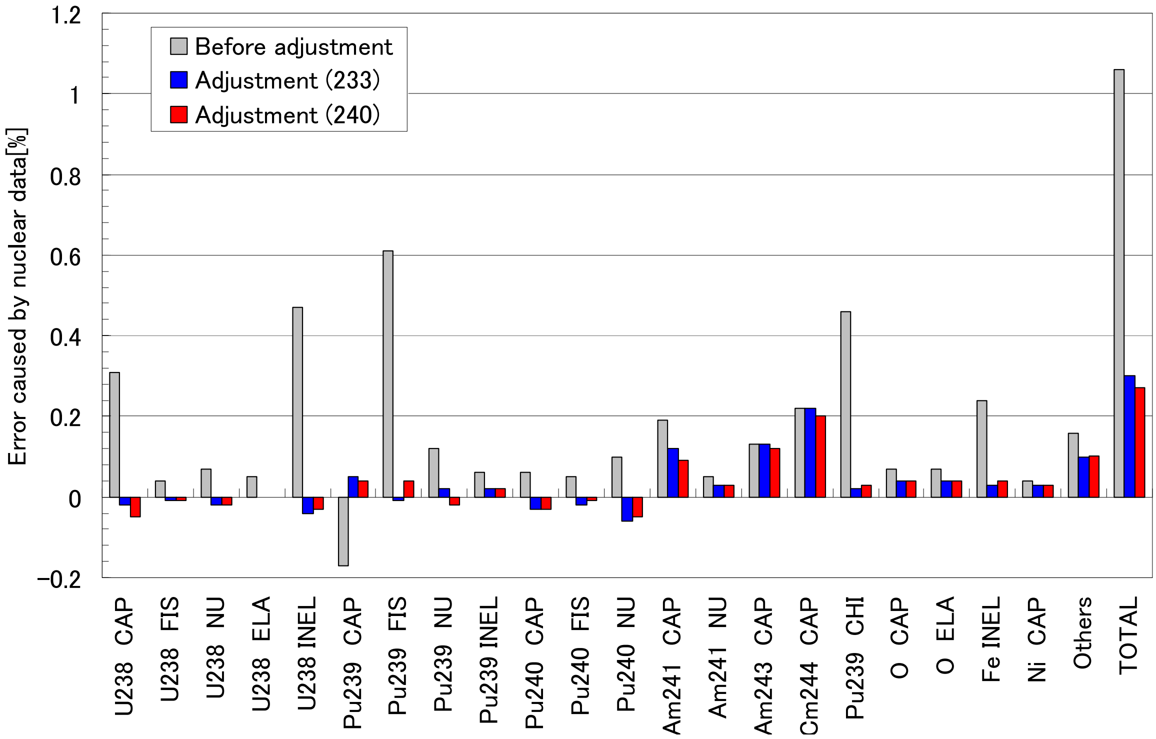

Fig. 5: Contribution of nuclides and reactions to errors caused by nuclear data (criticality, FR)

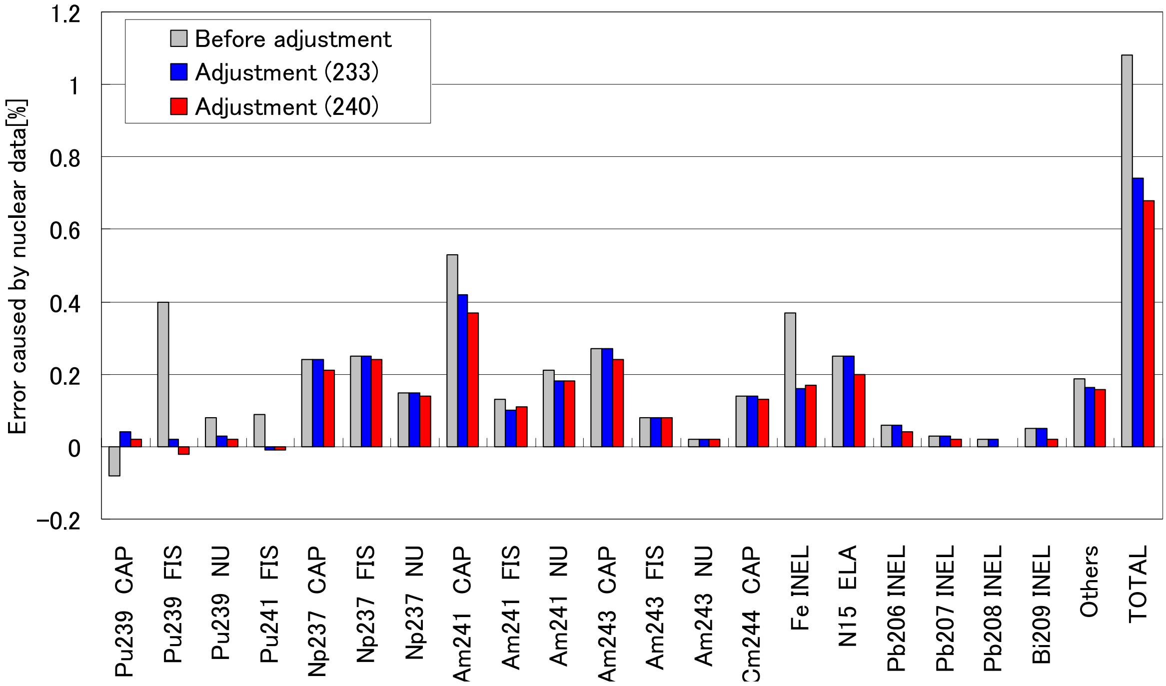

Fig. 6: Contribution of nuclides and reactions to errors caused by nuclear data (criticality, ADS)

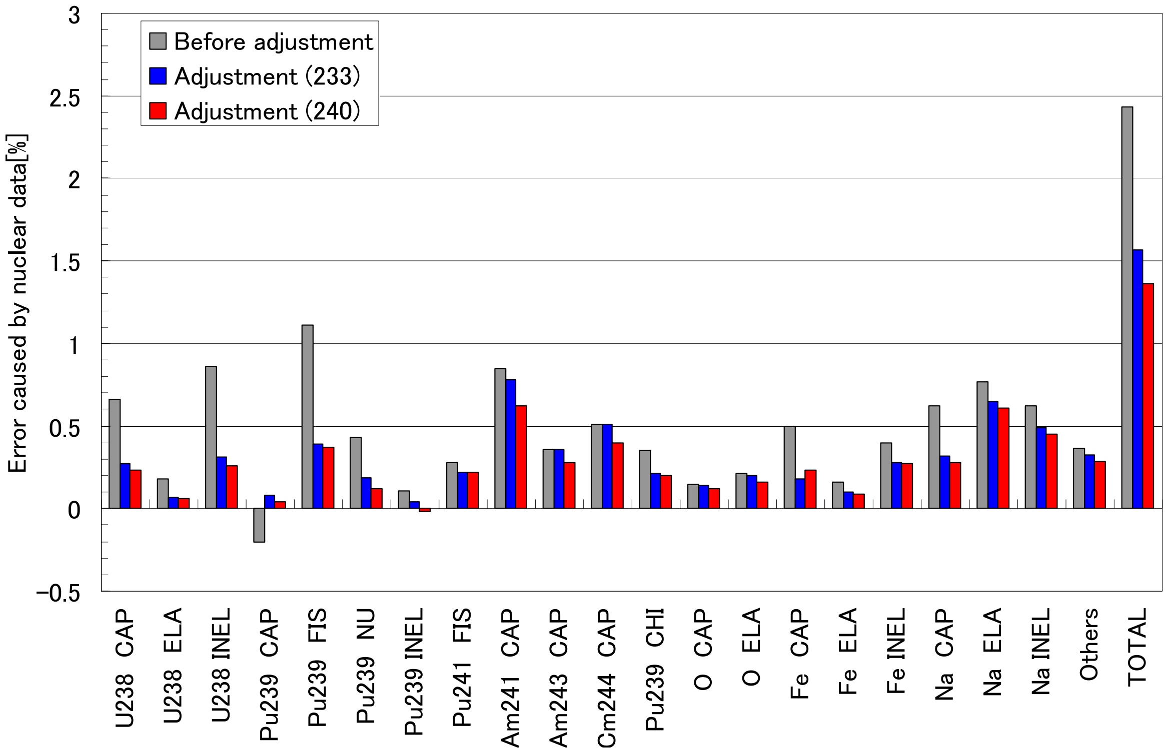

Fig. 7: Contribution of nuclides and reactions to errors caused by nuclear data (coolant void reactivity, FR)

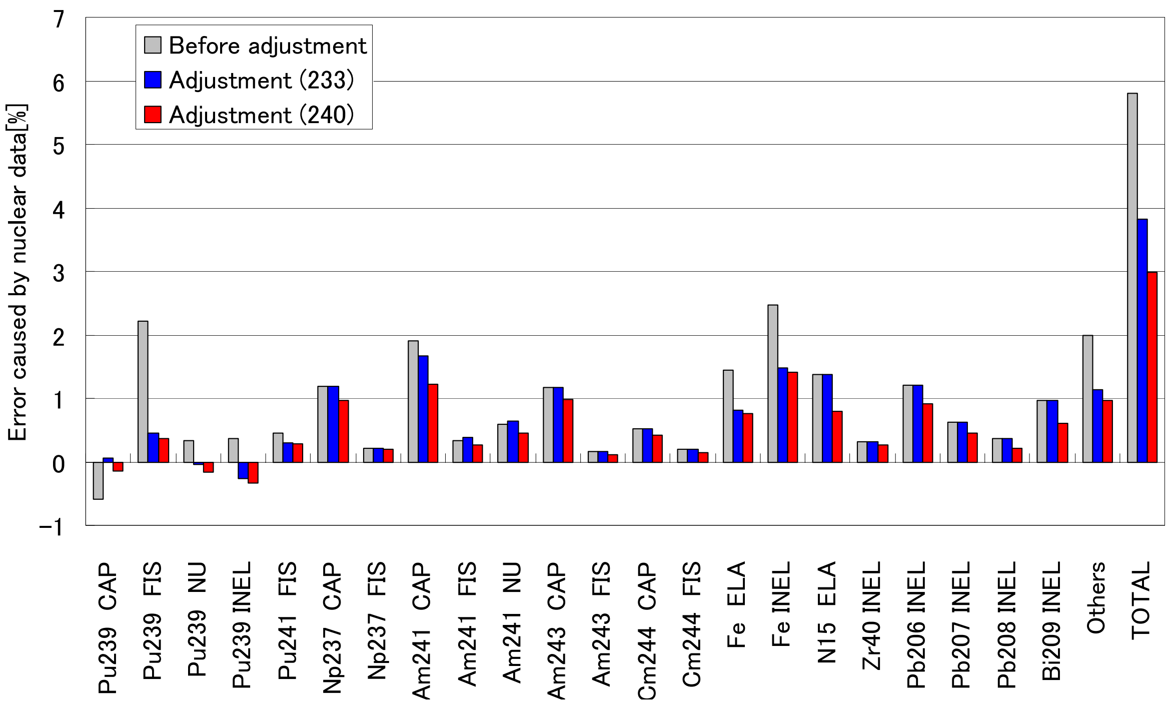

Fig. 8: Contribution of nuclides and reactions to errors caused by nuclear data (coolant void reactivity, ADS)

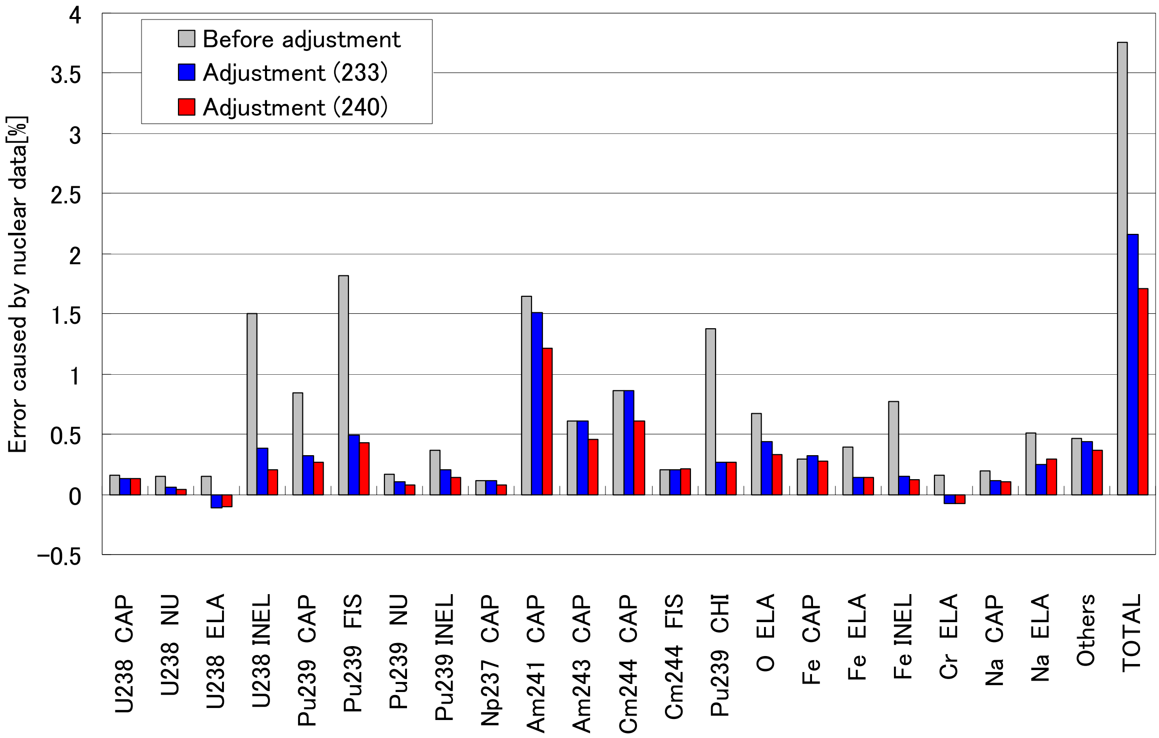

Fig. 9: Contribution of nuclides and reactions to errors caused by nuclear data (Doppler reactivity, FR)

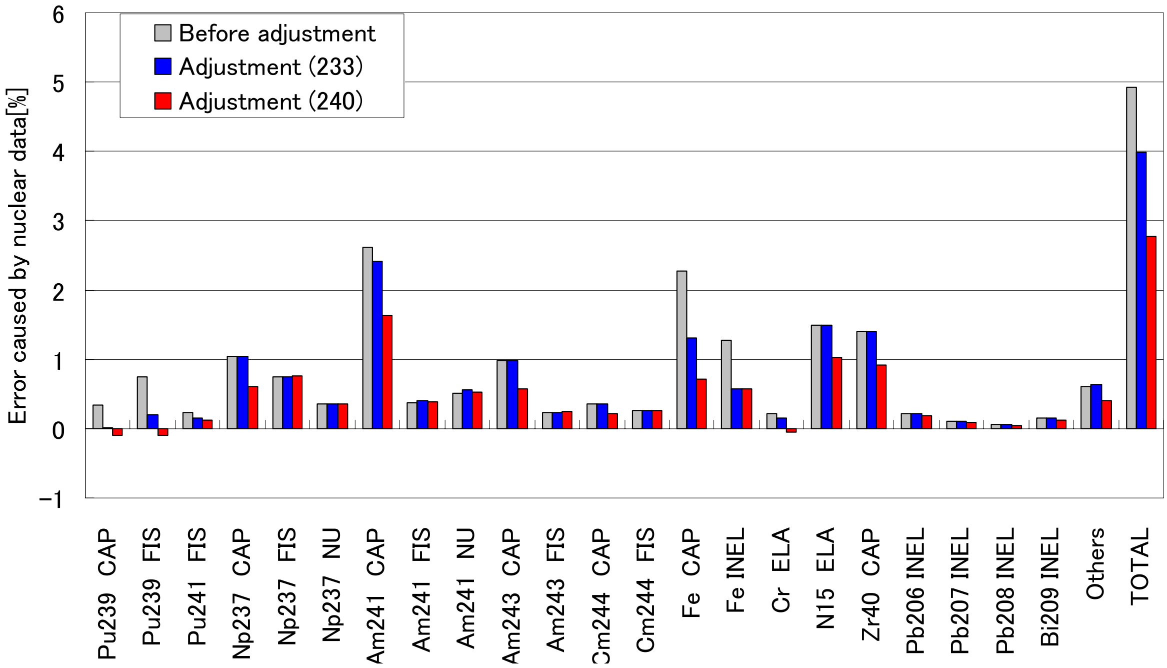

Fig. 10: Contribution of nuclides and reactions to errors caused by nuclear data (Doppler reactivity, ADS)