PHYSOR 2004 -The Physics of Fuel Cycles and Advanced Nuclear Systems: Global Developments
Chicago, Illinois, April 25-29, 2004, on CD-ROM, American Nuclear Society, Lagrange Park, IL. (2004)

Reduction of Cross-Section-Induced Errors of the BN-600 Hybrid Core Nuclear Parameters by Using BFS-62 Critical Experiment Data

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The present paper provides evaluation results of predicted uncertainty on nuclear parameters of the BN-600 hybrid core, a feasible option for Russian surplus weapons plutonium disposition. Covariance data for nuclear group constants, analysis errors, as well as experimental errors are considered to predict the uncertainties by applying the nuclear group constant adjustment method. Analysis results of BFS-62 mockup together with other fast reactor core experiments are reflected in the evaluation.

KEYWORDS: weapons plutonium disposition, MOX fuel, BN-600 hybrid core, BFS-2 facility, BFS-62 experiment, adjustment method, prediction uncertainty.

1. Introduction

In order to support the Russian surplus weapons plutonium disposition, Japan Nuclear Cycle Development Institute (JNC) has performed a collaborative research with Russian Institute of Physics & Power Engineering (IPPE) between 1999 and 2003. In the collaboration, a series of measurements was conducted in BFS-2 facility assembling several core configurations that simulate nuclear characteristics of the possible BN-600 core transition. Successively, by reflecting JNC's experimental analysis results of both the BFS-62 and other fast critical assemblies, uncertainties of key nuclear parameters on the BN-600 hybrid core were predicted by the nuclear group constant adjustment method, as well as the bias correction method. Effects of cross-section covariance changes on the uncertainties and comparison of predicted uncertainties among different approaches are mainly discussed.

2. BFS-62 Critical Experiment and the Analysis

2.1 BFS-62 Critical Experiment [1]

In the collaboration, measurements were done in six assemblies. The first four (BFS-62-1, 2, 3A and 4, referred generically as "BFS-62" in this paper) assemblies simulate the transition from the existing uranium dioxide (UO_2) fuelled core to so-called "hybrid core", where approximately 20% of the UO_2 fuel would be replaced by the uranium-plutonium mixed oxide (MOX) fuel and all the surrounding UO_2 blanket assemblies by stainless steel (SS) reflectors. Features of the BFS-62 assemblies are listed in Table 1. Various nuclear parameters including the criticality, fission rate ratio at the core center, fission reaction rate distribution both in radial and axial directions, control rod worth (CRW), and sodium void reactivity worth (SVRW), were measured.

2.2 Nuclear Characteristics Comparison between BFS-62-3A and BN-600 Hybrid Core

Nuclear characteristics of the BFS-62-3A are compared with those of the BN-600 hybrid

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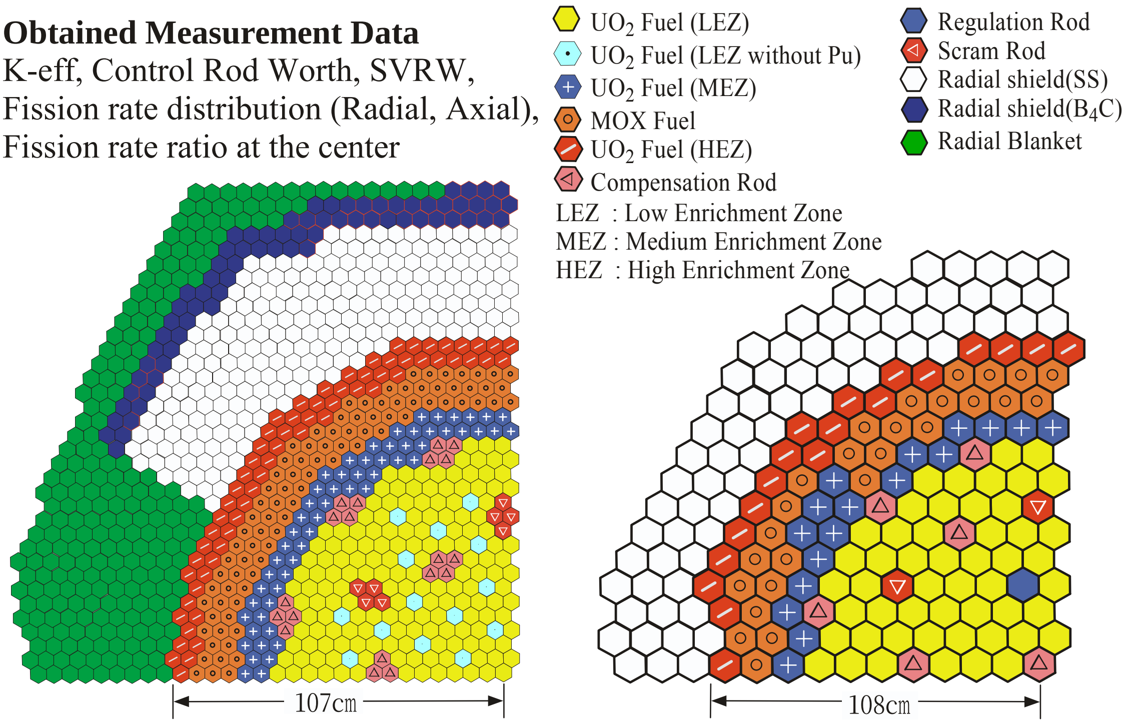
core, in order to clarify the significance of the measurement data. As shown in Fig. 1, good similarity is found for the radial dimension and layout of the core, in terms of the equivalent radius, as well as four types of fuel regions and the peripheral reflector arrangement. Good similarity is also confirmed for the axial configuration, in terms of the fuel height (approx. 104cm) accompanied with the upper/lower blanket and reflector arrangement. Fissile amounts in the fuel regions are slightly larger in the hybrid core because of the necessity for compensating temperature and burnup reactivity loss, while approximately same percentage of fission neutron generation in each fuel region of both cores is confirmed, suggesting essentially same fission reaction rate distribution. Control rod (CR) locations are well simulated and the differences of the worth are within 4% between two cores. Also confirmed are similar values of fission rate ratios ($^{238}U/^{235}U$, $^{239}Pu/^{235}U$), suggesting similar neutron energy spectra.

Table 1 Configurations and objectives of BFS-62 assemblies in JNC-IPPE collaboration

No.	Fuel Zones	Surrounding Zones	Main Objective
62-1	UO_2	UO_2 Blanket	Mock-up of the Existing BN-600 core
62-2	UO_2	SS Reflector	Replacement effect of UO_2 Blanket by SS Reflector
62-3A	UO_2+MOX	SS Reflector	Mock-up of the BN-600 Hybrid core
62-4	UO_2+MOX	UO_2 Blanket	Replacement effect of SS Reflector by UO_2 Blanket



(a) BFS-62-3A assembly in BFS-2 **(b) BN-600 hybrid core**

Fig.1 Comparison of horizontal layout between BFS-62-3A and BN-600 hybrid core

One item to be noted is relatively negative SVRW measured in BFS-62-3A than that calculated in the BN-600 hybrid core, as shown in Table 2. The significant difference in SVRW is mainly due to temperature and CR axial position differences. It surely suggests both difficulty in applying the bias correction method and possible effectiveness of the nuclear constant adjustment method, in decreasing predicted uncertainty of SVRW of the BN-600 hybrid core by reflecting BFS-62-3A measurement data.

Table 2 Comparison of SVRW*1 between BFS-62-3A and BN-600 hybrid core

(Unit in cent)

Sodium-voided*2 region	(a) BFS-62-3A	(b) BN-600 Hybrid core	Difference (a)-(b)
LEZ	-7.3	+7.1	*-14.4*
MEZ	-2.1	+0.7	*-2.8*
MOX	-5.4	-1.9	*-3.5*
HEZ	-10.3	-9.6	*-0.7*
All Fuel Regions	-22.1	-3.7	*-18.4*

*1 Exact perturbation theory based on diffusion calculation values using 3-D Hex model
*2 Sodium voided at 60-degree sector in all the fuel regions & those upper blanket regions

2.3 Analysis of BFS-62 Critical Experiment

2.3.1 Analysis Method

In the JNC's analysis, 70-energy-grouped nuclear constant set based on JENDL-3.2 (JFS-3-J3.2R) [2] was used for the standard scheme. The self-shielding effect was considered by the factor table interpolation method. One-dimensional (1-D) heterogeneous cell calculations were performed with a consideration of the background cross section evaluated by the collision probability density calculation. Whole core diffusion calculation was made by the CITATION-FBR code [3] with 3-D Hex-Z model, adopting the anisotropic diffusion coefficient. Transport and mesh-size corrections were made by using the MINIHEX (3-D, Hex-Z geometry) [4], or the TWOTRAN-II code (2-D R-Z geometry) [5]. In order to obtain more accurate treatment of the resonance interaction, additional analyses were made by adopting a newly developed nuclear constant set, consisting of the basic and fine parts. The VITAMIN-J 175-group structure [6] was used for the basic part. The fine part is for the energy range below 40.8keV, and the cross sections were produced by collapsing calculation results adopting more than 90,000 energy group structure. This new constant set is called UF (Ultra fine)-175 in this paper.

2.3.2 Analysis Results

Analyses on BFS-62 experiments were conducted by both JNC and IPPE independently, and good agreement with measurement in general was confirmed and reported in the previous conference [7]. Summarized JNC's results are shown in Table 3.

Table 3 Summary Results of BFS-62 assemblies by JNC's analysis system

Nuclear Parameter	**Difference* from Measurement**	**Note**
Criticality	0.4 - 0.5% underestimation	Improved by ～0.2% by UF-175
CRW	Within 6%	-
SVRW	15 - 30% underestimation	Within 10% after correction by UF-175
Fission Rate Distribution	Within ～5% for ^{235}U and ^{239}Pu, within ～10% for ^{238}U in fuel region	More than 20% overestimation in SS reflector region for ^{235}U and ^{239}Pu
Fission Rate Ratio	Within 3%	-

*; Based on analysis results obtained by the standard scheme

3. Procedure for Evaluation of Prediction Uncertainty

3.1 Evaluation Methods Employed for Predicting Uncertainty

In the present evaluation, three methods are employed for predicting uncertainties of nuclear parameters. The first method (referred as "Non-Exp. method") is to predict uncertainties for calculated values without reflecting any experimental analysis results.

The second one is the bias correction method, in which calculation-to-experiment (C/E) value of mock-up core (mainly BFS-62-3A core) would be utilized for correcting calculated values on the BN-600 hybrid core. The third one is the nuclear group constant adjustment method, in which the constants and those covariance would be adjusted so as to maximize the probability that the constants could give more reasonable analysis values comparing with the measurement values, based on the Bayesian theory. Predicted uncertainties for the three methods are expressed as shown in Table 4 [8].

Table 4 Predicted uncertainty of each method

Method	Predicted Uncertainty
Non-Exp.	$GMG^t + Vm$
Bias Correction	$\Delta GM\Delta G^t + \Delta Vm + Ve$
Group Constant Adjustment	$GM'G^t + Vm - A$ Here, $M' = M - MG^{(1)t}(G^{(1)}MG^{(1)t} + Ve^{(1)} + Vm^{(1)})^{-1}G^{(1)}M$

M, M' ; Covariance [9] of the basic nuclear constant before / after the adjustment
R ; Nuclear Characteristics, σ ; Cross-section
G ; Sensitivity coefficient of the target core ≡ $(dR/R)/(d\sigma/\sigma)$
Δ ; Difference between the target core & mock-up core
Ve ;Experimental error of the mock-up core, Vm ;Analysis error of the target core
(1) ; Group of critical experiment data used for the adjustment
A ; Value defined by correlation between critical experiment cores and the target core

Nominal values and analysis errors for each of nuclear parameters on the BN-600 hybrid core are calculated using a 3-dimensional HEX-Z model that has been employed in an IAEA project [10]. The model is established for representing a beginning of equilibrium cycle. The applied analysis scheme is essentially same as that described in 2.3.1. Accounted analysis errors include the ones from transport and mesh corrections as well as differences between UF-175 calculation results and the standard scheme ones. Experimental errors for BFS data were derived from IPPE's evaluation [1].

Table 5 List of fast reactor core data used for nuclear group constant adjustment

Fast Cores	keff	CRW	SVRW	RRD*1	RRR*2	Others	Features
ZPPR-9, 10	7	17	13	40	28	18	Middle size, MOX, 2-zone homo.
ZPPR-13	5	-	-	-	-	2	Middle size, MOX, Radial hetero.
ZPPR-17～19	7	18	1	26	17	-	Middle size, MOX, Axial hetero. Large 2-zone homo.（partial EU）
FCA	2	-	3	-	2	2	Small size , MOX & EU, with SS reflector
JOYO MK-I	1	-	-	-	-	6	Small size, MOX & EU, with UO2 blanket
MASURCA	-	-	-	-	-	2	High enriched MOX、 with SS reflector
BFS-58-1-I1	1	-	2	-	3	-	Large size, MOX, with U-free zone in the central
Los Alamos	5	-	-	-	-	-	Very small size, （EU, Pu, some with SS reflector）
BFS-62	4	24	7	45	8	-	Middle size, EU & partial MOX, small SVRW

*1; Reaction Rate Distribution *2; Reaction Rate Ratio

3.2 Used Data for Nuclear Group Constant Adjustment

316 in total experimental analysis data obtained for a variety of fast reactor cores, registered in JNC's database, including 88 from BFS-62 assemblies, were used for performing nuclear group constant adjustment, as shown in Table 5. Two sets of adjustment calculations were performed. All the data except BFS-62 ones were used in the first set (228 data in total), while truly all the data were used in the second set (316 data). The two sets

are named as “w/o BFS-62” and “with BFS-62” in the paper, respectively.

4. Results and Discussion on Predicted Uncertainty

4.1 Predicted Uncertainty of Nuclear Parameters on the BN-600 Hybrid Core

Uncertainties of nuclear parameters on the BN-600 hybrid core predicted by four methods are listed in Table 6. The values are equivalent to the standard deviation (one sigma) of the calculated nominal values of each parameter, and the units are the relative percentage. BFS-62-3A core is basically applied as the mock-up core in the bias correction method, however, due to lack of appropriate data, ZPPR-9 and JOYO MK-I core are tentatively applied as the mock-up core for Doppler reactivity and burn-up reactivity loss, respectively. Predicted uncertainties of SVRW for all the fuel regions (including their axial blankets) show large values exceeding 100%, because the nominal value is nearly zero. Adjusted values of cross sections do not show any excessive adjustment when considering those standard deviations. Furthermore, employing BFS-62 data does not cause significant degradation on C/E values of the other fast reactor cores. It means good consistency among various fast reactor core data used in the adjustment process.

Table 6 Predicted uncertainties of nuclear parameters on the BN-600 hybrid core

(Unit; relative % to the nominal value)

Nuclear Parameters \ Prediction Method	Non-Exp.	Bias Correction	Group Constant Adjustment	
	JFS-3-J3.2R		w/o BFS-62	with BFS-62
Criticality (k-eff)	0.87	0.33	0.27	0.21
F28*/F25 reaction rate ratio (core center)	4.9	2.2	2.5	1.2
F49/F25 reaction rate ratio (core center)	1.3	1.7	0.4	0.4
F25 reaction rate (LEZ, MEZ, MOX, HEZ)	0.5 - 4.7	2.6 - 4.4	0.2 - 1.5	0.2 - 1.0
F28 reaction rate (LEZ, MEZ, MOX, HEZ)	0.5 - 5.5	3.8 - 6.0	0.3 - 2.5	0.3 - 1.7
F28 reaction rate (SS Reflector region)	24.4	13.6	11.0	5.6
SVRW (LEZ region + Axial blanket)	20.3	66.6	16.0	13.9
SVRW (All fuel region + Axial blanket)	252	265	153	120
Control Rod Worth (core center)	6.0	3.3	2.1	1.2
Doppler Reactivity (Fuel 1500K->2100K)	11.8	10.7	8.2	8.1
Burnup reactivity loss (140 days operation)	4.0	5.8	2.1	1.7

* F; fission reaction, 28; ^{238}U, 25; ^{235}U, 49; ^{239}Pu

4.2 Comparison of Uncertainties among Prediction Methods

Several features are observed in Table 6. The group constant adjustment method shows remarkable reduction in uncertainties for all the parameters, comparing with both the Non-Exp. and the bias correction method. From the comparison of two sets of the adjustment results, it is confirmed that BFS-62 data make significant contribution toward decreasing the uncertainties. It suggests the importance of BFS-62 data for improving design accuracy on BN-600 hybrid core. As for the bias correction method, significant reduction in uncertainties is observed for certain parameters including the criticality, the center CRW, etc. for which good similarity of the sensitivity coefficients is confirmed. However, essentially same or even worse uncertainties than those which resulted from Non-Exp. method are observed for the SVRW, F49/F25 and burn-up reactivity. The reasons for the degradation include less good similarity of nuclear characteristics between mock-up cores and the BN-600 hybrid core, as well as relatively large experimental or analysis error. By checking the relationships of nominal values accompanied with the uncertainties among four methods, it can be confirmed that the adjustment results with BFS-62 data give more accurate values within the standard deviation comparing to the predicted by Non-Exp. method. One example is shown in Fig. 2 for SVRW (sodium-voided in all fuel regions and the axial blanket). Remarkable reduction in the uncertainty by the adjustment method can help verify the SVRW unlikely to exceed +1$, a design target of the BN-600 hybrid core.

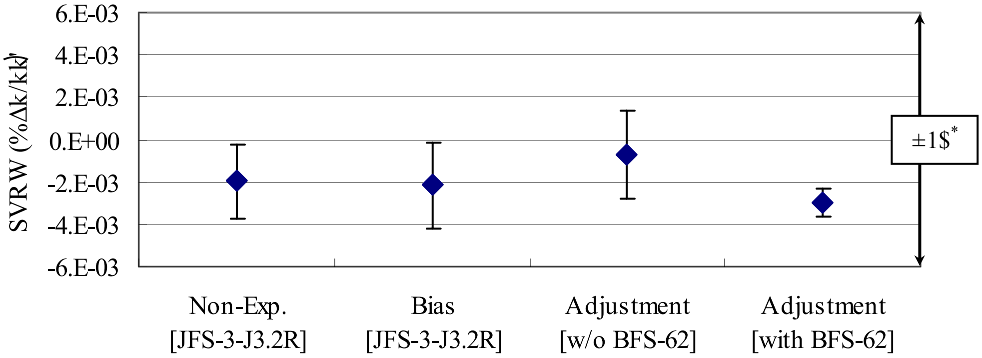


Fig. 2 Nominal values and the predicted uncertainties for SVRW (Sodium-voided in all fuel region & the axial blanket) [* $\beta eff = 5.87\times10^{-3}$]

5. Investigation on Reduction of Cross-Section-Induced Errors

5.1 Breakdown of Predicted Uncertainty into Nuclides & Reactions

Significant reduction in predicted uncertainty by the adjustment method is caused by the adjustment of the covariance data of the nuclear constants (that is, M → M' in Table 4). In order to clarify the main contributors, breakdown of predicted uncertainty into nuclides and reactions is reviewed for each nuclear parameter. The breakdown for SVRW (sodium-voided in all fuel regions and the axial blanket) is shown in Fig.3, where cross-section-induced errors (namely, GMG and GM'G in Table 4) before and after the adjustment are presented.

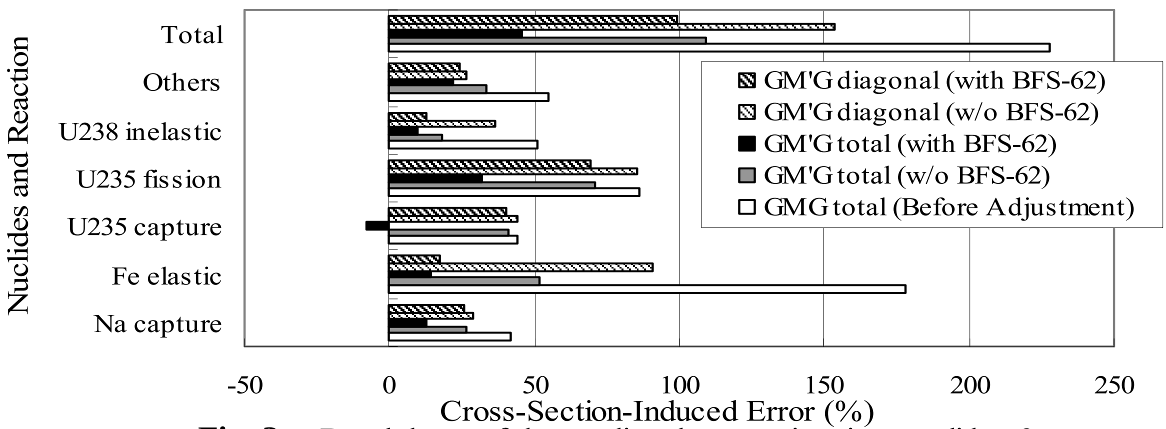


Fig. 3 Breakdown of the predicted uncertainty into nuclides & reactions (SVRE for all the fuel regions and the upper blanket)

As it is clearly shown in the figure, elastic cross section of Fe shows the most dramatic reduction in the error after the adjustment, although fission and capture cross section of ^{235}U show certain contribution. The tendency is commonly confirmed for other nuclear parameters. Diagonal component of the Fe elastic cross section covariance is plotted in Fig. 4. Relatively large value of the original covariance is evidently reduced by the adjustment in the energy region above approx. 200keV.

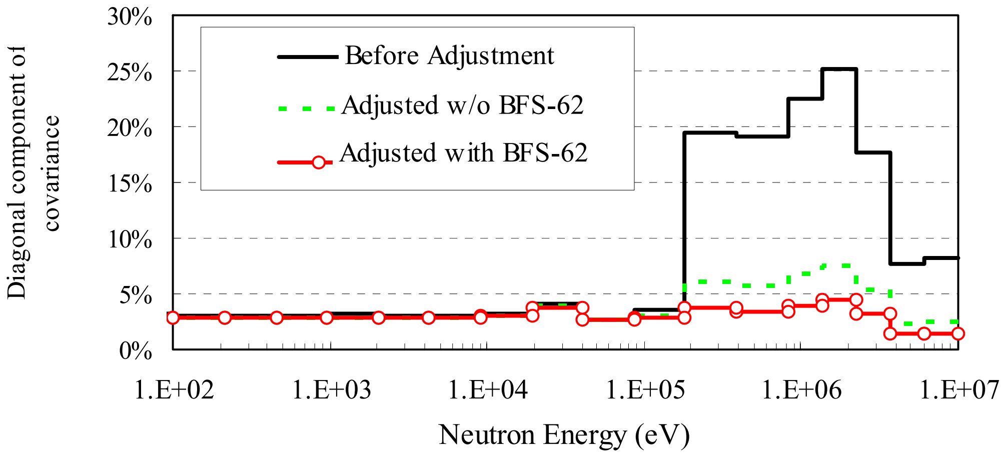


Fig. 4 Covariance of Fe Elastic Scattering Cross Section

5.2 Investigation on Significant Contribution of Fe Elastic Scattering Cross section

The dominant effect of Fe elastic scattering cross section covariance on the prediction uncertainty is quite a new experience in JNC's fast reactor core evaluations. For comparison, prediction uncertainty results for conventional sodium-cooled MOX-fuelled FBR (referred as "PNC-600", previously discussed in a design study), having similar features with the BN-600 hybrid core in terms of the electric power and the peripheral SS reflector, are reviewed. Main contributors to the uncertainty of k-effective are fission cross section and fission neutron spectrum of ^{239}Pu as well as inelastic scattering cross section of ^{238}U. Besides, the contribution of Fe elastic scattering is approximately one third of that obtained for the BN-600 hybrid core. Fig. 5 shows a comparison of region-wise sensitivity coefficient of Fe elastic scattering cross section to k-effective between the two cores. Calculated values for two intermediate cases, based on the BN-600 hybrid core, are also shown. One case is obtained by enlarging equivalent fuel region radius to the same one as PNC-600, and the other case by replacing all the UO_2 fuel by MOX fuel thereon. When an increase of Fe elastic scattering cross section is assumed, enhancement of the reflector effect (positive sensitivity) should be larger in smaller core, while reduction effect in neutron number per fission by softening the neutron spectrum (negative sensitivity) should be smaller in ^{235}U fuelled core. The combination of the two effects can explain much larger positive sensitivity observed in the BN-600 Hybrid Core.

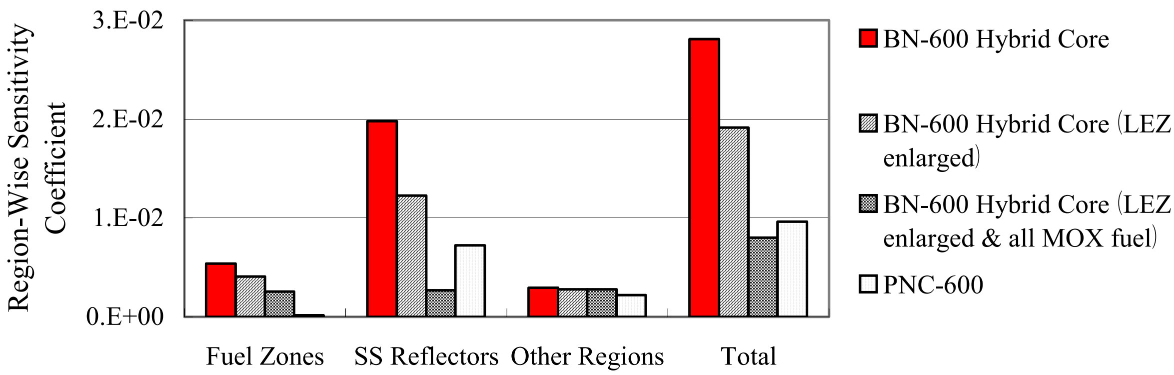


Fig. 5 Comparison of region-wise sensitivity coefficient of Fe elastic scattering cross section to k-effective

6. Conclusion

Main conclusions from the evaluation of predicted uncertainties of nuclear parameters on the BN-600 hybrid core obtained by JNC's analysis system are as following.

The nuclear constant adjustment method can largely reduce the uncertainty for all the discussed nuclear parameters. C/E values obtained from BFS-62 data show a significant contribution in the reduction.

The significant effect of Fe elastic scattering cross section on reducing uncertainties in the nuclear constant adjustment method results from the feature of the BN-600 hybrid core, which has relatively smaller fuel region, adopts ^{235}U rather than ^{239}Pu as the main fissile nuclide, and has the stainless steel reflector surrounding the fuel region.

It should be noted that the bias correction method may increase the uncertainty for nuclear parameters having large experimental/analysis error, or in the case that no appropriate mock-up experiment could be applied.

Good consistency of analysis results between the BFS and other fast reactor cores is confirmed, as C/E values on BFS-62 cores can be reasonably adjusted, without any unreasonable degradation of C/E values on other fast reactor cores (such as ZPPR, FCA, etc.).

Acknowledgement

The authors wish to thank Dr. A. Tsiboulya and Dr. I. Matveenko as well as other staffs of IPPE who made great efforts to maintain the BFS-62 mockup and supplied the detailed information.

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