Analysis of Innovative Water Reactor for Flexible Fuel Cycle in FCA using JENDL-3.3

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To obtain experimental data and to evaluate the prediction accuracy for the core characteristics in the design study of Innovative Water Reactor for Flexible fuel cycle (FLWR), critical experiments were carried out using a series of mock-up cores at FCA. Three mockup cores with different void fractions of the moderator were constructed to obtain experimental data in wide range of neutron spectra. Major items of the experiment are criticality, reaction rate ratios, moderator void reactivity worth and the Doppler effect. Conventional deterministic calculation systems were used to analyze the experiment with the use of the JENDL-3.2 and JENDL-3.3 libraries. The ratios of calculated and experimental (C/E) values were compared between both the JENDL libraries. The current analysis method showed good prediction accuracy in most of the experiments and no significant differences were observed in the C/E values between the libraries in this study.

1. Introduction

Innovative Water Reactor for Flexible fuel cycle (FLWR) [1] is a new reactor concept for the next generation proposed by JAERI. The FLWR is aimed at high breeding ratio and high burn up with the use of highly enriched MOX fuel in tight lattice. To estimate the accuracy of prediction for the core characteristics in the design study of FLWR, a program of critical experiments using the fast critical facility, FCA, was planned. This program consisted of three mock-up cores of different voidage of moderator. The principal aim of the program is focused on obtaining the nuclear characteristics of the MOX fueled core in tight lattice.

The purpose of this study is to analyze these experiments using the JENDL-3.2[2] and JENDL-3.3[3] libraries and to verify the impact of the revised nuclear data library by comparing the results.

2. Brief Description of Mockup cores and experiments

The FCA-FLWR mockup core, FCA-XXII-1 series core, is a coupled system of a central test zone and surrounding driver zone. The test zone is composed of a combination of uranium/plutonium fuel plates and moderator material (foamy polystyrene) plates to simulate the neutron energy spectrum of FLWR (see Fig. 1). The principal cell averaged parameters of the test zone of each core are shown in Table 1. The cell averaged enrichment of the test zone is 16 atom % of fissile plutonium and the hydrogen to heavy metal atomic number ratio (H/HM) is systematically changed from 0.09 to 0.8. The cross section view of the FCA-XXII-1(65V) core is shown in Fig. 2. The test zone is represented by a close to rectangular prism with about 38 cm in square base and 91 cm in height. It is surrounded by the enriched U driver zone and two radial blanket zones; an inner blanket zone of 30cm in thickness containing a significant amount of depleted uranium dioxide and sodium, and an outer blanket zone of 15cm in thickness containing only depleted uranium metal. The upper and lower axial blanket zones of 30cm in thickness containing natural uranium metal are also placed to cover the test zone.

The measurements were made for criticality (k_{eff} value), central reaction rate ratio and central reactivity worth (e. g. moderator void reactivity worth, ^{238}U Doppler effect and plutonium sample reactivity worth). The central reaction rate ratio was measured with the combination of foils and fission counters[4]. The void reactivity worth was measured with changing the void fraction of the polystyrene plates from 45% (or 65%) to 80% and 95% in the central cell of the test zone. The Doppler effect was measured as the reactivity change of cylindrical natural-uranium samples (Doppler samples) with the temperature change (from room temperature to 800℃) at the core center. As for the Pu sample reactivity worth, the reactivity worth caused by the change of plutonium isotope composition from 92% to 75% (Pu-fissile) was measured at the core center.

3. Calculation method

The nuclear reactions in the FLWR core are dominantly occurred in the resonance energy range. Two different conventional deterministic methods, therefore, were used to analyze the experiments; the SRAC code system [5] and a standard calculation code system for a fast reactor (FR code system) [6]. The effective microscopic cross sections in the resonance energy range were calculated by the resonance shielding factors given by the table-look-up method based on the narrow resonance approximation. As for the analysis of the central reaction rate ratio, the effective microscopic cross sections were calculated with the use of the PEACO for the SRAC code system and the PEACO-X[7] for the FR code system, which provide effective microscopic cross sections more precisely by the ultra-fine energy group calculation. The effective cross sections of the cylindrical Doppler samples were also calculated with those codes. The cell averaged macroscopic effective cross sections for each cell were obtained by the collision probability calculation with a one-dimensional infinite slab model. The k_{eff} values and the forward and adjoint fluxes were calculated by the diffusion calculation code CITATION[8] with considering the anisotropic effect of neutron leakage[9] and by the transport calculation code DANTSYS[10] with P_0-S_8 approximation. Two-dimensional R-Z model was employed for the analysis of the Doppler effect, while three-dimensional X-Y-Z model was employed for the other analyses. The first order perturbation method was employed for the Doppler effect analysis and the explicit perturbation method was employed for the other reactivity worth analyses.

4. Comparison between Calculation and Experiment

The comparison between calculated (C) and experimental (E) results, C/E value, is shown in Table 2 to 6.

Criticality: Table 2 shows that the SRAC code system gives better agreement between the calculated and experimental results than the FR code system: the discrepancies are in the range from +0.1%Δk to +0.2%Δk with the JENDL-3.3 library by the SRAC code system, while they are from –0.5%Δk to -0.3%Δk by the FR code system. When the results are compared between JENDL-3.2 and JENDL-3.3, JENDL-3.3 gives larger C/E values than JENDL-3.2 up to 0.16% except the FCA-XXII-1(95V) core. There are no discrepancies between the results with JENDL-3.2 and JENDL-3.3 in the hard neutron spectrum considering the experimental error.

Central reaction rate ratio: There are no significant differences in the C/E values between the SRAC and FR systems. The C/E values of the fission reaction rate ratio ^{238}U/^{235}U (F28/F25) are larger than those of ^{239}Pu/^{235}U (F49/F25). From this result, the calculation code systems have a tendency to give a harder neutron spectrum. Both the calculations overestimate the ratio of the capture reaction rate of ^{238}U to the fission reaction rate of ^{239}Pu (C28/F49) by about 10% in the XXII-1 (45V) core. The contribution of the reaction rate in giant resonance peaks (in the range of 48eV~29eV, 23eV~18eV and 8.3eV~5.0eV with the 107 group energy structure) to that in the whole energy range in the capture reaction rate of ^{238}U is 22%, 15% and 2% for the FCA-XXII-1(45V), FCA-XXII-1(65V) and FCA-XXII-1(95V), respectively. It is considered that the calculation accuracy of the giant resonance cross section of ^{238}U should be investigated more precisely. When the C/E values are compared between JENDL-3.2 and JENDL-3.3, there are no large differences.

Reactivity Worth: The SRAC code system shows good agreement between the calculation and experiment for the moderator void reactivity worth in both the cores, while the FR code system shows underestimation beyond the experimental errors. The calculation accuracy in the non-leakage term of the FR code system should be improved. As for the ^{238}U Doppler effect, both the code system agrees with the experiment within the measurement error in most cases. In the analysis of the Pu sample reactivity worth, both the systems show C/E dependency on the voidage of the test zone and the SRAC code system shows better agreement than the FR code system. When the C/E values are compared between JENDL-3.2 and JENDL-3.3 in the analyses of the central reactivity worths, there are no large discrepances.

5. Conclusion

The SRAC code system showed better agreement with the measurement than the FR code system in the analysis of the criticality and the moderator void and Pu sample reactivity worths. For the central reaction rate ratio, the C/E values of F28/F25 was larger than that of F49/F25 and the calculations gave large overestimation for C28/F49. No large C/E discrepances between JENDL-3.2 and JENDL-3.3 were observes in the analyses of this study.

The further detail analyses will be carried out to solve the problems (such as the overestimation in the C28/F49) and to evaluate calculation accuracy for the design study of the FLWR.

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Table 1 Cell averaged parameters of the test zones in the FCA FLWR mockup cores

	FCA FLWR mock-up cores			FLWR	
	XXII-1(45V)	XXII-1(65V)	XXII-1(95V)	Lower core	Upper core
Enrichment (%)	15.8	15.8	15.8	10~	10~
V_m/V_f *	0.6	0.6	0.6	0.18	0.18
Void fraction (%)	45	65	95	45	75
H/Fuel **	0.81	0.52	0.091	0.93	0.48

* Volume fraction of moderator to fuel plates in a cell

** Atomic number ratio between Hydrogen and Fuel materials in a cell

Table 2 Ratio of calculated to measured criticality (k_{eff} value)

Core name	Error*	SRAC code system J-3.2	SRAC code system J-3.3	FR code system J-3.2	FR code system J-3.3
XXII-1 (45V)	±0.02%	1.0002	1.0018	0.9936	0.9949
XXII-1 (65V)	±0.02%	1.0004	1.0017	0.9961	0.9970
XXII-1 (95V)	±0.02%	1.0007	1.0010	0.9975	0.9971

* Measurement error

Table 3 Comparison of central reaction rate ratios between calculation and experiment

Reaction	Core name	Error	SRAC J-3.2	SRAC J-3.3	FR J-3.2	FR J-3.3
F28/F25	XXII-1 (45V)	±0.9%	1.04	1.04	1.04	1.03
	XXII-1 (65V)	±0.9%	1.05	1.05	1.04	1.02
	XXII-1 (95V)	±1.0%	1.04	1.03	1.02	1.00
F49/F25	XXII-1 (45V)	±1.2%	0.97	0.97	0.99	0.99
	XXII-1 (65V)	±1.2%	1.01	1.02	1.02	1.02
	XXII-1 (95V)	±1.0%	1.00	1.00	1.00	1.00
C28/F49	XXII-1 (45V)	±1.8%	1.09	1.10	1.09	1.09
	XXII-1 (65V)	±1.8%	1.04	1.04	1.04	1.04
	XXII-1 (95V)	±1.7%	1.00	1.01	1.00	1.00

Table 4 Comparison of void reactivity worth between calculation and experiment

Core name	Void fraction	Error	SRAC J-3.2	SRAC J-3.3	FR J-3.2	FR J-3.3
XXII-1 (45V)	80%	±4.6%	1.00	1.00	0.85	0.84
	95%	±3.4%	0.99	0.99	0.85	0.83
XXII-1 (65V)	80%	±12%	0.94	0.93	0.77	0.78
	95%	±6.7%	0.97	0.96	0.82	0.82

Table 5 Comparison of U-238 Doppler effect between calculation and experiment

Doppler Sample	Core name	Error	SRAC J-3.2	SRAC J-3.3	FR J-3.2	FR J-3.3
U_{metal}	XXII-1 (45V)	±3.4%	1.01	1.02	1.04	1.04
	XXII-1 (65V)	±2.6%	0.99	1.01	1.04	1.05
	XXII-1 (95V)	±4.2%	0.99	1.02	1.00	1.01
UO_2	XXII-1 (45V)	±5.4%	1.00	1.01	1.03	1.04
	XXII-1 (65V)	±4.1%	0.99	1.01	1.05	1.06
	XXII-1 (95V)	±8.4%	1.04	1.07	1.06	1.08

The Doppler samples are 2.5cmϕx15cmL in size.

Table 6 Comparison of plutonium reactivity worth between calculation and experiment

Core name	Error	SRAC J-3.2	SRAC J-3.3	FR J-3.2	FR J-3.3
XXII-1 (45V)	±1.0%	0.95	0.94	0.90	0.89
XXII-1 (65V)	±1.4%	0.99	0.95	0.94	0.92
XXII-1 (95V)	±6.5%	1.05	1.02	1.08	1.07

Pu isotope ratio: 239/240/241/242: 91.7/8.0/0.2/0.1 -> 73.0/23.1/1.7/2.2.

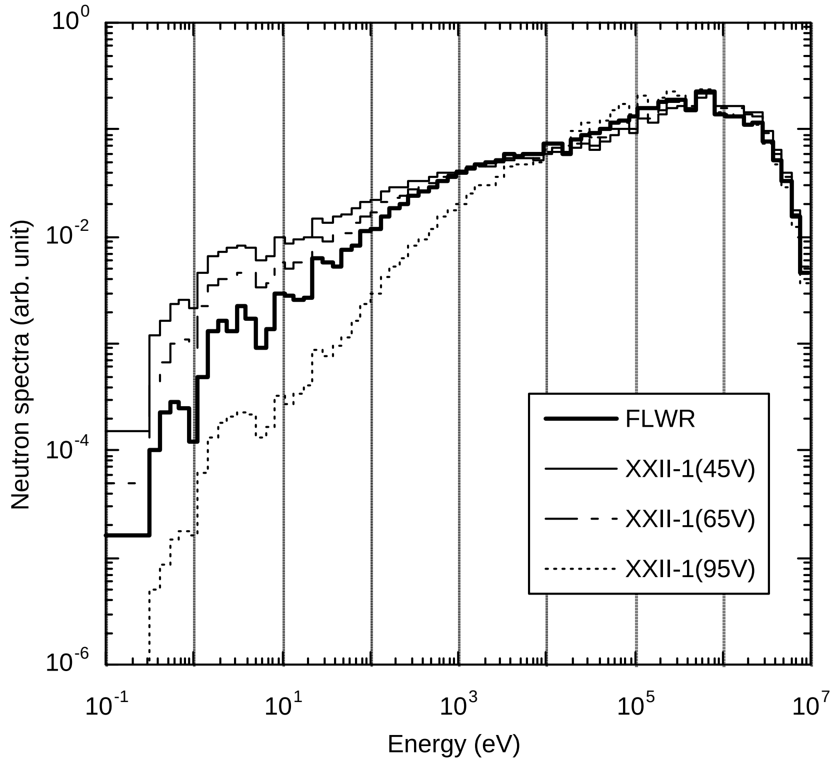

Fig. 1 Calculated neutron energy spectra in the FLWR (average of the upper and lower cores) and the FCA-XXII-1 series cores

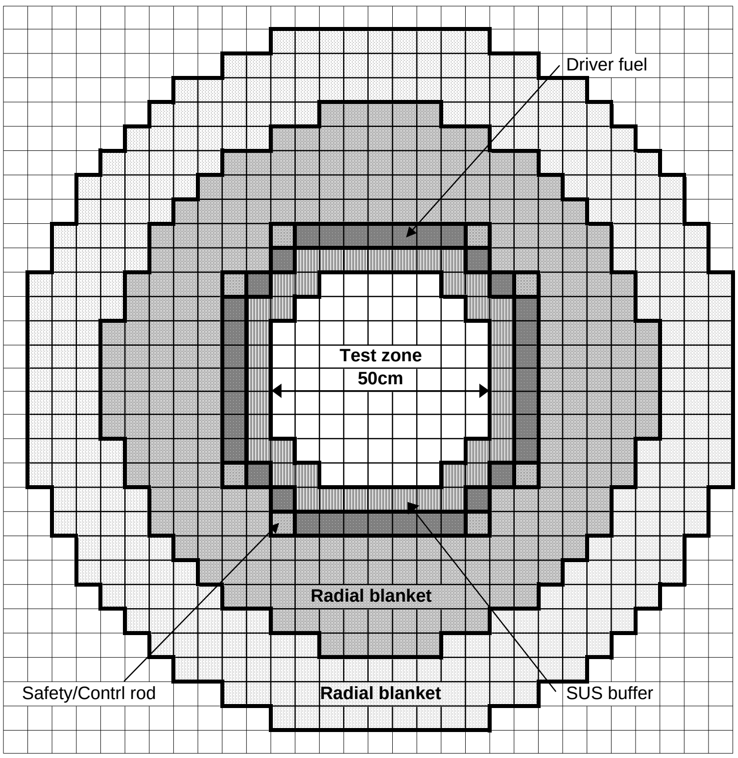

Fig. 2 Cross-section view of the FCA-XXII-1(65V) core