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# IMPLICATIONS OF JUPITER EXPERIMENT ANALYSIS IN NUCLEAR DATA

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Abstract: Critical assembly experiments on large fast breeder reactor were analyzed by a current neutronics analysis method for fast reactor core ,using a group constant set based on the JENDL-2 library[1]. It was made clear that there were some radial dependence of C/E(Calculation/Experiment) values for integral physics parameters, in addition to discrepancies between calculation and experiment. A cross section sensitivity analysis was conducted on the assembly to investigate sources of the radial dependence and discrepancies. The result showed that absolute values of sensitivities to the $^{239}$Pu fission and $^{238}$U capture cross sections were overwhelmingly large for most of integral physics parameters, compared with other cross sections. Next, the group constant set was adjusted by using these sensitivity coefficients and the C/E values. As the result of adjustment, the $^{239}$Pu fission cross section was increased by 2% for the energy range below 10keV, and the $^{238}$U capture cross section was decreased by about 6% for the 1keV-1MeV range.

(Fast Critical Experiment, Integral Physics Parameter,Neutronic Analysis, Sensitivity Coefficient, Cross Section Adjustment,JENDL-2 library,$^{238}$U Capture Cross Section)

## Introduction

Neutronics analysis methods for fast reactor core have been developed in Japan to support the national project on Liquid Metal Fast Breeder Reactor(LMFBR). From the standpoint of core design for large LMFBR, it is required to reduce the uncertainties for core design parameters, such as criticality, control rod reactivity worth and power distribution. Critical assembly experiments on large fast breeder reactor have been conducted to provide integral data on physics parameters. Integral data have been analyzed by the core analysis methods to confirm the prediction accuracies. In case of large cores, it was observed that C/E values for control rod reactivity worths and reaction rate distributions had tendencies to become higher gradually along with core radius, in addtion to some usual C/E discrepancies from unity which had been observed in case of small and intermediate cores. Results of analysis of integral data on large fast critical assemblies are presented.

As an attempt to investigate causes of radial dependence of C/E values and of other C/E discrepancies from unity, a sensitivity analysis was applied to the large fast critical assembly, using the cross section set of the core analysis method. Sensitivity coefficients are presented, and sources of the radial dependence and discrepancies are discussed.

A cross section adjustment was performed not only so that the radial dependence of C/E values might be solved, but also so that other C/E discrepancies from unity might be minimized at the same time. Based on the results of cross section adjustment, feedbacks and recommendations to nuclear data from integral experiments are discussed.

## Analysis of Integral Experiments

The JUPITER(Japanese-United States Program of Integral Tests and Experimental Researches) program[3] is the joint physics large LMFBR core critical experiment program between U.S. DOE and PNC, Japan, using the ZPPR facility at ANL-Idaho. ZPPR-9 and -10, assembled for the JUPITER-I program, were conventional homogeneous two-zone cores of 650~850 MWe-size. ZPPR-9 was a clean physics benchmark, and ZPPR-10 was a series of engineering benchmarks with hexagonal core boundary, i.e., ZPPR-10A through -10D, that included control rod positions and/or control rods. Sectional views of the cores are shown in Figure 1. Physics characteristics of large LMFBR cores were measured on these assemblies, and were analyzed in Japan by a current core analysis method, using the JFS-3-J2 cross section set[4]. JFS-3-J2 is a Bondarenko-type 70-group constant set, processed from the JENDL-2 library.

Results of analysis are summarized in Table 1 for main physics parameters. The criticality

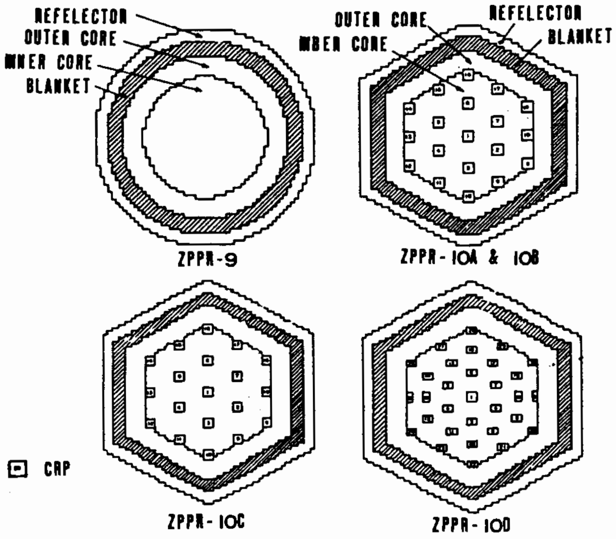

Fig. 1 Sectional views of ZPPR-9 and -10

is predicted fairly well for all assemblies, and the difference in C/E value between assemblies is less than 0.4%, in spite of their different core sizes and different control rod patterns. The C/E value for control rod reactivity worth is from 0.92 to 1.06. However, it is observed that the C/E value becomes higher with core radius, and the C/E value for the outermost ring is 4~12% higher than that for the central rod. As for the reaction rate ratio, C/E values for F5/F9($^{235}$U fission/$^{239}$Pu fission), C8/F9 and F8/F9 are 1.03~1.06, 1.05~1.10 and 0.97~1.01, respectively. An overprediction of C8/F9 by 5~10% is observed, as was expected. The reaction rate distribution of $^{239}$Pu fission shows a tendency of C/E value to become higher with core radius. The point-by-point C/E value became higher gradually with radius up to about 6% at the outer core relative to the core center. Approximately same tendencies were also observed for $^{235}$U fission, $^{238}$U fission and $^{238}$U capture rate distributions. These radial distributions of C/Es for reaction rates are roughly consistent with that for control rod reactivity worth, provided that the control rod reactivity worth error is proportional to twice the reaction rate error.

Table 1 C/E Values for Physics Parameters of ZPPR assemblies

| Physics Parameter | | Assembly Number | | C/E |
|---|---|---|---|---|
| Criticality | | 9 | | 0.9994 |
| | | 10A | | 0.9962 |
| | | 10B | | 0.9962 |
| | | 10C | | 0.9965 |
| | | 10D | | 0.9958 |
| | | 10D/1 | | 0.9958 |
| | | 10D/2 | | 0.9977 |
| Control Rod Worth | | 10A | Central | 0.951 |
| | | | Ring 1 | 0.947 |
| | | | Ring 2 | 0.988 |
| | | 10C | Central | 0.920 |
| | | | Ring 1 | 0.946 |
| | | | Ring 2 | 1.003 |
| | | 10D | Central | 0.943 |
| | | | Ring 1 | 0.954 |
| | | | Ring 2 | 1.003 |
| | | | Ring 3 | 1.064 |
| Reaction Rate Ratio | F5/F9 | 9 | | 1.027 |
| | | 10A | | 1.049 |
| | | 10B | | 1.020 |
| | | 10C | | 1.027 |
| | | 10D | | 1.057 |
| | C8/F9 | 9 | | 1.070 |
| | | 10A | | 1.058 |
| | | 10B | | 1.096 |
| | | 10C | | 1.052 |
| | | 10D | | 1.088 |
| | F8/F9 | 9 | | 0.988 |
| | | 10A | | 0.989 |
| | | 10B | | 0.974 |
| | | 10C | | 0.968 |
| | | 10D | | 1.009 |
| Reaction Rate Distribution ($^{239}$Pu fission) | | 9 | IC,inner | 1.009 |
| | | | IC,outer | 1.029 |
| | | | OC | 1.041 |
| | | 10A | IC,inner | 1.018 |
| | | | IC,outer | 1.020 |
| | | | OC | 1.031 |
| | | 10C | IC,inner | 1.010 |
| | | | IC,outer | 1.023 |
| | | | OC | 1.031 |
| | | 10D | IC,inner | 1.010 |
| | | | IC,outer | 1.019 |
| | | | OC | 1.031 |

IC,inner: the inner half of inner core
IC,outer: the outer half of inner core
OC: outer core

## Sensitivity Analysis

A sensitivity analysis was employed to investigate the sources of radial dependence of C/Es and of C/E discrepancies from unity. Nuclear data sensitivities for the integral physics parameters for ZPPR-9 were calculated with the generalized perturbation theory code SAGEP[5]. The RZ-model diffusion calculations were done using the 16 energy group cross sections to obtain the real and adjoint fluxes, which were used for the sensitivity calculation.

Total(energy-integrated) sensitivity coefficients to the reaction cross sections of major nuclides for ZPPR-9 were calculated for keff, control rod worth, Na void worth, reaction rate ratio and reaction rate distribution, and were given in Table 2. Though the ZPPR-9 core contained very low density of $^{235}$U, sensitivities to $^{235}$U cross sections were calculated so that the F5/F9 result could be used in the cross section adjustment. It is apparent from Table 2 that absolute values of sensitivities to $^{239}$Pu fission and $^{238}$U capture cross sections are overwhelmingly large for most of the physics parameters, compared with other cross sections. Sensitivities to $^{238}$U capture cross section are 0.9, 6.2 and 22.3 percents for reaction rate at IC inner, IC outer and OC, respectively. It means that if $^{238}$U capture cross section is decreased, then the tendency of C/E to become higher with core radius will be mitigated. On the other hand, sensitivities to $^{239}$Pu fission cross section are nearly zero for all the reaction rates at IC inner, IC outer and OC. So, any change in $^{239}$Pu fission cross section will not contribute to solve the tendency of C/E to become higher with core radius. It is also noted from Table 2 that sensitivities to scattering cross sections of $^{238}$U, Fe, Na and O are comparatively large negative values for Na void worth and for the center CR worth.

## Cross Section Adjustment

C/E values to be used for the cross section adjustment were selected from those listed in Table 1, because too many C/E values of different reliabilities or a random conbination of different kinds of C/E values do not necessarily result in a reasonable adjustment. An important point of the present adjustment is to solve the radial dependence of C/E values for control rod worth and reaction rate, as well as to minimize the C/E discrepancies from unity for various physics parameters.

Table 3 lists the C/E values before and after the adjustment. The 8% overprediction for C8/F9 was reduced to 3%. The radial dependence of C/E for control rod worth of about 13% is perfectly eliminated after the adjustment[6]. The

Table 2 Sensitivity Coefficients for $k_{eff}$,Control Rod Reactivity Worth,Na Void Reactivity Worth, Reaction Rate Ratio and Reaction Rate Distribution for ZPPR-9 (x$10^{-2}$)

| | | $k_{eff}$ | CR Worth Center | CR Worth Ring 2 | Na Void Worth | Reaction Rate Ratio F5/F9 | Reaction Rate Ratio C8/F9 | Reaction Rate Ratio F8/F9 | Reaction Rate (F9)* IC inner | Reaction Rate (F9)* IC outer | Reaction Rate (F9)* OC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | -6.4 | -6.4 | -2.6 | 33.7 | -2.7 | -1.8 | 8.0 | 0.1 | 0.6 | 2.3 |
| $^{239}$Pu | F | 58.3 | -55.6 | -56.7 | -88.3 | -105.3 | -105.8 | -79.3 | -0.0 | 0.0 | 0.3 |
| | S | -0.1 | -2.4 | -0.3 | -1.7 | 0.3 | 0.4 | -1.8 | 0.1 | 0.3 | 0.6 |
| | C | -25.7 | -42.5 | 3.0 | 50.9 | -10.2 | 88.8 | 32.6 | 0.9 | 6.2 | 22.3 |
| $^{238}$U | F | 9.4 | -16.6 | -23.1 | 4.6 | 0.1 | 0.3 | 96.7 | -0.1 | -0.7 | -2.1 |
| | S | -3.7 | -40.7 | 4.0 | -37.9 | 5.7 | 9.3 | -37.2 | 0.9 | 5.4 | 14.1 |
| | C | -0.1 | -0.3 | 0.0 | 0.4 | -0.1 | -0.0 | 0.2 | 0.0 | 0.0 | 0.1 |
| $^{235}$U | F | 1.0 | 0.2 | -1.4 | -1.9 | 100.0 | -0.1 | 0.5 | -0.0 | -0.3 | -0.4 |
| | S | 0.0 | -0.1 | 0.0 | 0.1 | 0.0 | 0.0 | -0.1 | 0.0 | 0.0 | 0.0 |
| Fe | C | -1.6 | -1.9 | 0.2 | 4.0 | -0.6 | -0.6 | 1.7 | 0.0 | 0.3 | 1.1 |
| | S | -1.2 | -23.7 | -1.5 | -20.0 | 3.2 | 3.7 | -17.8 | 0.5 | 2.9 | 5.9 |
| Na | C | -0.2 | -0.4 | 0.1 | 6.2 | -0.1 | -0.1 | 0.2 | 0.0 | 0.1 | 0.2 |
| | S | -1.0 | -19.5 | -3.5 | 57.1 | 4.0 | 2.5 | -10.4 | 0.4 | 2.2 | 3.5 |
| O | C | -0.2 | -0.0 | 0.2 | -0.8 | 0.0 | 0.0 | -0.3 | 0.0 | 0.0 | 0.1 |
| | S | -1.9 | -39.7 | -5.8 | -32.3 | 7.8 | 8.1 | -6.1 | 0.7 | 4.4 | 9.3 |

C :Capture  F :Fission  S :Scattering
*Relative reaction rate normalized at core center

Table 3 C/E Values Before and After Adjustment

| Physics Parameter | Assembly Number | C/E Before | C/E After |
|---|---|---|---|
| $k_{eff}$ | 9 | 0.999 | 1.003 |
| | 10A | 0.996 | 1.003 |
| | 10D | 0.996 | 0.998 |
| CR Worth | 10D(Center) | 0.943 | 0.990 |
| | (Ring 3) | 1.128* | 1.003 |
| Reaction Rate Ratio | 9 25F/49F | 1.027 | 1.006 |
| | 28C/49F | 1.070 | 1.011 |
| | 28F/49F | 0.988 | 1.014 |
| | 10D 25F/49F | 1.057 | 1.036 |
| | 28C/49F | 1.088 | 1.030 |
| | 28F/49F | 1.009 | 1.033 |
| Reaction Rate Distribution (F9) | 9 (IC,inner) | 1.009 | 1.006 |
| | (IC,outer) | 1.029 | 1.015 |
| | (OC) | 1.041 | 1.015 |
| | 10A(IC,inner) | 1.018 | 1.016 |
| | (IC,outer) | 1.020 | 1.008 |
| | (OC) | 1.041 | 1.011 |
| | 10D(IC,inner) | 1.010 | 1.004 |
| | (IC,outer) | 1.019 | 0.997 |
| | (OC) | 1.031 | 0.986 |

(IC,inner) :the inner half of inner core
(IC,outer) :the outer half of inner core
(OC) :outer core
*C/E for the ratio of ring 3 control rods to center control rod

spatial discrepancies of the $^{239}$Pu fission rate distribution of 4% and 3% for ZPPR-10A and 10D are reduced to within 2% after the adjustment. Thus the remarkable disagreement between calculation and experiment has been significantly improved by the adjustment.

Table 4 lists the relative change of cross sections before and after the adjustment. The $^{239}$Pu fission cross section was decreased by about 1% above 10keV and was increased by about 2% below 10keV. The $^{238}$U capture cross section was decreased by about 6% for the 1keV∿1MeV range. The $^{238}$U fission cross section was decreased by about 0.4%. The solution of radial dependence of C/E for control rod worth and the mitigation of radial dependence of C/E for reaction rate are the results of 6% decrease of $^{238}$U caputure cross section.

Table 4 Cross Section Change due to Adjustment(%)

| Group No. | Upper Energy | U-238 Capture | U-238 Fission | Pu-239 Capture | Pu-239 Fission |
|---|---|---|---|---|---|
| 1 | 10.0MeV | -17.0 | -0.7 | 2.7 | -0.6 |
| 2 | 6.1 | -1.9 | -0.8 | 2.7 | -0.7 |
| 3 | 3.7 | -0.1 | -0.8 | 2.7 | -1.0 |
| 4 | 2.2 | -3.2 | -0.6 | 2.7 | -0.9 |
| 5 | 1.4 | -10.3 | -0.5 | 4.7 | -1.3 |
| 6 | 820keV | -6.3 | -0.3 | 2.9 | -1.9 |
| 7 | 390 | -4.4 | -0.2 | 4.2 | -1.6 |
| 8 | 180 | -3.3 | -0.1 | 6.0 | -1.2 |
| 9 | 87keV | -2.6 | -0.0 | 1.1 | -0.7 |
| 10 | 41 | -6.5 | -0.3 | 3.4 | -0.5 |
| 11 | 19 | -9.1 | -0.4 | 3.3 | -0.4 |
| 12 | 9.1keV | -7.6 | -0.4 | 3.8 | 2.3 |
| 13 | 4.3 | -6.6 | 0.0 | 7.3 | 2.3 |
| 14 | 2.0 | -6.3 | -0.4 | 10.3 | 2.3 |
| 15 | 96eV | -4.0 | -0.4 | 5.6 | 2.3 |
| 16 | 45 | -0.2 | -0.4 | -0.3 | 2.3 |

## Conclusion

A sensitivity analysis was conducted on large fast critical assemblies to investigate the sources of C/E discrepancies from unity for integral physics parameters. The result showed that the $^{239}$Pu fission and $^{238}$U capture cross sections had overwhelmingly large values of sensitivities for most of physics parameters, compared with other cross sections.

A fast reactor group constant set based on the JENDL-2 library was adjusted by using these sensitivities and integral data from the fast critical experiment analysis. As the result of adjustment, the $^{239}$Pu fission cross section was increased by 2% for the energy range below 10keV.

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