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

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ABSTRACT

JUPITER is a joint research program involving U.S.DOE and PNC of Japan, and is a series of experiments performed using a large fast critical facility. JNC (formerly PNC) has analyzed almost all of the JUPITER experiments using its own code system, and the results of analyses have been utilized for the FBR nuclear design study in Japan.
On the other hand, the European analysis system ERANOS is under validation and was applied to an analysis of the JUPITER experiments.

This paper describes the analyses performed using the two code systems and subsequent intercomparisons of the results. Two-region homogeneous core ZPPR-9 (the reference of JUPITER cores) and 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.

1. INTRODUCTION

JUPITER (Japanese-United States Program of Integral Tests and Experimental Researches)[1, 2, 3] is a joint research program between U.S. Department of Energy (DOE) and Power Reactor and Nuclear Fuel Development Corporation (PNC) of Japan, conducted between 1978 and 1988. The JUPITER experiments were performed using ZPPR; the Zero Power Physics Reactor, which is a large fast critical facility at Argonne National Laboratory (ANL)-Idaho. JUPITER consists of 4 experimental phases, and three types of cores were assembled; middle-size 2-region homogeneous cores in JUPITER-I (600 through 800MWe mock-up), the middle-size radially-heterogeneous in JUPITER-II (650MWe mock-up), the middle-size axially-heterogeneous and the large-size 2-region homogeneous in JUPITER-III (650 and 1000MWe mock-up, respectively) and the large-size 2-region homogeneous in JUPITER-Io (1000MWe mock-up). The aims of these programs are to evaluate the accuracy of core design methods in phase I, II and III, and to measure the neutronic decoupling and enriched uranium sector effect in phase Io.

This paper describes analyses of two representative assemblies as shown in Fig. 1. One is for ZPPR-9 of JUPITER-I, which is the simplest of all JUPITER cores, so it could be a standard of JUPITER cores. In addition various experiments were performed using ZPPR-9. This paper considers criticality, reaction rate distribution, reaction rate ratio, sample Doppler reactivity, sodium void reactivity and control rod worth. Another is for ZPPR-13A of JUPITER-II, which includes the internal blanket and that causes difficulty in calculating flux distribution. Therefore this paper focuses the discussion of ZPPR-13A analyses on the evaluation of reaction rate distribution and its effect to other parameters.

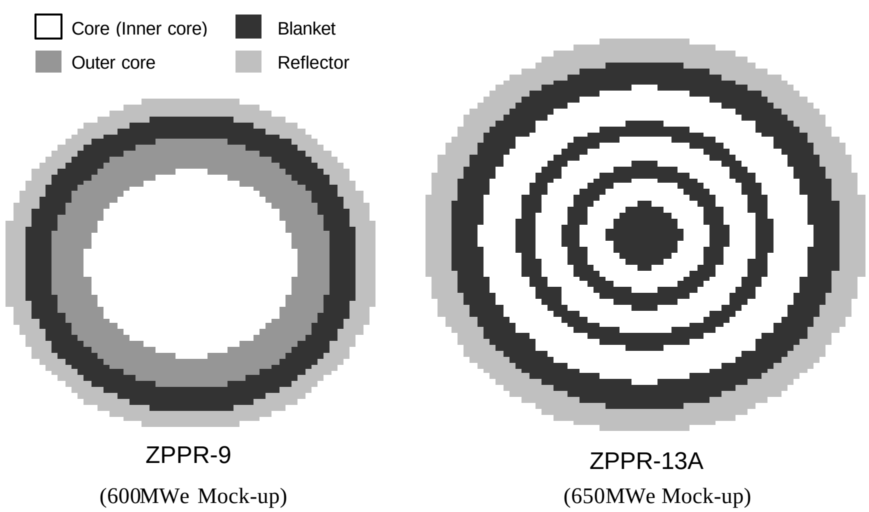


Fig. 1 The core configurations of ZPPR-9 and ZPPR-13A

2. CALCULATION SCHEMES

Table 1 summarizes the comparison of calculation schemes between ERANOS[4] and the JNC system[5]. The treatment of the continuous energy Monte Carlo method[6] is added for the reference. Commonly core calculations were performed in 3-dimensional XYZ geometry using transport theory. Sodium void and sample Doppler reactivity were calculated by the exact and first order perturbation theory, respectively. Details of each system are described in the followings.

2.1 THE ERANOS SCHEME

In the analysis using ERANOS, 2 nuclear data libraries were used; the European Joint Evaluated Library JEF2.2[7] and the adjusted nuclear library ERALIB1[8]. Fundamental calculations were performed using the heterogeneous cell model with the coarse groups (33-groups) library. The collapsing corrections of library from the fine groups (1968-groups) to the coarse groups were evaluated using the macrocell calculation, which models whole core in 1-dimensional geometry and takes account of the spectrum interaction between different regions, for example between core and blanket. Therefore the corrected results correspond to those obtained using the effective cross section produced by the fine groups library, and it is specified by the simple notation "ERANOS" or "The reference ERANOS" in Chapter 3. The notations "ERANOS with 33-gourps" and "ERANOS (33G)" designate the results without collapsing correction. Further the collapsing correction may show the effectiveness of the fine groups cell calculation for preparing group cross sections. ERANOS treats self-shielding of cross sections with the subgroup method, which is carried out by ECCO[9]. For core calculations, variational nodal transport theory[10], which does not require the spatial mesh correction, was applied for analyses of criticality, reaction rate and control rod worth, and finite difference transport theory was adopted for those of sample Doppler reactivity and sodium void reactivity, which need the application of the perturbation theory. In preparation of the effective cross section of the Doppler sample, the supercell model that consists of the Doppler sample and surrounding core fuel was used, and cell calculation was performed using the fine groups library in order to consider the resonance and spectrum interaction between them.

2.2 THE JNC ANALYTICAL SCHEME

Cell calculations were performed using 70-groups fast reactor constant set based on the Japanese Evaluated Nuclear Data Library JENDL-3.2[11, 12], and self-shielding was treated by its factor table interpolation method. All parameters obtained by core calculations were corrected to results based on the transport theory with zero mesh-size in space and angle (direction). The resonance interaction between the Doppler sample and core fuel was evaluated using the ultra fine energy groups cell calculation for preparation of effective cross section of the Doppler sample.

Table 1 Comparison of the analytical methods relating to this study

	ERANOS	JNC	Monte Carlo (MVP)
Nuclear data library	JEF2.2, ERALIB1	JENDL-3.2	JENDL-3.2
Energy groups of the library	1968 and 33	70	(Continuous)
Treatment of self-shielding	Subgroup method	Backgroud cross section by Tone's method + Interpolation of self-shielding factor	Exact treatment and probability table method for the unresolved resonance energy range
Treatment of spatial mesh	Variational nodal and finite difference	Finite difference	Exact
Treatment of angular mesh	P3	S4	Exact
Treatment of anisotropic scattering	P1 (Extended P0)	P1 (Extended P0)	Kinetics for elastic scattering and probability table for inelastic scattering

3. RESULTS AND DISCUSSIONS

This chapter describes the accuracy of ERANOS and subsequent comparison with the JNC system. Experimental and analytical uncertainties could be criteria for the consideration of the discrepancy in calculation over experiment (C/E) values from 1.0, and those uncertainties are briefly summarized in Table 2[13]. The notation without library name specifies the results with JEF2.2 for ERANOS and with JENDL-3.2 for the JNC system.

Table 2 Uncertainties of the JUPITER experiments and analyses

Parameteres \ Uncertainty	Experimental	Analytical	Cross section induced	Total
Criticality	0.04	0.31	1.59	1.62
F49 distribution	1.00	2.10	1.78	2.93
F25 distribution	1.00	2.10	1.72	2.89
F28 distribution	2.50	3.40	2.14	4.73
C28 distribution	1.00	2.10	1.73	2.90
F25/F49 ratio	2.20	1.00	3.10	3.93
F28/F49 ratio	2.50	2.00	5.65	6.49
C28/F49 ratio	2.20	1.00	3.68	4.40
Sample Doppler reactivity	1.17	5.40	7.52*	9.33
Na void reactivity	2.00	9.00	10.23	13.77
Control rod worth	1.20	2.40	4.30	5.07

Unit: % *: Tentative evaluation

3.1 CRITICALITY (CRITICAL MASS)

Figure 2 represents the summary of analytical results of criticality for ZPPR-9 and ZPPR-13A. For ZPPR-9, the result obtained by the reference ERANOS agreed well with that by the JNC system and with ERANOS with 33-groups, too. On the other hand, the reference ERANOS underestimated for ZPPR-13A by 0.9% while ERANOS with 33-groups and the JNC system undervalued just by 0.6% and 0.4%, respectively. However, the reference ERANOS was more similar to the continuous energy Monte Carlo results than ERANOS with 33-groups and the JNC system in comparison of the tendency or relative difference of C/E values between ZPPR-9 and ZPPR-13A. Therefore it is considered that there is a room for an improvement of the JNC system in group structure of cell calculation.

The main difference between ZPPR-9 and 13A is obviously whether the internal blanket region is included or not, which might affect the result of criticality analysis, and that is discussed in next section in detail.

The use of ERALIB1 improved the criticality of both cores constantly by 0.5% and it brought C/E values near to 1.0.

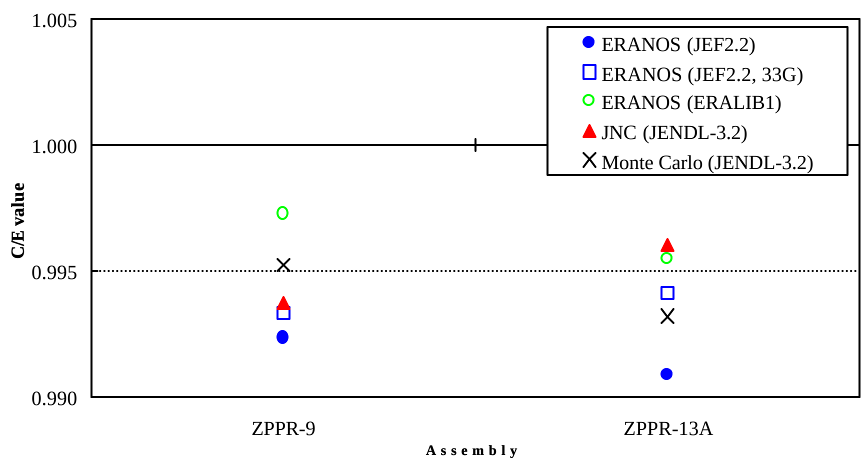
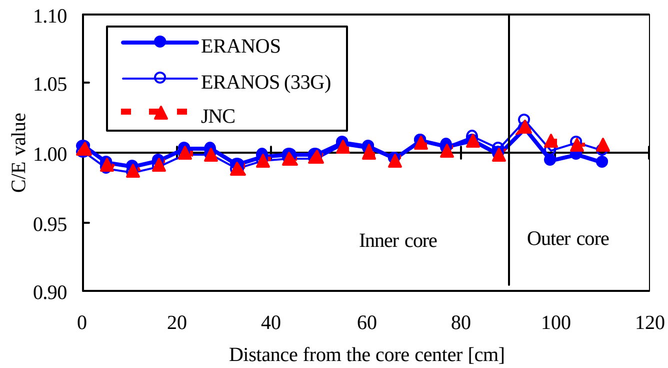


Fig. 2 Summary of results of the criticality analyses for ZPPR-9 and ZPPR-13A

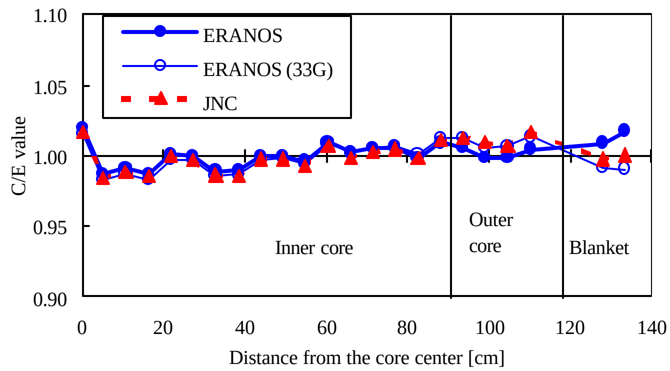
3.2 REACTION RATE DISTRIBUTION (REACTION RATE TRAVERSE)

Note that following abbreviations of reaction type are used in this and next sections; F49 for Pu-239 fission, F25 for U-235 fission, F28 for U-238 fission and C28 for U-238 capture.

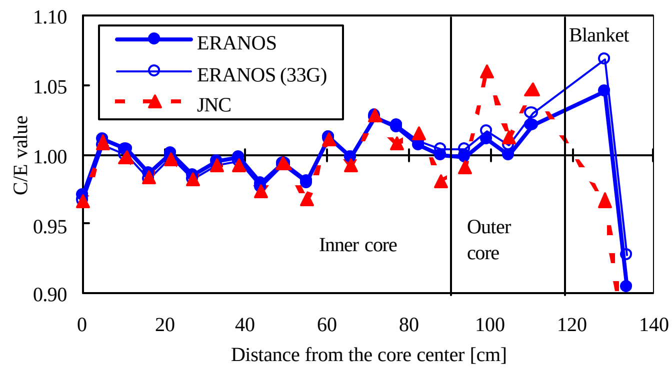
ZPPR-9: Figure 3-1 represents the comparison of results between ERANOS and the JNC system in the 4-types (F49, F25, F28 and C28) of the ZPPR-9 reaction rate distribution. Results by ERANOS and the JNC system agreed well with each other and ERANOS evaluated the reaction rate in the blanket region a little bit better. Accordingly, the use of the fine groups cell calculation is effective in improving the accuracy of reaction rate distribution. Regarding C28, systematic underestimation was observed in the blanket region, and that is detailed in next paragraph.



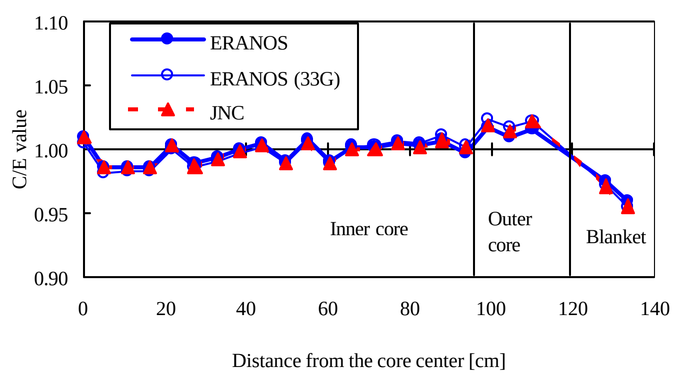
- F49; Pu-239 fission -



- F25; U-235 fission -

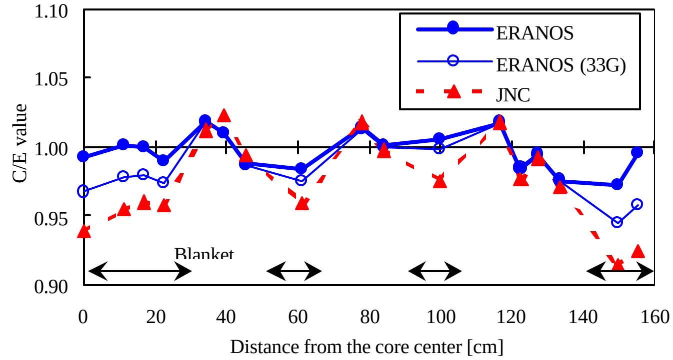


- F28; U-238 fission -

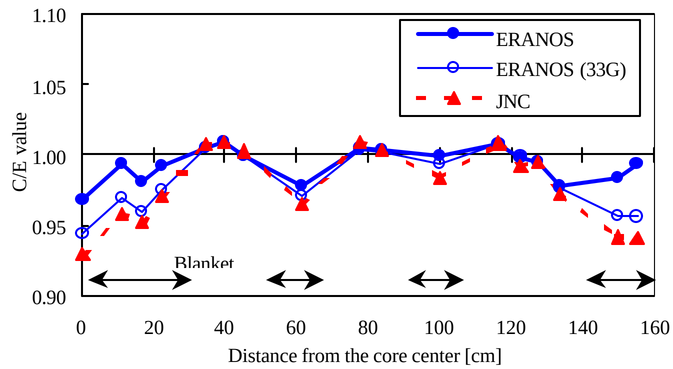


- C28; U-238 capture -

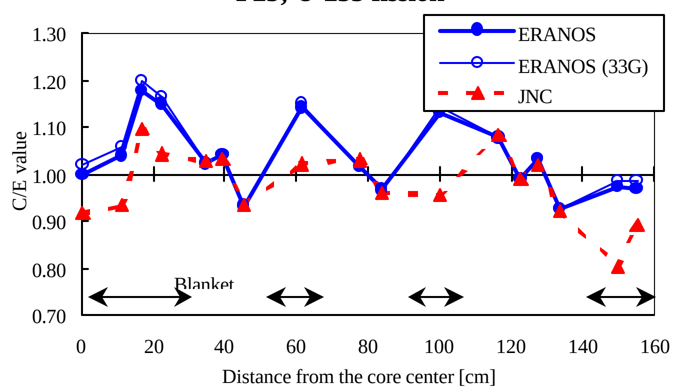
Fig. 3-1 The results of the reaction rate distribution analyses for ZPPR-9



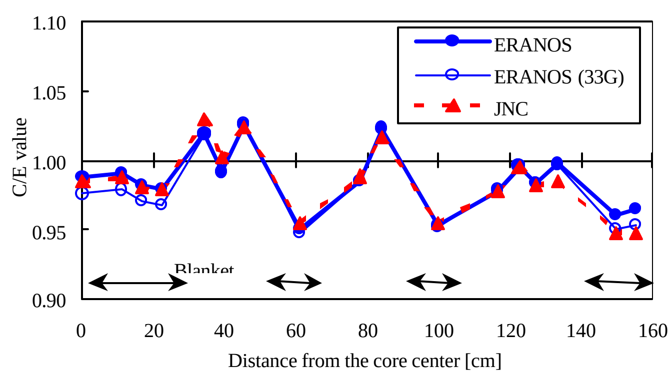
- F49; Pu-239 fission -



- F25; U-235 fission -



- F28; U-238 fission -



- C28; U-238 capture -

Fig. 3-2 The results of the reaction rate distribution analyses for ZPPR-13A

ZPPR-13A: Figure 3-2 shows the results of the 4-types of the ZPPR-13A reaction rate distribution analyses using ERANOS and the JNC system. The reference ERANOS evaluated F49 and F25 well, while the JNC system and ERANOS with 33-groups underestimated considerably them in the blanket region. Therefore, it is considered that the fine groups cell calculation is very effective for good evaluation of the reaction rate in the blanket region. On the other hand, ERANOS overestimated F28 in the blanket region whether the fine groups cell calculation was applied or not. However, the reason for the overestimation has not been clarified, and the further investigation is required. Concerning C28, results by ERANOS and the JNC system agreed well with each other, and all methods underestimated C28 in the blanket region. C28 is more sensitive than F49 and F25 to the resonance energy range of structural materials (5 through 100keV), therefore it is considered that there is a room for improvement of all methods in the evaluation of flux in this energy range.

As above mentioned the evaluated reaction rate in the blanket region was discrepant among the reference ERANOS, ERANOS with 33-groups and the JNC system. This discrepancy might affect other parameters as shown in the result of criticality analyses (See Fig. 1), i.e. it was observed that the above three methods showed discrepant results for ZPPR-13A while agreed well for ZPPR-9. Thus parameters are sensitive to the flux in the "internal" blanket and accuracy of its evaluation is essential.

The difference of results by ERANOS between with JEF2.2 and with ERALIB1 was negligible for both ZPPR-9 and ZPPR-13A, therefore they were omitted in Fig. 3-1 and 3-2.

3.3 REACTION RATE RATIO (SPECTRUM INDEX)

Figure 4 shows the results of analyses of the 3-types of reaction rate ratio for ZPPR-9 and 13A. Results by ERANOS and the JNC system agreed well with each other and all discrepancies of C/E value from 1.0 were less than total uncertainties shown in Table 2.

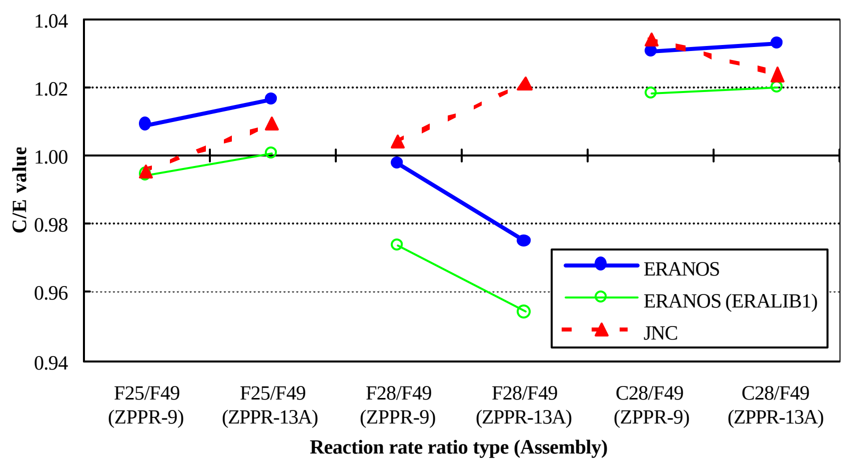


Fig. 4 Summary of results of the reaction rate ratio analyses for ZPPR-9 and ZPPR-13A

The use of ERALIB1 shifted generally C/E values to 1.0.

3.4 SAMPLE DOPPLER REACTIVITY

Figure 5 summarizes the C/E values of the ZPPR-9 sample Doppler reactivity obtained by ERANOS and the JNC system. The C/E values produced by ERANOS were 0.90 through 0.94, while the JNC system underestimated by more than 15%. The use of the fine groups cell calculation raised amount of reactivity by 3 through 6%, depending on the temperature change, and it did not compensate the large underestimation by the JNC system. Thus the basic cause of such underestimation in the JNC results has not been clarified yet.

The use of ERALIB1 worsened the result by 4%. The investigation clarified that the 4% -shift was not only due to the difference of the capture cross section but also due to the difference in flux contribution, i.e. the flux distribution calculated with ERALIB1 estimated smaller amount of reactivity than that obtained with JEF2.2.

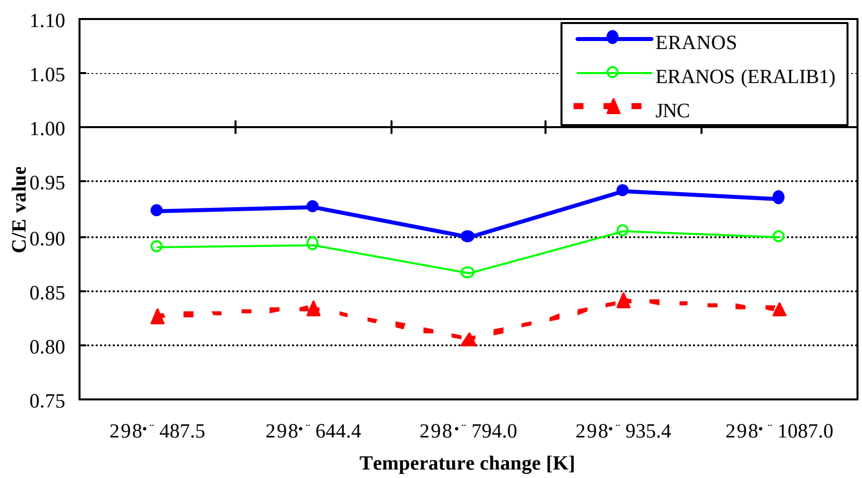


Fig. 5 Summary of results of the ZPPR-9 sample Doppler reactivity analyses

3.5 SODIUM VOID REACTIVITY

Figure 6 shows the comparison of analytical results of sodium void reactivity for ZPPR-9 void step 1 through 6 and ZPPR-13A step 3. The void region had been expanded according to the increase of step number. ERANOS produced 0.86 through 1.02 in C/E value for ZPPR-9, and agreed well with the JNC system. However, for ZPPR-13A, the JNC system overestimated by 20% though the reference ERANOS calculated 0.96 of C/E value. The large overestimation by the JNC system was not due to the lack of the fine groups cell calculation as ERANOS with 33-groups did not overestimate, and the reason for such overestimation has not been clarified.

On the other hand, the use of ERALIB1 worsened the results and the reason for the change has been tracked back to an insufficient adjustment of the sodium cross sections.

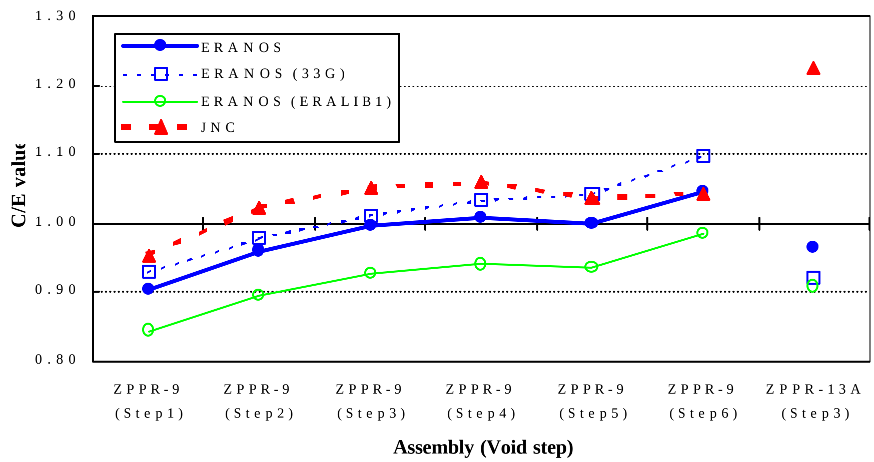


Fig. 6 Summary of results of the sodium void reactivity analyses for ZPPR-9 and ZPPR-13A

3.6 CONTROL ROD WORTH

Figure 7 shows the results of ZPPR-9 pair control rod analyses using ERANOS and the JNC system. The systematic discrepancy of C/E values was observed between ERANOS and the JNC system, but it is due to the 4% difference of calculated effective delayed neutron fraction (β_{eff} value). Except for the contribution of the β_{eff} difference, ERANOS with both libraries and the JNC system agreed well with each other and C/E values produced by them were approximately 1.0.

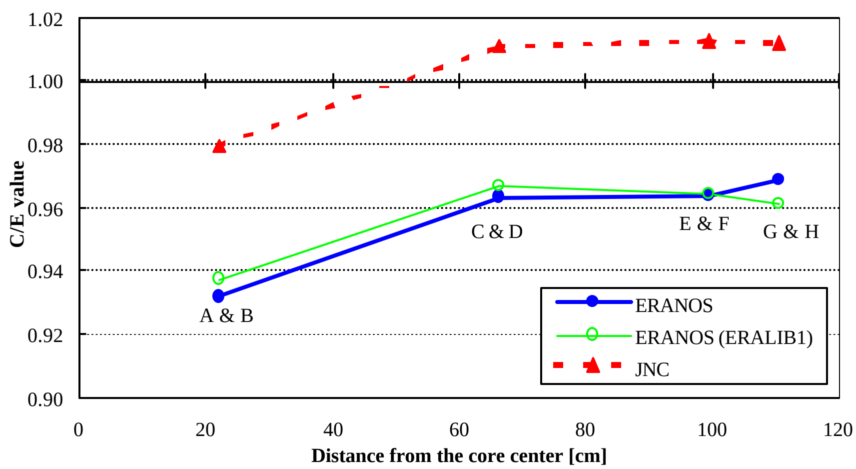


Fig. 7 Summary of results of the ZPPR-9 control rod worth analyses

4. CONCLUSION

An analysis of the JUPITER experiment using the ERANOS system has been performed, and the results of this analysis were compared with those obtained by the JNC system.

Comparisons between calculations and experiments showed good agreement. Generally the results by ERANOS agreed well with those by the JNC system. The use of the ERALIB1 adjusted library improved almost all the results, but there is a room for improvement concerning sodium void reactivity. Further, it is confirmed that the fine groups library and related cell calculation is very effective for a precise analysis of the parameters that are sensitive to the flux in the blanket region. Therefore it is judged that the ERANOS system has good performance to evaluate the parameters of large fast reactor cores.

Concerning the JNC system, the incorporation of much finer groups constant set would be effective for the improvement of accuracy. In addition further investigation is required in analyses of the sample Doppler reactivity and the sodium void reactivity.

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