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ANALYSES OF EXPERIMENTS IN THE JOYO FAST REACTOR USING THE ERANOS AND JNC CODE SYSTEMS

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ABSTRACT

JOYO is an experimental fast reactor in Japan. JNC has analyzed some of the JOYO MK-I experiments using its own latest code system. On the other hand, the European analysis system ERANOS is under validation and was applied to an analysis of the JOYO experiments. The first step in this comparison was the common analysis of the JUPITER experiments, and had been reported in the PHYSOR2000 conference. This paper describes the analyses performed using the two code systems and subsequent intercomparisons of the results. One-region homogeneous core with blanket, JOYO MK-I (the first phase core of JOYO), has been considered. The calculated parameters are criticality (critical mass) and burnup reactivity coefficient. Further, sensitivity analyses for differences among nuclear data libraries have been performed in order to clarify the effect of library and to determine the effect of analytical method.

The use of ERALIB1 adjusted library in ERANOS improves not only the results of the JUPITER core but also those of the burnup reactivity coefficient of JOYO MK-I core. However, it worsens the result of the criticality of JOYO MK-I core. There is a room for improvement concerning the criticality of small uranium-enriched cores like JOYO MK-I. On the burnup reactivity coefficient, the use of U-235 capture cross-section in JEF-2.2 and β_{eff} obtained by ERANOS improves the results in the JNC system.

1. INTRODUCTION

JNC (formerly PNC) has analyzed data from past critical experiments and power reactor operation using its neutronics code system, and the results of these analyses have been utilized for FBR nuclear design study in Japan[1]. The data and analytical results include the ones for the experimental fast reactor JOYO and the JUPITER experiments. JUPITER[2] was a joint research program between US DOE and PNC using ZPPR (Zero Power Physics Reactor) facility at ANL-Idaho from 1978 to 1988. On the other hand, JOYO is an experimental fast reactor, which has been constructed and operated within the Fast Breeder Reactor Development Program in Japan. JOYO attained first criticality in 1977. After a period of operation at 50MWth, the nominal reactor power was raised to 75MWth. This first phase of operation at 50MWth and 75MWth is called Mark-I core (MK-I), which ended in 1981. Some of the characteristics of JOYO MK-I have been analyzed with the latest JNC neutronic code system[3]. Criticality of the minimum core (critical mass)[4] and burnup reactivity coefficient [5] of JOYO MK-I core are considered.

On the other hand, the European fast reactor analysis code system ERANOS[6] has gone intensive numerical and experimental validation and applied successfully to the PHENIX and SUPER-PHENIX core designs. Both JNC and CEA recognized that comparisons between the two code systems need to be investigated to better assess the validity of their predictions.

The first step in this comparison was the common analysis of the JUPITER experiments. In a previous paper[7], the two-region homogeneous core ZPPR-9 (the reference of JUPITER cores) and the radially-heterogeneous core ZPPR-13A have been considered. The calculated parameters are criticality (critical mass), reaction rate distribution (reaction rate traverse), reaction rate ratio (spectrum index), sample Doppler reactivity, sodium (Na) void reactivity and control rod worth.

In this paper, the study has been applied to the analysis of the JOYO MK-I core. Since it is a power reactor, measurements performed such as the burnup-characteristics complement those of critical facilities and are worth investigating. The criticality of the minimum core and burnup reactivity coefficient of JOYO MK-I have been analyzed by ERANOS, and the results have been compared with those evaluated by the JNC code system. Figure 1 shows the configuration of the JOYO MK-I minimum core. The JOYO MK-I core consisted of mixed plutonium and enriched uranium fuel with the volume of 240 liters. Its core is much smaller than those of JUPITER, which were considered in the previous step of this study.

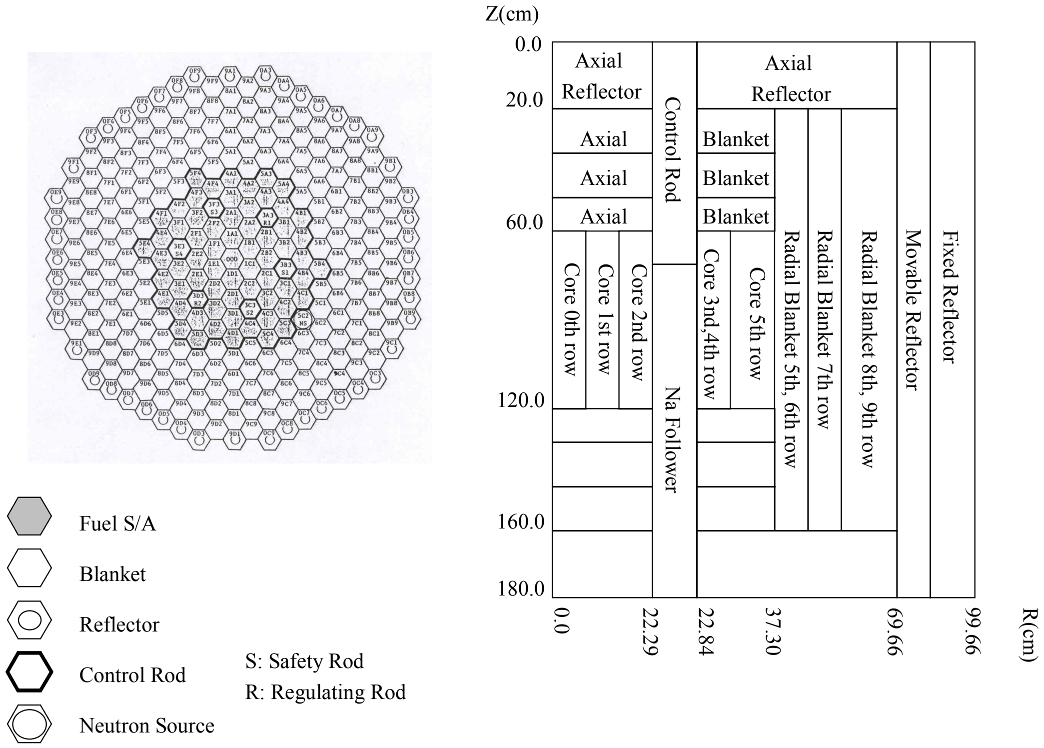


Figure 1. Fast experimental reactor "JOYO" MK-I minimum critical core

Further, criticality values of ZPPR-10A and ZPPR-10B cores of the JUPITER experiments have been considered in this study. These cores are middle-size two-region homogeneous cores in JUPITER-I phase (650MWe mock-up). Figure 2 shows the ZPPR-10A configuration. ZPPR-10A is a mock-up core of the end of cycle (EOC) and has control rod follower regions. ZPPR-10B has the same configuration as ZPPR-10A but is a mock-up core of the beginning of cycle (BOC) and has control rod regions.

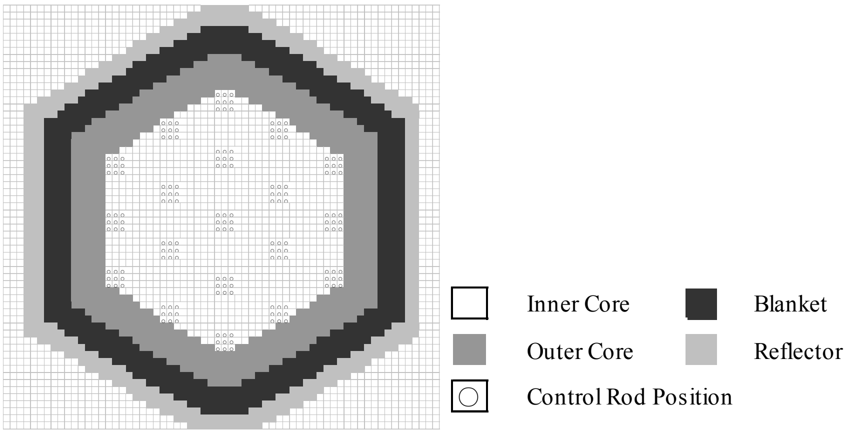


Figure 2. The core configuration of ZPPR-10A

2. METHOD OF ANALYSIS

Table I summarizes the main features of the JNC and CEA calculation schemes used for JOYO MK-I in this study. On the ZPPR-10A and -10B, the calculation schemes used for ZPPR-9 and -13A[7] were applied.

Table I. Comparison of the analytical methods for JOYO MK-I relating to this study

	ERANOS	**JNC**
Nuclear data library	JEF-2.2, ERALIB1	JENDL-3.2
Energy groups of the library	1968 and 33	70
Treatment of self-shielding	Subgroup method	Background cross-section by Tone's method + Interpolation of self-shielding factor
Treatment of spatial mesh	Variational nodal (and Finite difference in diffusion theory)	Finite difference
Treatment of angular mesh	P3	S8
Treatment of anisotropic scattering	P1 (Extended P0)	P1 (Extended P0)
Geometrical model of cell calculation	2D exact model	1D ring model
Geometrical model of core calculation	3D Hex-Z	3D Tri-Z and 3D XYZ
Homogenization method of control rod	Reactivity preservation method with 2D XYZ model	Reaction rate ratio preservation method with 1D ring model

2.1 THE ERANOS CALCULATION SCHEME

In the analysis using ERANOS, two nuclear data sets were used: the European Joint Evaluated Library JEF-2.2[8] and the adjusted cross-section library ERALIB1[9]. Fundamental calculations were performed using the heterogeneous cell model with the coarse group (33-group) library. The group collapsing correction from the coarse groups to the fine groups (1968-groups) were evaluated by using the macrocell calculation option, which models whole core in one-dimensional (1D) geometry and takes into account the resonance and spectrum interaction between core and blanket regions.

The corrected results by the group collapsing correction, which correspond to those obtained by using the effective cross-section produced by the fine groups library, is specified by the simple notation "ERANOS" in Chapter 3. The notation "ERANOS(33G)" represents the results without group collapsing correction.

ERANOS treats the self-shielding of cross-sections with the subgroup method with the ECCO[10] cell code. In the cell calculation, a 2D cell model representation as shown in Figure 3 was applied. For the homogeneous cross-section of the control rod, an ERANOS scheme based on reactivity preservation method[11] was used.

For core calculations, variational nodal transport theory[12], which does not require the spatial mesh correction, was applied for analyses of both criticality and burnup reactivity coefficient. In order to analyze the burnup coefficients, the PROJERIX scheme[11] in ERANOS was applied to treat reloading the fuel subassemblies exactly.

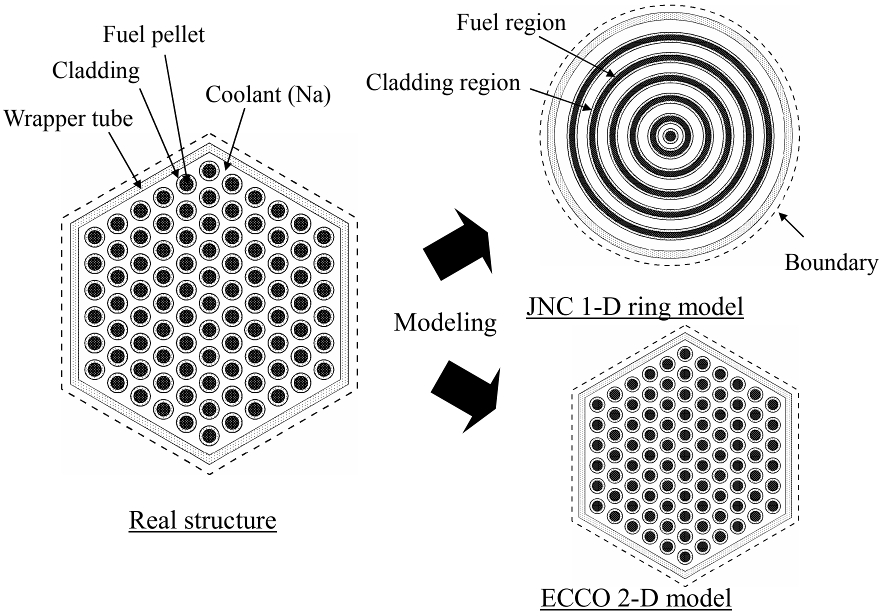


Figure 3. Calculation model for the JOYO MK-I fuel sub-assembly

2.2 THE JNC CALCULATION SCHEME

In the JNC's analysis, 70-group fast reactor constant set based on the Japanese Evaluated Nuclear Data Library JENDL-3.2[13] (JFS-3-J3.2R[14]) was used for all core parameters. JFS-3-J3.2R was recently revised to correct an error of processing its weighting function.

Cell calculations were performed with 1D model for both fuel and blanket subassemblies[15] and self-shielding was treated by the factor table interpolation method. In order to calculate the homogeneous cross-section of the control rod, reaction rate ratio preservation method[16] was used.

All the parameters obtained by core calculations were corrected to results based on the transport theory with zero mesh-size in space and angle.

2.3 SENSITIVITY ANALYSIS

In order to investigate the effects due to the use of different libraries, a sensitivity analysis was also performed. The sensitivity coefficient of a core parameter, R, to cross-section, σ, is defined as follows:

$$S_{m,x,g} = \frac{\mathrm{d}R/R}{\mathrm{d}\sigma_{m,x,g}/\sigma_{m,x,g}} \tag{1}$$

where the subscripts m, x and g represent nuclide, reaction type and energy group number, respectively. Contribution of each cross-section to a core parameter change is evaluated as follows:

$$\frac{R'-R}{R} = \sum_{m,x}\sum_{g}\left[S_{m,x,g}\cdot\frac{\sigma'_{m,x,g}-\sigma_{m,x,g}}{\sigma_{m,x,g}}\right] \tag{2}$$

Sensitivity coefficients were calculated in order to investigate the results. They were calculated by SAGEP[17] and SAGEP-BURN[18] codes in the JNC system, which are based on the generalized perturbation theory, including burnup characteristics[19].

3. RESULTS AND DISCUSSION

This chapter describes the accuracy of ERANOS and subsequent comparison with the JNC system. Experimental and analytical uncertainties are worth being considered when analyzing the discrepancy in calculation over experiment (C/E) values from unity. The analytical uncertainties are based on an evaluation in the cross-section adjustment study of JNC[1]. Further, uncertainties induced from cross-section must be considered, and they are evaluated by using the latest covariance data file for JENDL-3.2[20] , which are processed to group-wise data by ERRORJ code[21]. Those uncertainties are summarized in Table II. This table shows that the cross-section induced uncertainties are large in both parameters. Figure 4 and 5 show the contributions to the cross-section induced uncertainty to criticality and burnup reactivity coefficient, respectively.

Table II. Uncertainties of the JOYO MK-I experiments and analyses

	Experimental	**Analytical**	**Cross-section induced**	**Total**
Criticality	0.04	0.13	0.83	0.84
Burnup reactivity coefficient	5.3	0.6	2.6	5.7

Unit: %

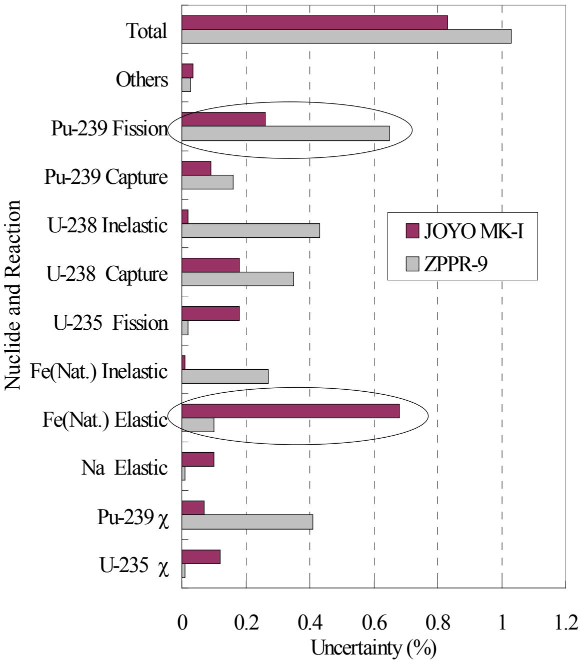


Figure 4. Nuclide-wise cross section induced uncertainties for criticality

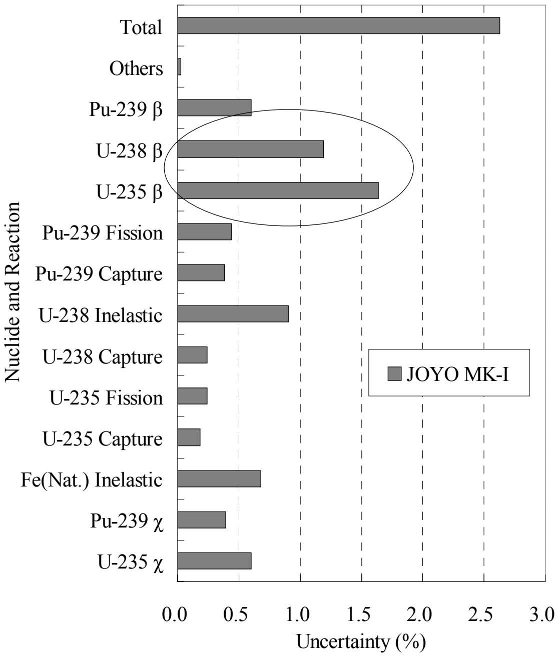


Figure 5. Nuclide-wise cross section induced uncertainties for burnup coefficient

On the uncertainty of the criticality, JOYO MK-I has different trend from ZPPR-9. The uncertainty induced from Fe elastic scattering cross-section becomes dominant to JOYO MK-I, though Pu-239 fission cross-section is the main contribution to ZPPR-9.

On burnup coefficient, it is necessary to calculate an effective delayed neutron fraction (β_{eff}) because the experimental value was obtained in dollar unit. Therefore, the uncertainty of the burnup coefficient has contributions of the delayed neutron fraction (β). The uncertainties induced from the delayed neutron fractions of U-235 and U-238 are dominant to JOYO MK-I burnup coefficient.

3.1 CRITICALITY

Figure 6 shows the summary of results on criticality. The effect of difference between 2D as-built cell model and 1D ring cell model was evaluated by ECCO and it is confirmed that the effect is very small for criticality (~0.02%Δk/kk') and negligible. This figure includes the results of JUPITER cores. The results of ZPPR-10A and ZPPR-10B have the same tendency as the other JUPITER cores (ZPPR-9 and ZPPR-13A).

For the minimum core criticality of JOYO MK-I, the result evaluated by ERANOS with JEF-2.2 is in agreement with that evaluated by the JNC system with JENDL-3.2. However, these two results include some effects by difference of methods and libraries. They are discussed in the followings.

(1) Group collapsing effect:
It is found by comparing ERANOS(JEF-2.2) and ERANOS(JEF-2.2, 33G) that the group collapsing effect for JOYO MK-I core is ~0.4%dk/kk' and is as large as that for ZPPR-13A. Due to the small core of JOYO MK-I, the interaction between core and blanket region is becoming important.

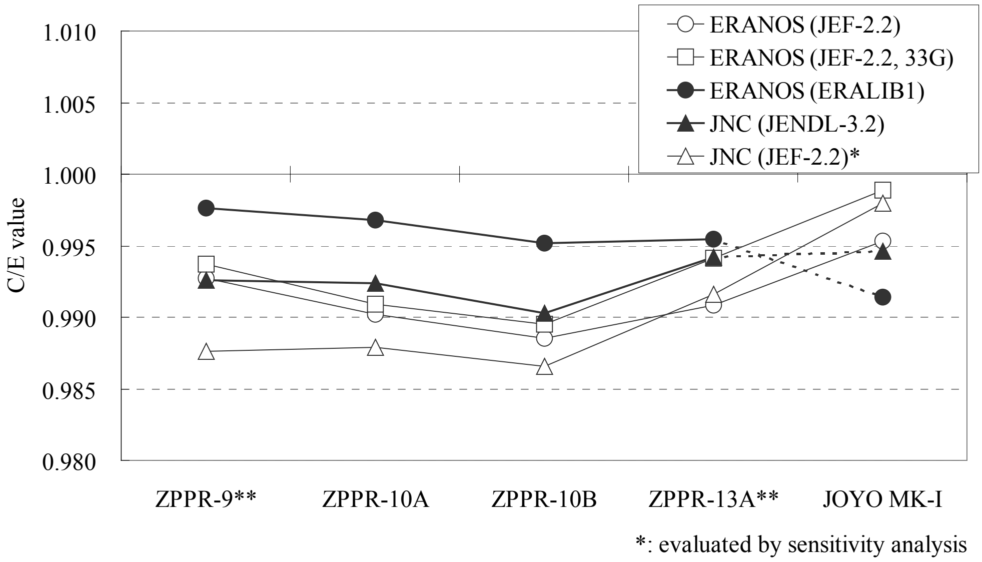


Figure 6. Summary of results on the criticality

(2) Library effect (JEF-2.2 and JENDL-3.2):
For JUPITER cores, it is predicted by sensitivity analysis that the use of JEF-2.2 decreases C/E value compared to JENDL-3.2. Figure 7 shows the break-down of the reactivity change when replacing the JENDL-3.2 library by the JEF-2.2 one. It is caused by a lot of nuclide and reaction contributions (mainly Pu-239 ν and fission). For JOYO MK-I core, the use of JEF-2.2 increases C/E value due to Fe elastic scattering cross-section and U-235 ν. The JOYO MK-I core is sensitive to the elastic scattering cross-section that affect the length of neutron mean free path because it is very small core and has large neutron leakage from the core. Further, the JOYO MK-I core is not sensitive to the Pu-239 due to the uranium-enriched fuel, compared with JUPITER cores that consisted of Pu fuel.

(3) ERALIB1 effect:
ERANOS with JEF-2.2 systematically underestimates the criticality of the JUPITER cores and the use of ERALIB1 improves it well. However, the use of the ERALIB1 worsens the C/E value for JOYO MK-I core. Figure 8 shows the break-down of the reactivity change when replacing the JEF-2.2 library by the ERALIB1 one. In this figure, it is seen that the reactivity change has various nuclide and reaction contributions. The main contributions of the improvement for JUPITER core are Pu-239 fission cross-section and ν value. On the other hand, the main difference on JOYO core criticality is the Na elastic scattering cross-section.

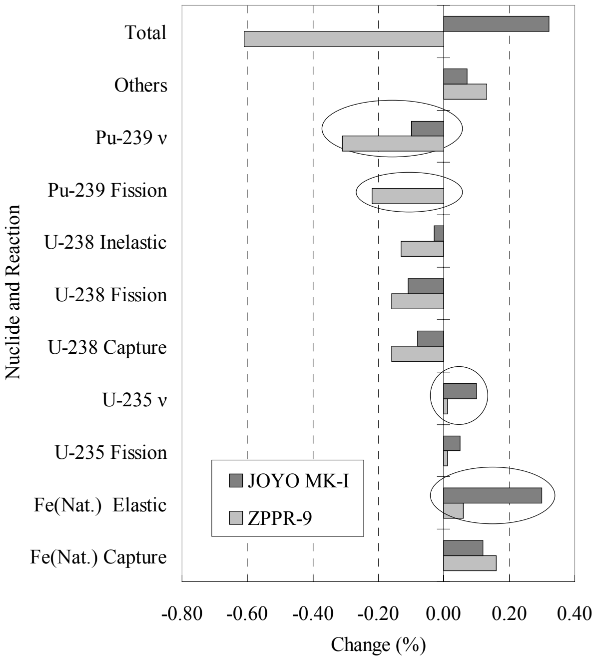


Figure 7. Nuclide-wise contribution to criticality (Difference between JEF-2.2 and JENDL-3.2)

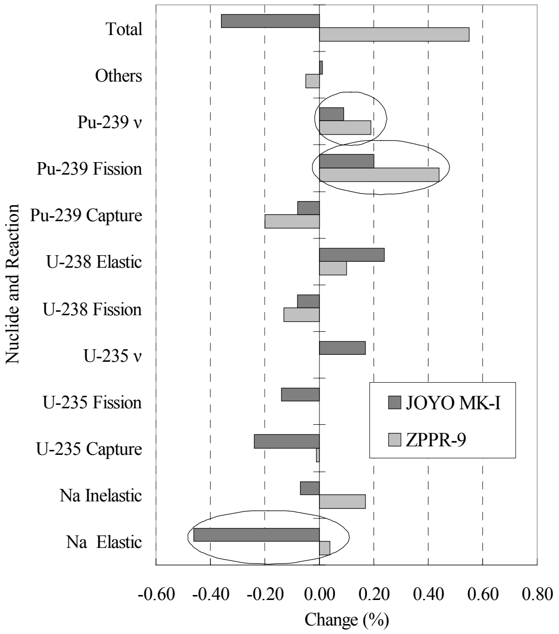
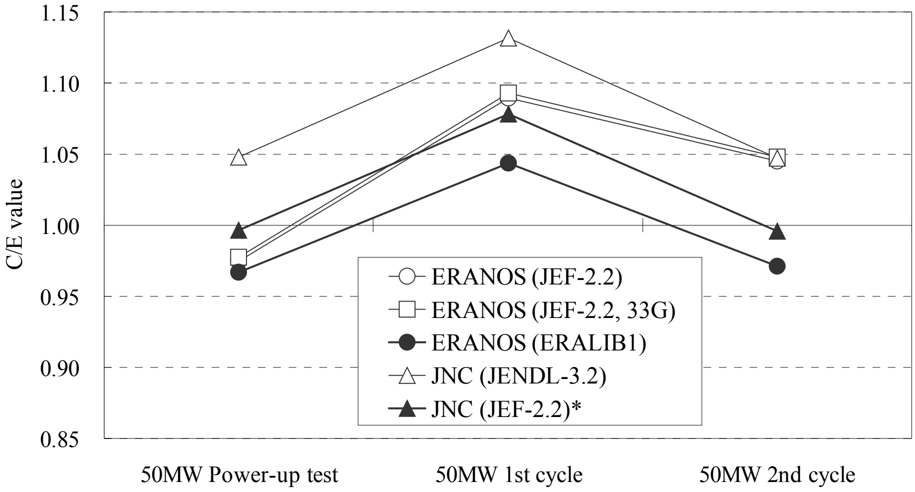


Figure 8. Nuclide-wise contribution to criticality (Difference between ERALIB1 and JEF-2.2)

3.2 BURNUP REACTIVITY COEFFICIENT

Figure 9 shows the summary of the results of the burnup reactivity coefficient. For the burnup reactivity coefficient, the JNC system systematically overestimates the measurements. On the other hand, ERANOS with JEF-2.2 yields better results. The use of ERALIB1 further improves the C/E's, resulting in analytical results in agreement with the experimental ones within the uncertainties.



*: evaluated by sensitivity analysis and used β_{eff} obtained by ERANOS

Figure 9. Summary of results on bunnup reactivity coefficient

It is seen that the group collapsing effect for JOYO MK-I is very small (0.3%) and can be considered as negligible. The main reason of difference between JNC(JENDL-3.2) and ERANOS (JEF-2.2) is β_{eff}, whose difference is 2.6%. Further, the change of nuclear data library (JEF-2.2 and JENDL-3.2) causes a significant difference. Figure 10 shows the nuclide-wise contribution to the library effects. It is found that if U-235 capture cross-section of JEF-2.2 is used the burnup reactivity coefficient decreases by 2%. The use of U-235 capture cross-section in JEF-2.2 and β_{eff} obtained by ERANOS improves the results in the JNC system.

On the other hand, the control rod worth for ZPPR-9, which described in reference 7, has a discrepancy between ERANOS(JEF-2.2) and JNC(JENDL-3.2) because of β_{eff}. In this case, the use of β_{eff} obtained by ERANOS worsens the results. Further discussion about β_{eff} will be necessary.

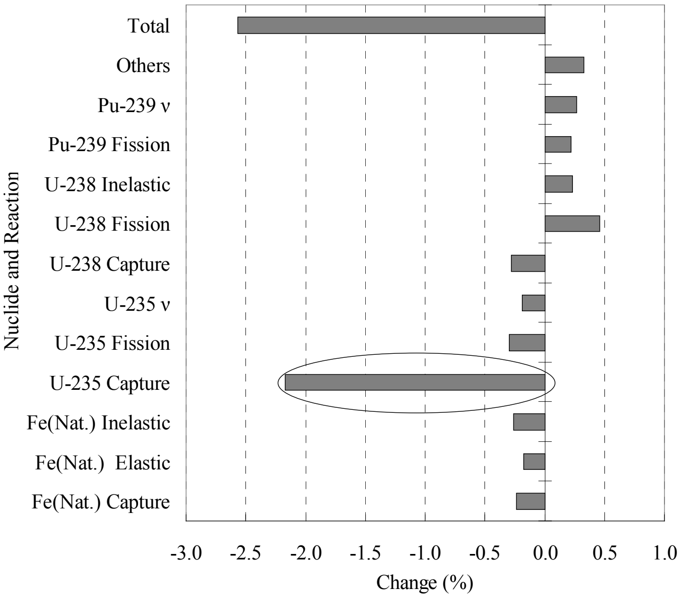


Figure 10. Nuclide-wise contribution to burnup coeffiecient (difference between JEF-2.2 and JENDL-3.2)

CONCLUSIONS

An analysis of the JOYO MK-I experiments using the ERANOS system has been performed, and the results of this analysis were compared with those obtained by the JNC system. In summary, ERANOS has a good performance for evaluating the characteristics of the small uranium-enriched fast reactor, including the burnup reactivity coefficients. The use of ERALIB1 adjusted library improves not only the results of the JUPITER core but also those of the burnup reactivity coefficient of JOYO MK-I core. However, it worsens the result of the criticality of JOYO MK-I core. There is a room for improvement concerning the criticality of small uranium-enriched cores like JOYO MK-I.

Concerning the JNC system, the incorporation of much finer groups constant set would be effective for the improvement of accuracy for JOYO MK-I core. In addition further investigation is required in the effective delayed neutron fraction (β_{eff}). In future work, the other core parameters of JOYO will be considered.

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