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Validation of Pb Nuclear Data by Sample Reactivity Experiments at Kyoto University Critical Assembly

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1. Introduction

In the nuclear design of lead-bismuth eutectic (LBE) cooled Accelerator-Driven System (ADS) proposed by JAEA[1], a considerable difference between JENDL-4.0[2] and JENDL-3.3[3] was found in the analyses of the multiplication factor and the void effect of the coolant. From a subsequent analysis [4], it has been concluded that the difference caused by the update of cross section of Pb isotopes strongly affect the precision of the nuclear design because Pb is composed of coolant material in ADS by JAEA. For the evaluation of cross section accuracy of Pb isotopes from experimental analyses, the sample reactivity experiments were carried out at the Kyoto University Critical Assembly (KUCA) core by the substitution of Al (reference) for Pb (test) materials. Then, numerical simulations were performed with the Monte Carlo calculation code MCNP6.1[5] together with nuclear data libraries JENDL-3.3, JENDL-4.0, ENDF/B-VII.0[6] and JEFF-3.1[7]. To evaluate the contributions of reaction types and energy groups, the sensitivity analysis based on the generalized perturbation method was performed by SAGEP[8] with JENDL-4.0 in the deterministic analyses.

The purpose of the present study was to conduct a comparative study on the accuracy of the cross sections of Pb isotopes, with a focus on the differences between JENDL-4.0 and the three other libraries, and to identify the reactions and neutron energy resulting in major contribution to the sample reactivity.

2. Sample reactivity experiment

2.1 Core configuration

The sample reactivity experiments were carried out at the solid-moderated and reflected core in the KUCA A core as shown in **Figure 1**. The numerals 40 and 14 correspond to the number of fuel plates in the partial fuel assembly used for reaching the criticality mass. The core was surrounded by reflector rods composed of polyethylene.

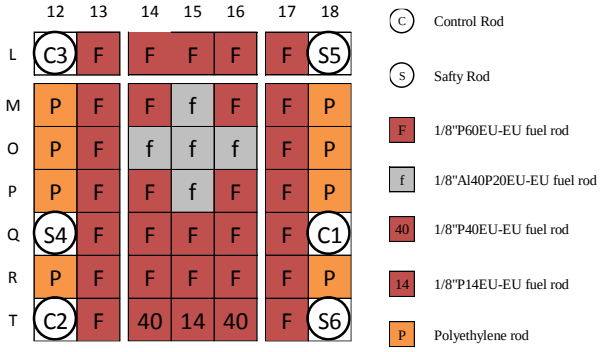

Fig. 1. Core configuration in sample reactivity experiments.

In the sample reactivity experiments, a test-zoned fuel region was arranged for measuring the effect of substituting Al plates for Pb ones upon the criticality. In the test zone, five test fuel assemblies were set around the core at positions (14, O), (15, M), (15, O), (16, O) and (15, P), as shown in Figure 1. The patterns of sample reactivity experiments were ranging between three and five, as shown in **Figure 2**.

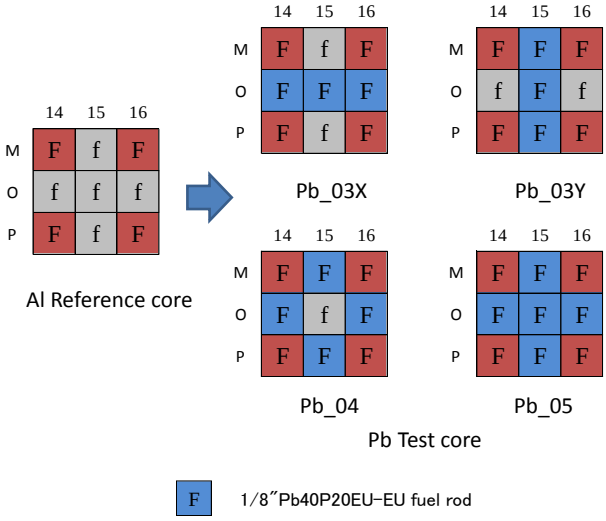

Fig. 2. Patterns of sample reactivity experiments.

The sample reactivity was experimentally obtained through the difference between the excess reactivities of Al reference core and Pb test core (Figure 2). The uncertainty of measured sample reactivity was calculated by taking the variance of excess reactivities measured in several times.

2.2 Monte Carlo analysis method

The numerical approach of sample reactivity can be generally expressed as follows, in case of substituting Al plates for Pb ones:

$$\Delta\rho^{Cal}_{Al->Pb} = \rho^{Cal,Pb}_{Excess} - \rho^{Cal,Al}_{Excess} = \left(1-\frac{1}{k^{Cal,Pb}_{Clean}}\right) - \left(1-\frac{1}{k^{Cal,Al}_{Clean}}\right) = \frac{1}{k^{Cal,Al}_{Clean}} - \frac{1}{k^{Cal,Pb}_{Clean}}, \quad (1)$$

where $k^{Cal,Al}_{Clean}$ and $k^{Cal,Pb}_{Clean}$ indicate the effective multiplication factors in super-critical cores.

By introducing the evaluation methodology of the numerical sample reactivity shown in Eq.(1), $\Delta^{YYZZZ}_{J40->XXX}$ is investigated on the numerical sample reactivity as follows, when the nuclear data libraries and isotopes are varied in the MCNP calculations:

$$\Delta^{YYZZZ}_{J40->XXX} = \left(\frac{1}{k^{Cal,Al}_{Clean,J40,All}} - \frac{1}{k^{Cal,Pb}_{Clean,J40,All}}\right) - \left(\frac{1}{k^{Cal,Al}_{Clean,XXX,YYZZZ}} - \frac{1}{k^{Cal,Pb}_{Clean,XXX,YYZZZ}}\right), \quad (2)$$

where J40 indicates the JENDL-4.0 library, *All* means all the related isotopes and *xxx* indicates the nuclear data library: JENDL-3.3 or ENDF/B-VII.0 or JEFF-3.1, *yy* an isotope and *zzz* a mass of isotopes.

2.3 Deterministic analysis method

To evaluate the contributions of reactions and energy groups, the sensitivity analysis based on the generalized perturbation method was conducted by SAGEP. A collision probability method code PIJ in a general purpose neutronics calculation code system SRAC [9] was employed to generate the effective cross sections in the 107 energy groups.

The sensitivity coefficient of reactivity is defined as follows:

$$S_\rho = (d\rho/\rho)/(d\sigma/\sigma). \quad (3)$$

The obtained sensitivities were multiplied to relative differences in the cross sections as follows:

$$\Delta\rho_{\substack{xxx \\ n,i,g}} = \frac{\sigma^{xxx}_{n,i,g} - \sigma^{J40}_{n,i,g}}{\sigma^{J40}_{n,i,g}} \times S_{\rho,\sigma^{J40}_{n,i,g}} \times \rho_{J40}, \quad (4)$$

where *n* indicates isotopes, *i* reactions, *g* energy groups, S_ρ sensitivity coefficient and ρ_{J40} sample reactivity calculated by the use of JENDL-4.0. The reactivity contribution by replacing the cross section library from JENDL-4.0 to JENDL-3.3 or ENDF/B-VII.0 or JEFF-3.1 were obtained by Eq.(4).

3. Results and discussion

3.1 Monte Carlo analysis

The numerical analyses were conducted with the use of the Monte Carlo code MCNP6.1 together with the JENDL-3.3, JENDL-4.0, ENDF/B-VII.0 and JEFF-3.1 nuclear data libraries. The results are shown in **Table 1**.

Table 1. Comparison between the results of measured and calculated sample reactivities evaluated by Eq.(1).

Core	Experiment [pcm]	C/E			
		JENDL-4.0	JENDL-3.3	ENDF/B-VII.0	JEFF-3.1
Pb_03X	94 ± 7	1.13 ± 0.10	1.63 ± 0.13	0.79 ± 0.08	0.89 ± 0.09
Pb_03Y	110 ± 6	1.07 ± 0.08	1.53 ± 0.10	0.85 ± 0.07	0.97 ± 0.07
Pb_04	145 ± 6	1.12 ± 0.06	1.65 ± 0.08	0.94 ± 0.05	1.00 ± 0.05
Pb_05	156 ± 7	1.13 ± 0.06	1.76 ± 0.08	0.94 ± 0.05	0.98 ± 0.05

By comparing JENDL-3.3 and JENDL-4.0, the calculated values with JENDL-4.0 improved more with a high-accuracy of 30% in the C/E values than with the values calculated with JENDL-3.3. For the cases with ENDF/B-VII.0 and JEFF-3.1, the calculation results were corresponded to the experimental values with about 10% differences.

Major contributions of individual isotope to sample reactivity defined as Eq.(2) are shown in **Figure 3**.

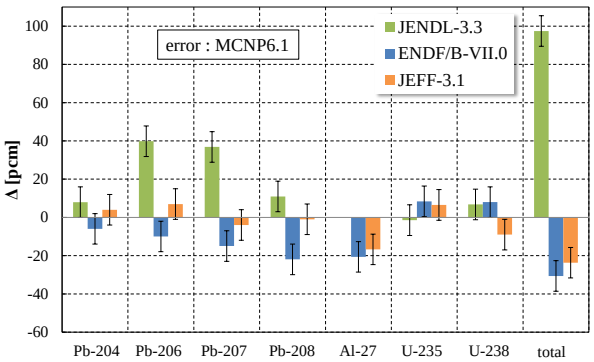

Fig. 3. Major contribution of individual isotope to sample reactivity defined as Eq.(2). (Ref. [10])

A comparison between the two JENDL libraries showed a significant effect on the reactivity resulting from large differences among ^{206}Pb and ^{207}Pb. From the results of ENDF/B-VII.0, a small effect of the difference compared inversely with that in JENDL-4.0 about 20 pcm in all cases, with regard to ^{207}Pb, ^{208}Pb and ^{27}Al. The difference between JENDL-4.0 and JEFF-3.1 was considered notably minor within the allowance of relative errors.

3.2 Deterministic analysis

To identify the reactions and energy region resulting in major contribution to the sample reactivity, sensitivity analyses based on the generalized perturbation method were conducted with the use of SAGEP. Here, neutron capture, elastic and inelastic cross sections were employed in the present study. The contributions of the reactions for Pb isotopes between JENDL-3.3 and JENDL-4.0 are shown in **Figure 4**.

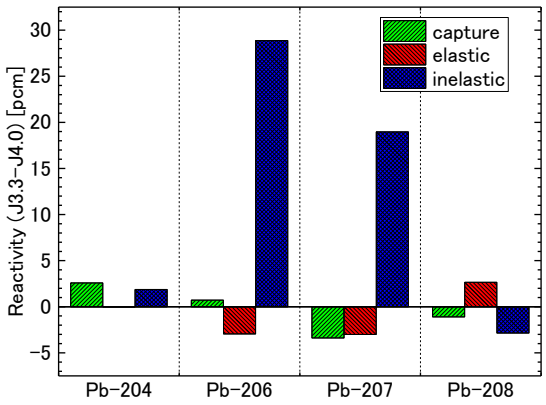

Fig. 4. Contribution to sample reactivity.

Major contributions to the change in the sample reactivity were observed in the inelastic cross sections of ^{206}Pb and ^{207}Pb. Energy breakdown of the contribution of the inelastic cross section of ^{206}Pb and ^{207}Pb are shown in **Figure 5.**

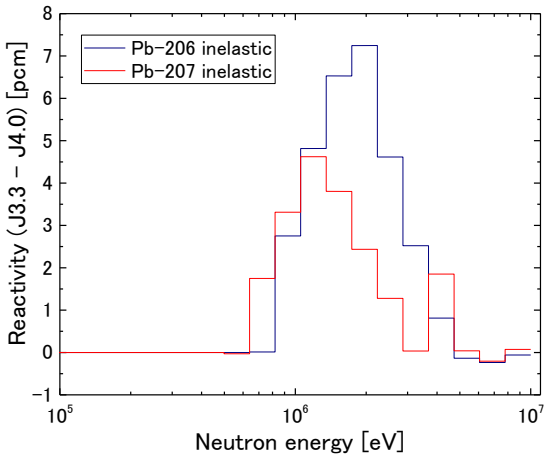

Fig. 5. Energy breakdown of contribution for inelastic of ^{206}Pb and ^{207}Pb.

The change in sample reactivity was mainly attributed to the difference of cross section ranging between 8×10^5 and 4×10^6 eV energy region. This is due to the decrease of cross section by the update and especially larger sensitivities than other energy groups.

4. Conclusions

The sample reactivity experiments were carried out at KUCA to examine the uncertainties of cross sections of Pb isotopes. The comparison between the experiments and the calculations by MCNP6.1 revealed that the library update from JENDL-3.3 to JENDL-4.0 improved more with a high-accuracy of 30% in the C/E values. This was caused by the differences especially in the evaluation of ^{206}Pb and ^{207}Pb.

The sensitivity analysis based on the generalized perturbation method was conducted by SAGEP to evaluate the contributions of reactions and energy groups. The major contributors to difference of sample reactivity between JENDL-3.3 and JENDL-4.0 were the inelastic cross sections of ^{206}Pb and ^{207}Pb, especially ranging between 8×10^5 and 4×10^6 eV energy region.

As the future work, the same analyses can be applied to sample reactivity experiments by a substitution of Al plates for Pb-Bi or Bi ones for investigating uncertainties of Bi isotopes. Then we can evaluate the cross sections of Pb and Bi isotopes more accurately with the use of the nuclear-data adjustment method to reduce the uncertainty deduced from the covariance data.

Acknowledgements

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