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Evaluation of Pin Power Distribution Uncertainty for KRITZ-2:13 and KRITZ-2:19 critical experiment benchmarks by McCARD

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1. Introduction

KRITZ reactor operated at Studsvik, Sweden, during the first half of the 70s. The KRITZ-2 reactor included light water moderated rectangular lattices with uranium oxide and mixed-oxide fuel rods, at cold and hot temperatures. In 2005, the OECD/NEA working party on the physics of plutonium fuels and innovative fuel cycles arranged an international benchmark for the KRITZ UO_2 and MOX critical experiments. The goal of this benchmark is to investigate the predictive capability of various codes and nuclear data libraries and to compare the accuracy of the predictions for them. They provided UO_2 fuel based three benchmarks (KRITZ-2:1h, KRITZ-2:13c, and KRITZ-2:13h) and MOX fuel based two benchmarks (KRITZ-2:19c and KRITZ-2:19h). The detailed modeling dimensions and results for each benchmark can be found in Reference [1,2].

In this study, the KRTIZ-2:13c, KRITZ-2:13h, and KRITZ-2:19c benchmark analyses were performed to estimate the accuracy of the criticality and pin power distribution capability for Monte Carlo (MC) particle transport code, McCARD [3]. To examine the sensitivity due to the evaluated nuclear data library, ENDF/B-VII.1, ENDF/B-VIII.0, JENDL-4.0, and JENDL-5.0 cross section libraries [4] were used for the benchmark analyses.

2. Calculation tool and Results

2.1 McCARD code and modeling

In this study, all the McCARD eigenvalue calculations were conducted on 1,000 cycles including 50 inactive cycles with 10,000 neutron histories per cycle. Table I shows the specification of the KRITZ-2:13 and KRITZ-2:19c benchmarks.

Table I: Configuration of the KRITZ-2:13, 2:19c core

Parameters	KRITZ-2:13c	KRITZ-2:13h	KRITZ-2:19c
Rod number	44×44		25×24
Rod type	UO_2		MOX
Pin pitch (mm)	16.3500	16.4150	18.000
Water height (mm)	961.7	1109.6	665.6
Temperature (^oC)	22.1	243.0	21.1

Figures 1 and 2 present the horizontal (X-Y plane) and vertical (X-Z plane) cross sections of the KRITZ-2:13c benchmark, respectively. The cross sections were plotted by the McVIEW [5], McCARD input visualizer utility.

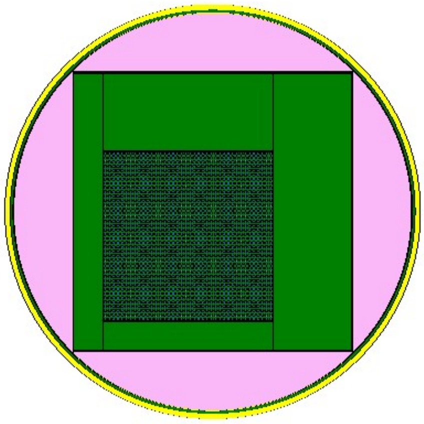

Fig. 1. Horizontal cross section of KRITZ-2:13c core

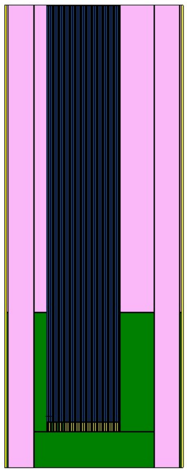

Fig. 2. Vertical cross section of KRITZ-2:13c core

2.2 Evaluation of criticality with various evaluated nuclear data library

Table II shows the k_{eff} values of the KRITZ-2:13c, KRITZ-2:13h, and KRITZ-2:19c benchmarks by the McCARD code with the ENDF/B-VII.1, ENDF/B-VIII.0, JENDL-4.0 and JENDL-5.0 cross section libraries. As the temperature in the core increases, the absorption resonances broaden, and the absorption cross section (i.e., ^{238}U) in the fuel rods increases because of the Doppler effect. Then, the increase of the absorption cross sections leads to the decrease of the resonance escape probability, and it has a negative impact on the reactivity. The increase of the water level compensates this negative impact on the reactivity to maintain the critical state in the KRITZ-2:13 core. Table III presents the C/M-1 (%) values of k_{eff} for each benchmark. C and M indicate a calculated k_{eff} by McCARD and a measured k_{eff}. The maximum errors were -0.17 %, -0.24 % and 0.35 % in the KRITZ-2:13c with ENDF/B-VIII.0, the KRITZ-2:13h with JENDL-4.0 and the KRITZ-2:19c with JENDL-4.0, respectively.

Table II: k_{eff} for KRITZ-2:13c, KRITZ-2:13h, KRITZ-2:19c benchmarks by McCARD with various evaluated nuclear data library

Core	KRITZ-2:13c	KRITZ-2:13h	KRITZ-2:19c
ENDF/B-VII.1	0.99950	0.99779	1.00228
ENDF/B-VIII.0	0.99830	0.99835	0.99819
JENDL-4.0	0.99953	0.99761	1.00348
JENDL-5.0	0.99980	0.99900	0.99874

Table III: C/M-1(%) values of k_{eff} for each benchmark by McCARD with various evaluated nuclear data library

Core	KRITZ-2:13c	KRITZ-2:13h	KRITZ-2:19c
ENDF/B-VII.1	-0.06	-0.22	0.23
ENDF/B-VIII.0	-0.17	-0.17	-0.18
JENDL-4.0	-0.05	-0.24	0.35
JENDL-5.0	-0.02	-0.10	-0.16

2.3 Pin power distribution

Figure 3 plots the locations of the measured fuel pin rods for KRITZ-2:13c, KRITZ-2:13h, and KRITZ-2:19c for better understand. Figures 5~6 presents the pin power distributions calculated by the McCARD code with four evaluated nuclear data libraries. The calculated pin power values normalized to the maximum pin power. Then, it was calculated by averaging the value of the pin symmetrical in the core.

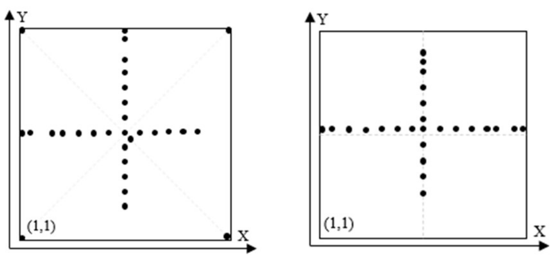

Fig. 3. Measured pin locations for KRITZ-2:13c, KRITZ-2:13h core (left) and KRITZ-2:19 (right) (Each left bottom pin position is X=1, Y=1)

Figures 6~7 compares C/M-1 values for the normalized pin power distributions. Table IV represents the root mean square (RMS) errors for the fuel pin power distributions of the McCARD analyses using the ENDF/B-VII.1, ENDF/B-VIII.0, JENDL-4.0 and JENDL-5.0 evaluated nuclear data libraries. The maximum RMS errors of KRITZ-2:13c and KRITZ-2:13h were 1.00% and 1.43 % in ENDF/B-VII.1. In the KRITZ-2:19c case, the maximum RMS error was 1.32% with ENDF/B-VIII.0. Overall, the results were good agreement between the measurements and McCARD.

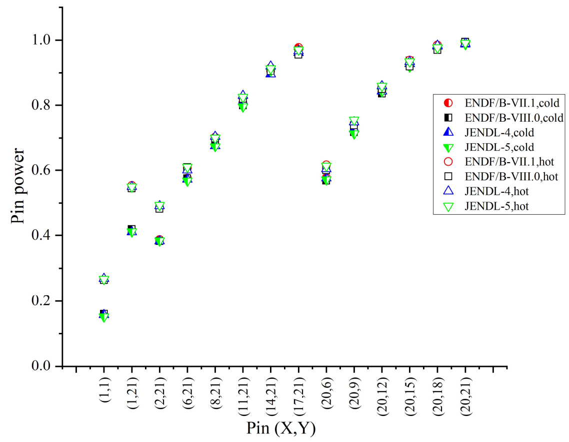

Fig. 4. Pin power distribution for KRITZ-2:13

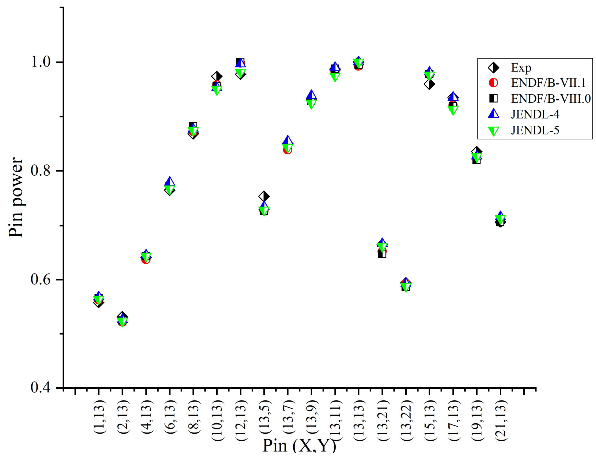

Fig. 5. Pin power distribution for KRITZ-2:19c

Table IV. RMS error of pin power distributions by the McCARD with various evaluated nuclear data libraries

RMS error (%)	ENDF/B-VII.1	ENDF/B-VIII.0	JENDL-4.0	JENDL-5.0
KRITZ-2:13c	1.00	0.87	0.78	0.66
KRITZ-2:13h	1.43	0.70	1.30	1.37
KRITZ-2:19c	1.22	1.32	1.13	1.19

2.4 Uncertainty analysis of pin power distributions by Wilk's formula

Firstly, the Bartlett's tests were performed to check if the KRITZ-2:13c, KRITZ-2:13h and KRITZ-2:19c pin power distribution results are from populations with equal variances. The number of samples are 78 from 3 subsets (k). Table V shows the χ^2 values at 95% confidence level by Bartlett's tests. It was confirmed that the pin powers except the JENDL-5.0 case are normally distributed because the calculated χ^2 values were less than the upper tail critical value (=5.99) with 95% confidence level, $\chi^2_{2,\,0.05}$.

Table V. χ^2 values by the McCARD with various evaluated nuclear data libraries

$\chi^2_{2,0.05}$	χ^2 values of pin power distributions			
	ENDF/B-VII.1	ENDF/B-VIII.0	JENDL-4	JENDL-5
5.99	5.74	5.57	5.70	10.93

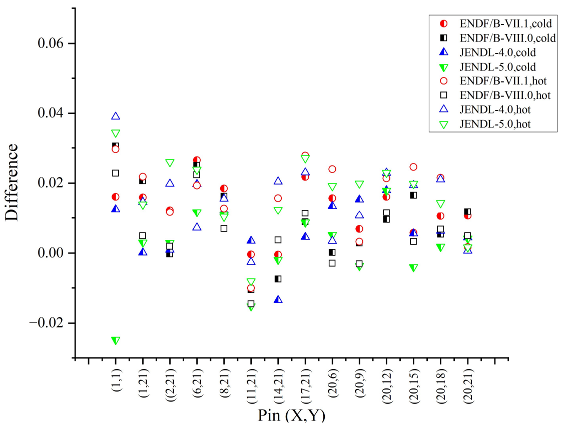

Fig. 6. KRITZ-2:13, Comparison of pin powers(C/M-1)

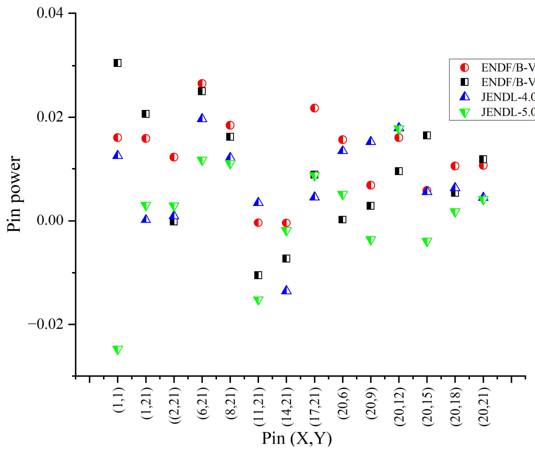

Fig. 7. KRITZ-2:19c, Comparison of pin powers(C/M-1)

Figures 8~11 represent the distributions of the uncertainty of pin power. Because the Wilk's formula [6] can apply the estimation of their uncertainties regardless of the population. In this study, the uncertainty of the pin power predictive capabilities of the McCARD code with various evaluated nuclear data libraries were calculated with the Wilk's formula.

$$\sum_{k=0}^{n-p} {}_nC_k \alpha^k (1-\alpha)^k \geq \beta \qquad (1)$$

$$X^{95\times95} = \bar{X} + k_s^{95\times95} \cdot \sigma_s(X) \qquad (2)$$

Equation (1) shows the one-sided order Wilk's formula to obtain the number of input sample to calculate α×100 (%) confidence that will be located above the β×100 (%). Because the 78 samples were used in this study, the Wilk's formula considering the first-order one sided 95% confidence 95% upper limit $X^{95\times95}$ by Eq. (2) was used.

As shown in Figs. 8~11, it is observed that the uncertainties of the pin power distribution by the McCARD code with ENDF/B-VII.1, ENDF/B-VIII.0, JENDL-4.0, JENDL-5.0 are 2.62 %, 2.71 %, 2.76 % and 2.37 %, respectively. In this study, the variance bias of the local tally in MC eigenvalue calculations was not considered. This may lead to the overestimation of the uncertainties of the pin power distributions [7]. In the near future, the estimation of the variance bias for the KRITZ critical experiment benchmark will be conducted by McCARD.

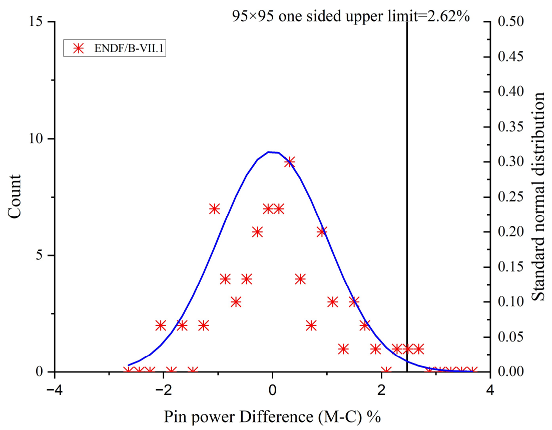

Fig. 8. Uncertainty of pin power with ENDF/B-VII.1 library

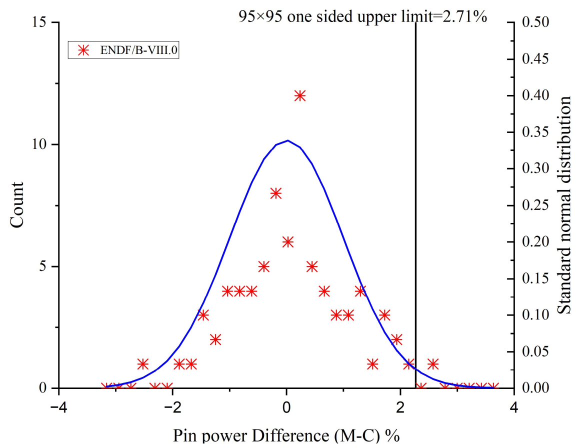

Fig. 9. Uncertainty of pin power with ENDF/B-VIII.0 library

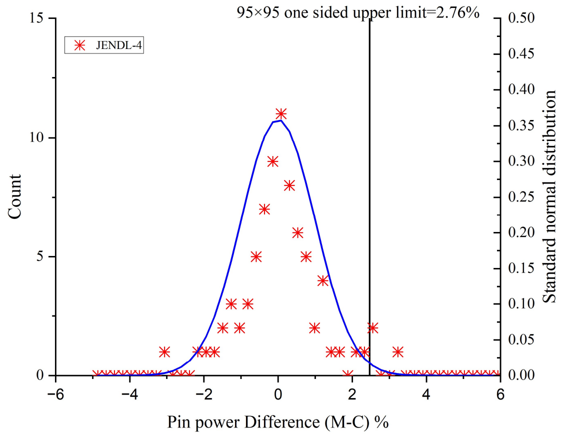

Fig. 10. Uncertainty of pin power with JENDL-4.0 library

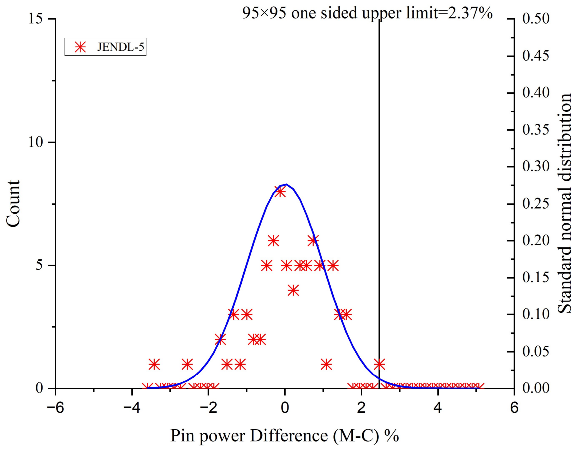

Fig. 11. Uncertainty of pin power with JEND-5.0 library

3. Conclusions

The purpose of this study is to determine the accuracy of the prediction results of the McCARD code analyzing UO_2 and MOX fuel systems at different temperatures, and to compare the accuracy of the prediction results and uncertainty of the pin power distribution with the ENDF/B-VII.1, ENDF/B-VIII.0, JENDL-4.0, and JENDL-5.0 evaluated nuclear data libraries.

The k_{eff} errors from reference data to measured data were less than 0.35 % while the RMS errors of the pin power distributions are less than 1.43%. The difference in the RMS errors of the pin power distributions for each evaluated nuclear cross section library is not significant because of its normalization procedure. However, it is noted that the up-to-date libraries (i.e., ENDF/B-VIII.0 and JENDL-5.0) predict the criticality better than the existing libraries (i.e., ENDF/B-VII.1 and JENDL-4.0).

In addition, the uncertainty analyses for the pin-power prediction by the McCARD were performed with the one-sided order Wilk's formula. It was concluded that the maximum uncertainty of the pin power distribution by the McCARD code is 2.76%. A further in-depth analysis on the effect for variance bias will be carried out to confirm the source of the errors in the pin power distribution.

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