A Comparative Study of the MONJU Fast Reactor Physics Tests with the ERANOS and JAEA Code Systems

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Abstract

MONJU is the prototype fast breeder reactor in Japan. Criticality and control rod worth measurements, performed as part of the MONJU fast reactor system start-up tests (1994), has been analyzed with the JAEA and ERANOS code systems.

In spite of differences in the nuclear data and methods used in either system, the calculation results have been found to agree with each other, and with the measured values within the analysis accuracy.

The library effect has also been checked (JENDL-3.2 and JEF-2.2 libraries both used with the JAEA code system). It has been found that the JENDL-3.2 library overestimates the criticality and also the control rod reactivity worth compared with the JEF-2.2 library. With regard to this difference, the contribution for all the nuclides has been checked by carrying out a sensitivity analysis. In criticality, Pu-239 ν, Pu-239 fission, and Fe capture mainly showed a large contribution. It was clarified that the contribution of Fe was due to the difference between JENDL-3.2 and JEF-2.2.

1 Introduction

JAEA is currently reassessing the design margins of MONJU by re-analyzing some of the system start-up tests, especially the core physics tests data, in order to contribute to the planned upgrade of the MONJU core. The objective is to extend the plant operating cycles and to allow irradiation tests in some well-defined positions.

Within the collaboration agreement for the reactor physics field between JAEA (formerly JNC) and CEA, it became possible to perform analysis using the CEA code system and libraries inside JAEA.

In this analysis, JAEA uses both its own calculation system [1] and the ERANOS-2.0 [2] code system developed by CEA and relevant organizations, each with its own sets of nuclear data libraries. This comparative analysis is intended to test the validity and consistency of the two systems, and to identify possible areas of improvements in terms of physics models or nuclear data.

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Results are reported for criticality and control rod reactivity worth measurements performed as part of the MONJU system start-up tests. The calculation-versus-measurement (C/E) results are discussed.

However, as these results include some effects due to differences in methods and nuclear data libraries, the exact contribution of each calculation condition is not fully understood. Checks on the library effect of different calculation conditions of the versatility of both systems has been carried out. Furthermore, the contribution from all the nuclides has been checked by carrying out a sensitivity analysis with regard to the library effect.

2 MONJU core model and experimental data

MONJU achieved initial criticality with 168 fuel sub-assemblies (SAs) on April 5, 1994. The configuration of the initial full core loaded with 198 fuel SAs was completed on May 20, 1994. The performance data of MONJU are shown in Table 1. In physics tests, we measured the criticality and the reactivity worth of absorber rods, fixed absorbers, fuel SAs and coolant.

[Measurement of Criticality]

Criticality was first achieved with 168 fuel SAs with all the absorber rods withdrawn except for the central control rod (CCR1) partly inserted in the core. The arrangement of the initial critical core is shown in Fig.1. The "rods up" experimental k_{eff} value was determined by calibrating this control rod.

[Measurement of the control rod reactivity worth]

The arrangement of the absorber rods in MONJU is shown in Fig.2. There are 10 coarse control rods (CCR), 3 fine control rods (FCR) and 6 back-up control rods (BCR). The measurements were performed for CCR1 by using the periodic method. For the measurement of the other absorber rod worth, the balancing method was used. Control rod worth were measured per $ unit. In this paper, CCR1 was analyzed.

Table 1: Principal design and performance data of MONJU

Reactor Type	Sodium-Cooled Loop-type
Thermal Output	714 MW
Electrical Output	280 MW
Fuel Material	PuO2-UO2
Core Dimensions	
Equivalent Diameter	179 cm
Height	93 cm
Plutonium Enrichment	(Inner Core/ Outer Core)
Initial Core	15 / 20 Pu Fissile %
Equilibrium Core	16 / 21 Pu Fissile %
Fuel Inventory	
Core (U+Pu metal)	5.9 ton
Blanket (U metal)	17.5 ton
Blanket Thickness	
Upper/Lower/Radial	30 / 35 / 30 cm

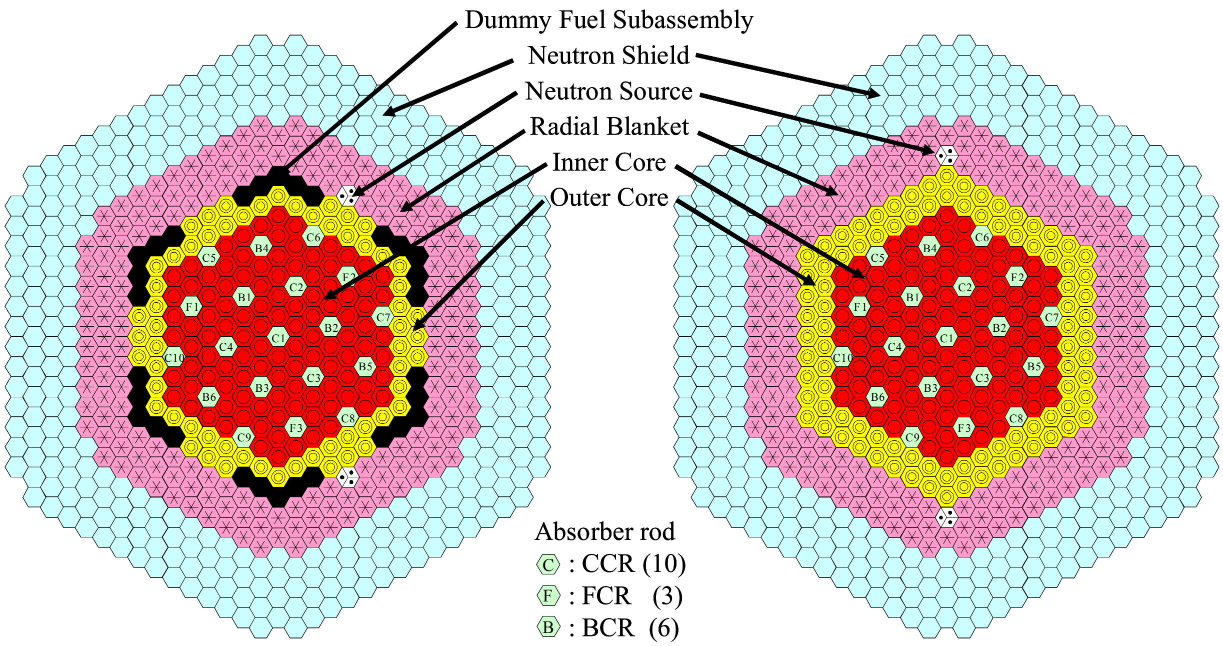

Fig. 1: Initial critical core
(168 fuel & 30 dummy S/A)

Fig. 2: First start-up core
(198 fuel S/A)

Table 2: Main characteristics of the ERANOS and JAEA code systems

	ERANOS (V2.0)	JAEA system
Source of evaluated nuclear data files	JEF-2.2	JENDL-3.2
Libraries	JECCOLIB2 ERALIB1 (adjusted set)	JFS-3-J3.2R ADJ2000R (adjusted set)
Energy group structure	1968 groups for the main nuclides, 172 or 33 for the others	70 groups, ultra fine (100,000-group below 50keV)
Self-shielding	Sub-group method	Bondarenko-type interpolation method
Cell/assembly calculation	1-D or 2-D collision probability method	1-D collision probability method
Cross section homogenization for control rods	Reactivity equivalence method	Reaction rate ratio preservation method
Core calculation	2-D or 3-D, diffusion or transport methods in 33 groups	2-D or 3-D diffusion or transport finite-difference method in 18 groups

3 Analysis method

Table 2 shows the main calculation options available in the ERANOS and JAEA code systems for the MONJU core analysis. It can be seen that the nuclear data sets, the methods and the approaches are completely different. In particular, while ERANOS adopts a 1968 neutron energy group structure with the sub-group method, the JAEA system uses a 70 energy group structure (ABBN type, JFS-3 format) and a self-shielding calculation method. In addition to this in JAEA, the ultra fine (100,000-group below 50keV) group set [3] may be used.

The hexagonal fuel sub-assembly is approximated by a one-dimensional cylindrical model in the JAEA system, while an explicit two-dimensional model is used in ERANOS.

Homogenized control rod cross sections are processed by the Reaction Rate Ratio Preservation method (RRRP) [4] with a 1-D cylindrical model in the JAEA system, while the Reactivity Equivalence Method (REM) [5] with a 2-D model is used in ERANOS. Past studies [6] have shown that such special homogenization procedures are required to obtain sufficiently accurate predictions of control rod reactivity worth.

4 Description of the analysis

4.1 Criticality

In the JAEA analysis, both the 70-group fast reactor constant set (JFS-3-J3.2R) based on the Japanese Evaluated Nuclear Data Library JENDL-3.2 [7] and the adjusted cross section library ADJ2000R [8] were used for all core parameters. Cell calculations were performed by the SLAROM cell code [9] with 1-D homogeneous model except for the control rod region.

Control rod homogenized cross section was created using the RRRP method in the CASUP cell code [10]. The code, with an improved for input-and-output data processor of DIF3D finite difference diffusion code [11], was used with 3-D Tri-Z model. The following corrections have been performed to obtain the best estimation.

- Mesh correction
- Transport correction
- Ultra-fine group correction [12]
- Cell heterogeneity correction

In the analysis using ERANOS, two nuclear data sets were used: JECCOLIB2 based on the European Joint Evaluated Library JEF-2.2 [13] and the adjusted nuclear data library ERALIB1 [14]. A 1968 group energy mesh was used. Cell calculations were performed by the ECCO cell code [15] with explicit 2-D heterogeneous model for fuel SAs, and macrocell model for blanket SAs. Macrocell model used 1-D geometry for the whole core and takes into account the resonance and spectrum interaction between the core and the blanket regions.

Control rod homogenized cross section was created using the REM. The nodal transport code TGV/VARIANT [16] with a 3-D Hex-Z model was used for core calculation. The corrections applied to the results of above JAEA calculations are not needed here, because nodal method transport calculation (negligible mesh effect and no transport correction), explicit 2-D heterogeneous cell model (no cell heterogeneity correction) and super-fine 1968 group (negligible energy mesh effect) were chosen as calculation options.

4.2 Control rod reactivity worth

The analysis method is the same as for criticality. β_{eff} was further evaluated using perturbation calculation in both systems, and the control rod worth in $ unit was compared. The effective delayed neutron fraction was calculated with Tuttle's yield data [17] in JAEA analysis.

In ERANOS, only U-238 calculated from ENDF/B-VI was used for the delayed neutron fission spectrum, and the delayed neutron yields and was taken from JEF2.2 data. The following corrections have been performed to the obtained JAEA results.

- Mesh correction
- Transport correction
- Ultra-fine group correction [12]
- Rod shadowing effect correction

As correction to the result of ERANOS, only a rod shadowing effect was applied among the corrections applied to the result of JAEA calculations, because of the same reasons as for criticality.

4.3 Library effect

The library effect was checked using the JFS-3-JEF2.2 library which edited JEF-2.2 into the JFS-3 format. The nuclear data processing system NJOY [18] and TIMS (only for unresolved resonance region) [19] were used for creation of JFS-3-JEF2.2.

4.4 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:

$$S_{m,x,g} = \frac{dR/R}{d\sigma_{m,x,g}/\sigma_{m,x,g}}$$

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

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

Sensitivity coefficients were calculated in order to investigate the results. They were calculated by the SAGEP [20] code in the JAEA system, based on generalized perturbation theory.

5 Results and Discussions

5.1 Criticality

Table 3 and Figure 3 show the results on criticality. A corrected C/E value of 0.998 has been obtained with the JECCOLIB2+ERANOS system, and 0.996 with the JFS-3-J3.2R+JAEA system. These results were in agreement within the targets of analysis accuracy, even if this amounts to half of the design accuracy (±1%). In order to check that the relatively small 0.4% Δk discrepancy in the JAEA C/E result did not result from fortuitous error compensations, an independent, exact calculation was performed with the continuous energy Monte Carlo transport code MVP [21], using the same JENDL-3.2 library. A C/E value of 0.997 has been found. It was therefore concluded that the JAEA standard calculation method is satisfactory. This shows that the two systems, JAEA and ERANOS can predict accurately the MONJU initial critical mass. The small discrepancy between the JAEA calculation and the measurement probably originates in the JENDL-3.2 library.

Analyses were performed using the adjusted cross section libraries (ERALIB1, ADJ2000R) available in both systems. It has been found that both adjusted libraries increase the predicted reactivity, by 0.6% for ERANOS, and by 0.7% for JAEA.

5.2 Control rod reactivity worth

Table 4 and Figure 4 show the results on control rod worth. The central control rod (CCR1) was analyzed. A corrected C/E value of 0.986 has been obtained with the JECCOLIB2 +ERANOS system, and 0.953 with the JFS-3-J3.2R+JAEA system. The unit of reactivity is in Δk/kk', where effective delayed neutron fraction of JFS-3-J3.2R was used to convert the measured value from $ unit to Δk/kk' unit. These results were in agreement within the analysis accuracy, even if this amounts to half the required design accuracy (±10%). A C/E value of 0.964 has been obtained by MVP with JENDL-3.2. These results show that the two systems, JAEA and ERANOS, can predict accurately the MONJU control rod worth.

The unit of the above-mentioned results are in Δk/kk' and the relative difference in control rod worth between the two systems is then about 3.5%. In order to convert into $ unit, β_{eff} was estimated by each system. A β_{eff} value of 0.00359 has been obtained with the JECCOLIB2 +ERANOS system, and 0.00343 with the JFS-3-J3.2R +JAEA system: the relative difference is about 4.7%. C/E was computed on $ values using these results. A corrected C/E value of 0.946 has been obtained with the ERANOS system, and 0.957 with the JAEA system. The relative difference in control rod worth prediction between the two systems then reduced to 1.1%.

Analyses were performed using adjusted cross section libraries. A C/E value of 0.945 has been obtained with the ERANOS system, and 0.930 with the JAEA system in $ unit. The relative difference becomes 1.6%.

These results were consistent with those found in the ERALIB1 +ERANOS analyses of the PHENIX and SUPERPHENIX control rod reactivity worth. Indeed, the C/E values ranged from 0.98 to 1.01 for PHENIX, and from 0.93 to 1.01 for SUPERPHENIX, respectively.

Table 3: Results of criticality analysis

Code	Library	C/E
ERANOS	JECCOLIB2	0.9983
	ERALIB1	1.0043
JAEA	JFS-3-J3.2R	0.9955
	ADJ2000R	1.0019
MVP	JENDL-3.2	0.9970

Table 4: Results of control rod worth analysis

Code	Library	**C/E [Δ k/kk']**	β_{eff}	**C/E [$]**
ERANOS	JECCOLIB2	0.986	0.00359	0.946
	ERALIB1	0.973	0.00355	0.945
JAEA	JFS-3-J3.2R	0.953	0.00343	0.957
	ADJ2000R	0.938	0.00348	0.930
MVP	JENDL-3.2	0.964	0.00343	0.968

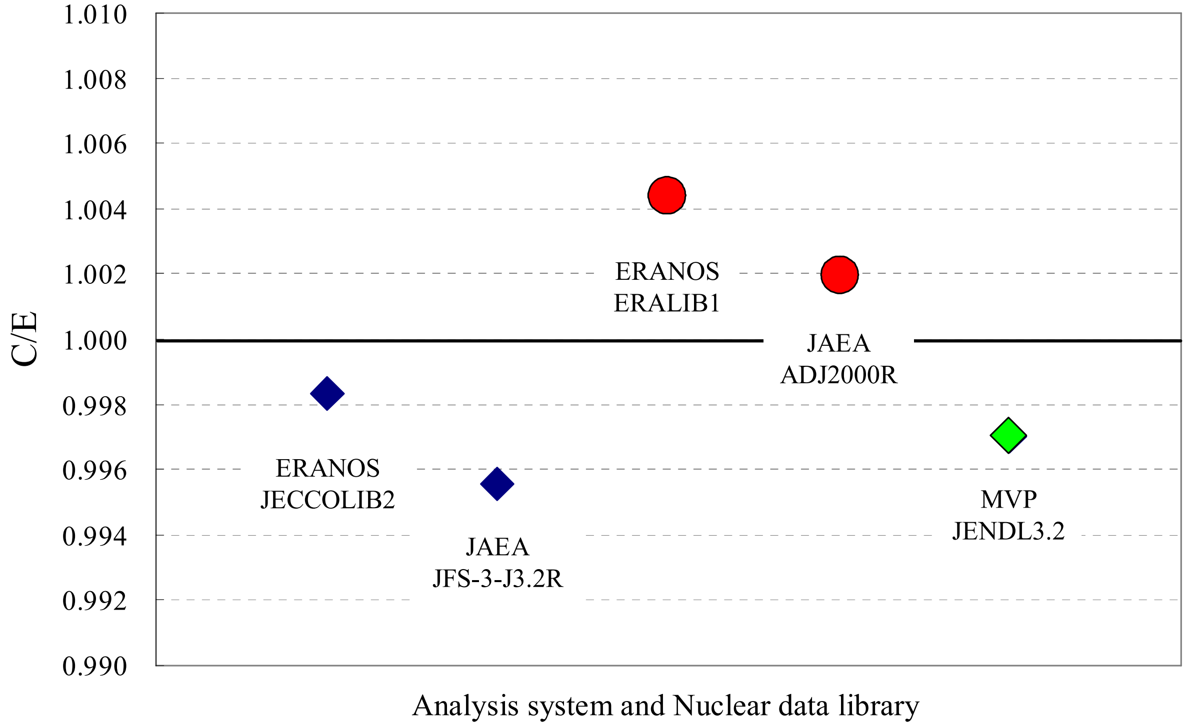

Fig. 3: Results of criticality analysis

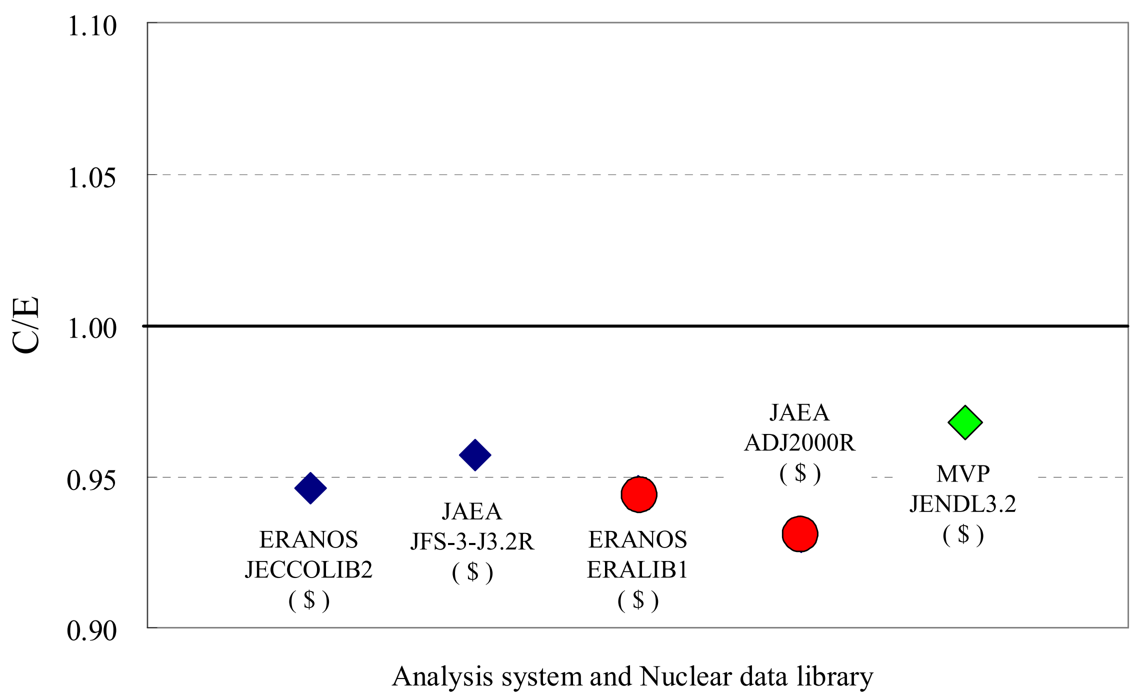

Fig. 4: Results of control rod worth analysis

5.3 Library effect & Sensitivity analysis

As described in 5.1 and 5.2, when the standard analysis options were used for each system, ERANOS gave higher results for criticality while JAEA gave higher results for control rod worth in $.

In order to isolate (as much as possible) library effects, calculations were run with the JAEA code system and the JFS-3-JEF2.2 library. It has been found that the JFS-3-J3.2R library estimate larger the MONJU criticality by 0.3% and also estimate larger the MONJU control rod reactivity worth by 0.4% compared with the JFS-3-JEF2.2 library by direct calculation.

The contribution for all the nuclides has been checked by carrying out a sensitivity analysis about the library effect. Figure 5 and 6 show the results.

With regard to criticality, the influence of Pu-239 ν, Pu-239 fission and Fe capture cross section is large. The reasons are the large sensitivity coefficient of Pu-239, and large cross section difference of iron. With regard to control rod worth, in addition to the influence of Pu-239 and iron, the influence of U-238 fission can also be checked.

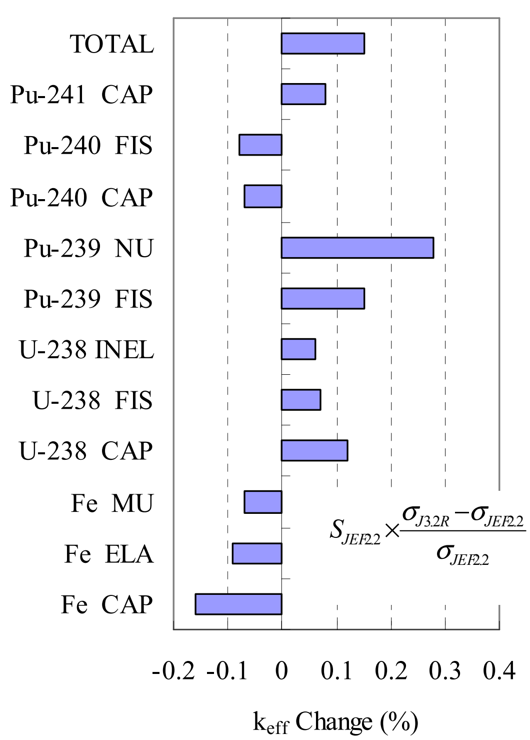

Fig. 5: Nuclide-wise contribution (Criticality)

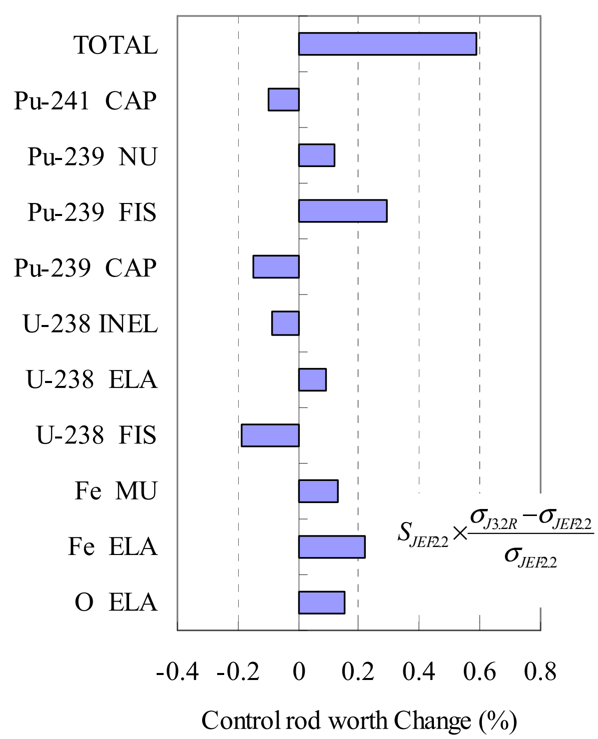

Fig. 6: Nuclide-wise contribution (CR-Worth)

6 Conclusions

Criticality and control rod worth measurements performed as part of the MONJU fast reactor system start-up tests (1994) were analyzed with the JAEA and ERANOS code systems.

In spite of differences in the nuclear data library and methods used in either system, the calculation results have been found to agree with each other, and with the measured values.

(Criticality C/E: ERANOS 0.998, JAEA 0.996, difference 0.3%)
(Control rod worth C/E: ERANOS 0.95, JAEA 0.96, difference 1%)

The library effect has also been checked (JENDL-3.2 and JEF-2.2 libraries both used with the JAEA code system). It has been found that the JENDL-3.2 library overestimates the criticality by 0.3%, also overestimates the control rod reactivity worth by 0.4% compared with the JEF-2.2 library. The contribution for all the nuclides has been checked by carrying out a sensitivity analysis. In criticality, Pu-239 ν, Pu-239 fission, and Fe capture mainly showed a large contribution. It was clarified that contribution of Fe was due to the difference between JENDL-3.2 and JEF-2.2.

7 References

[1] M. Ishikawa et al., 'Development of a Standard Data Base for FBR Core Nuclear Design (VIII) –Compilation of JUPITER Analytical Results-', PNC TN9410 97-099 (Nov. 1997)
[2] G. Rimpault et al., 'The ERANOS Data and Code System for Fast Reactor Neutronic Analyses', International Conference on the New Frontiers of Nuclear Technology: Reactor Physics, Safety and High-Performance Computing, PHYSOR 2002, Seoul, Korea, October 7-10 (2002).
[3] (1) K.Sugino: "JUPITER Experimental Analyses Using a New Constant Set Based on JENDL-3.2", J. Nucl. Sci. Technol., Supplement 2, pp.1002-1005 (2002).
(2) T.Hazama, G.Chiba, et al.: "Development of SLAROM-UF; a Cell Calculation Code with Fine and Ultra-fine group calculation", J. Nucl. Sci. Technol. (to be published).
[4] K. Sugino, and T. Iwai, 'Advances in Methods of Commercial FBR Core Characteristics Analyses - Investigations of a Treatment of the Double-heterogeneity and a Method to Calculate Homogenized Control Rod Cross Sections', PNC TN9410 98-067 (July 1998).
[5] S. Czernecki, "Avancées dans le Calcul Neutronique des Réacteurs à Neutrons Rapides - Démonstration sur le Réacteur Super-Phénix", PhD Thesis (in French), Université de Provence - Aix-Marseille I, (Nov. 10, 1998).
[6] T. Kitada et al., 'New Control Rod Homogenization Method for Fast Reactors', Journal of Nuclear Science and Technology, 31[7] (Jul. 1994).
[7] T.Nakagawa, K.Shibata, et al.: "Japanese Evaluated Nuclear Data Library Version 3 Revision-2: JENDL-3.2", J. Nucl. Sci. Technol., 32 [12], pp.1259-1271 (1995)
[8] M.Ishikawa, K.Sugino, et al.: "Development of a Unified Cross-section Set ADJ2000 based on Adjustment Technique for Fast Reactor Analysis", J. Nucl. Sci. Technol., Supplement 2, pp.1073-1076 (2002).
[9] M.Nakagawa, et al.: "SLAROM: A Code for Cell Homogenization Calculation of Fast Reactor," JAERI 1294, Japan Atomic Energy Research Institute (1984)
[10] T.Tone, "A Numerical Study of Heterogeneity Effects in Fast Reactor Critical Assemblies," J. of Nucl. Sci. and Technol. 12 (8), P.467 (1975).
[11] "DIF3D 7.0: Code System for Solving Finite Difference Diffusion Theory Problems," RSIC, CCC-649, (1997)
[12] K.Sugino and T.Iwai: "MONJU Experimental Data Analysis and its Feasibility Evaluation to Build up the Standard Data Base for Large FBR Nuclear Core Design", Proc. Inter. Conf. on the Advances in Nuclear Analysis and Simulation (PHYSOR 2006), Vancouver, BC, Canada (2006).
[13] J.L.Rowlands and N.Tubbs, "The Joint Evaluated File: A New Nuclear Data Library for

Reactor Calculation", Santa Fe Symposium (1985)
[14] E.Fort, W.Assal, et al.: Realisation and Performance of the Adjusted Nuclear Data Library ERALIB1, Proc. of Int. Conf. on the Physics of Reactors (PHYSOR 96), Mito Japan (Sep. 1996)
[15] M.J.Grimstone, G.Rimpault, et al.: The Geometrical Treatment in the New European Cell Code ECCO, Top. Mtg. on Advances in Nuclear Engineering Computation and Radiation Shielding, Santa Fe, New Mexico (Apr. 1989)
[16] G. Palmiotti, E. E. Lewis, et al.: "VARIANT: VARIational Anisotropic Nodal Transport for Multidimensional Cartesian and Hexagonal Geometry Calculation", Argonne National Laboratory Report, ANL-95/40 (1995).
[17] R. J. Tuttle, “Delayed-neutron yields in nuclear fission,” Meeting on Delayed Neutron Properties, IAEA, Vienna, INDC (NDS)-107/G+Special, 29(1979).
[18] R.E.MacFarlane, D.W. Muir, The NJOY Nuclear Data Processing System, Version 91, LA-12740-M, (1994)
[19] H.Takano, et.al., "TIMS-1: A Processing Code for Production of Group Constants of Heavy Resonant Nuclei", JAERI 1267, (Sep. 1980)
[20] A.Hara, T.Takeda, et al.,”SAGEP: Two-Dimensional Sensitivity Analysis Code Based on Generalized Perturbation Theory”, JAERI-M 84-027 (Feb. 1984) [written in Japanese]
[21] T. Mori et al., ‘MVP/GMVP General Purpose Monte Carlo Codes for Neutron and Photon Transport Calculations Based on Continuous Energy and Multi group Methods’, JAERI-Data/Code 94-007 (Aug. 1994).