Available online at www.sciencedirect.com
ScienceDirect
Nuclear Data Sheets 118 (2014) 405–409
Nuclear Data Sheets
www.elsevier.com/locate/nds

Benchmark Calculations for Reflector Effect in Fast Cores by Using the Latest Evaluated Nuclear Data Libraries

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Benchmark calculations for reflector effects in fast cores were performed to validate the reliability of scattering data of structural materials in the major evaluated nuclear data libraries, JENDL-4.0, ENDF/B-VII.1 and JEFF-3.1.2. The criticalities of two FCA and two ZPR cores were analyzed by using a continuous energy Monte Carlo calculation code. The ratios of calculation to experimental values were compared between these cores and the sensitivity analyses were performed. From the results, the replacement reactivity from blanket to SS and Na reflector is better evaluated by JENDL-4.0 than by ENDF/B-VII.1 mainly due to the $\bar{\mu}$ values of Na and ^{52}Cr.

I. INTRODUCTION

The impact of the scattering angular distributions (i.e. $\bar{\mu}$) and scattering cross sections on evaluation of neutron multiplication factors (k_{eff}) has been recently pointed out for small fast reactor cores with reflector. In the Working Party on International Nuclear Data Evaluation Cooperation of OECD/NEA, subgroup 35 has been established for re-evaluation of scattering angular distribution in the fast energy [1]. The subgroup focuses on the issues to improve evaluation method of scattering angular distributions and to identify integral benchmarks where scattering data play an important role.

In the present paper, integral benchmark tests for reflector effects in fast cores are carried out by using the major evaluated nuclear data libraries, JENDL-4.0 [2], ENDF/B-VII.1 [3] and JEFF-3.1.2 [4]. The FCA X-1 core with radial depleted uranium blanket and the FCA X-2 core with stainless steel (SS) and sodium (Na) reflector [5] are selected as suitable integral experiments for reflector effects. The tendencies of ratios of calculation to experimental (C/E) values between these cores are discussed to validate the reliability of scattering data of structural materials. Further, the ZPR experiments given in the International Criticality Safety Benchmark Evaluation Project (ICSBEP) handbook are tested [6, 7]. The benchmark calculations for k_{eff} values of these cores are done by using the continuous energy Monte Carlo code MVP [8]. Furthermore, the sensitivity analyses are performed to clarify differences between the libraries.

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http://dx.doi.org/10.1016/j.nds.2014.04.092
0090-3752/2014 Published by Elsevier B.V.

II. BRIEF DESCRIPTION OF CORES

The specifications of the FCA and ZPR cores are summarized in Table I. The compositions of their outer radial regions are shown in Table II. FCA X-1 and X-2 were constructed at the Fast Critical Assembly (FCA) facility of JAEA for the mock-up experiments of the Joyo Mk-II core. In the FCA cores, the fuel regions were commonly composed of plutonium, low enriched metal uranium, depleted uranium oxide, sodium and Al_2O_3. FCA X-1 had the depleted uranium blanket and FCA X-2 the reflector composed of SS and Na. ZPR-3/53 [6] and -3/54 [7] were constructed at the Zero Power Reactor (ZPR) critical assembly of Argonne National Laboratory for benchmark experiments of fast reactor physics data and methods. In the ZPR cores, the fuel regions were commonly composed of Pu-Al alloy, Pu-U-Mo alloy and graphite. ZPR-3/53 had the depleted uranium blanket and ZPR-3/54 the iron reflector.

III. BENCHMARK RESULTS

The benchmark tests for k_{eff} values are performed by the MVP code. For the k_{eff} values of the FCA X-1 and X-2, the as-built models with heterogeneous cell structure in the 3-dimensional XYZ geometry are adopted. The experimental uncertainties in k_{eff} values of the FCA cores are less than $0.1\%\Delta k/k$. In contrast, the k_{eff} values of ZPR-3/53 and -3/54 are tested by the RZ models given in the ICSBEP handbook [6, 7]. The correction factors in the handbook are adopted for the transformation of k_{eff} from the RZ benchmark models to the as-built models. The experimental uncertainties in k_{eff} values of the ZPR cores are about up to $0.27\%\Delta k/k$.

TABLE I. Specification of benchmark cores.

Core	FCA X-1	FCA X-2	ZPR-3/53	ZPR-3/54
Core region	Pu+Enriched Uranium ($Pu^{*}: 28wt\%, ^{235}U^{**}: 12wt\%$)		Pu+Depleted Uranium ($Pu^{*}: 40wt\%$)	
Radius (cm)	28.71	28.03	34.36	32.08
Outer radial region	Depleted uranium blanket	Stainless steel (SS) + Na reflector	Depleted uranium blanket	Iron (Fe) reflector
Thickness (cm)	33.03	33.71	34.14	32.61

* : Plutonium content, ** : ^{235}U enrichment

TABLE II. Compositions of outer radial regions ($\times 10^{22}$/cc).

Nuclide	FCA X-1 Blanket	FCA X-2 SS+Na refl.	ZPR-3/53 Blanket	ZPR-3/54 Fe refl.
^{235}U	0.008	-	0.008	-
^{238}U	4.020	-	3.993	-
C	-	0.016	0.001	0.056
Na	-	0.574	-	-
Si	-	-	0.006	0.006
Cr	0.181	1.159	0.111	0.114
Mn	0.012	0.063	0.004	0.055
Fe	0.647	4.022	0.452	7.471
Ni	0.079	0.511	0.045	0.046

TABLE III. Ratio of calculation to experimental values (C/E).

Library	FCA X-1 Blanket	FCA X-2 SS+Na refl.	ZPR-3/53 Blanket	ZPR-3/54 Fe refl.
JENDL-4.0	1.0017	1.0025	1.0091	1.0125
difference*	0.08%		0.34%	
ENDF/B-VII.1	0.9979	0.9953	1.0067	1.0092
difference*	−0.26%		0.25%	
JEFF-3.1.2	1.0037	1.0020	1.0045	1.0087
difference*	−0.17%		0.42%	

*Difference of C/E values between blanket and reflector cores

Since the fuel components are the same between the core with blanket and that with reflector, the uncertainty in the replacement reactivity from blanket to reflector can be assumed to be much less than that in the k_{eff} values. In addition, we assume that the correction factors given for an ENDF library are similar between ZPR-3/53 with blanket and ZPR-3/54 with reflector, and apply these factors for the calculation results by JENDL-4.0. Under these assumptions, a comparison between the ZPR cores is available to test the replacement reactivity from ^{238}U blanket to iron reflector and a comparison between the FCA cores is available to test the replacement reactivity from ^{238}U blanket to SS and Na reflector. The number of neutron histories is 10 million for each calculation. The statistical uncertainties by Monte Carlo calculation are less than 0.01%$\Delta k/k$. The C/E values for k_{eff} are summarized in Table III.

As for the ZPR cores, the C/E values by all the nuclear data libraries commonly increase by replacing ZPR-3/53 with -3/54, which means overestimations of the replacement reactivity from blanket to iron reflector. The differences of the C/E values between the ZPR cores are in the range from 0.25 to 0.42%.

The tendencies of C/E values between FCA X-1 and X-2 are as follows. For JENDL-4.0, the stable tendency of the C/E values by replacing FCA X-1 with X-2 means that the replacement reactivity from blanket to SS and Na reflector agrees with the experimental value. The differences of the C/E values between the FCA cores are −0.26% and −0.17% for ENDF/B-VII.1 and JEFF-3.1.2, respectively.

IV. SENSITIVITY ANALYSES

Sensitivity analyses are done to specify sources of k_{eff} difference between the nuclear data libraries. By using the diffusion calculation code CITATION [9] and the generalized perturbation code SAGEP [10], sensitivity coefficients based on JENDL-4.0 are evaluated as

$$S^{J40}_{m,x,g} = \left(\frac{\Delta k_{eff}/k_{eff}}{\Delta\sigma_{m,x,g}/\sigma_{m,x,g}} \right)_{J40} . \quad (1)$$

Here, x, m and g denote reaction type, nuclide and energy group, respectively. The effective cross sections are calculated by using the cell calculation code SLAROM-UF [11]. The differences in k_{eff} from JENDL-4.0 to the other libraries are obtained as

$$(\Delta k/k)_{J40\rightarrow other} = \sum_{m,x,g} S^{J40}_{m,x,g} \cdot \frac{\sigma^{other}_{m,x,g} - \sigma^{J40}_{m,x,g}}{\sigma^{J40}_{m,x,g}} . \quad (2)$$

Fig. 1 shows the difference in k_{eff} by changing JENDL-4.0 to ENDF/B-VII.1 for the ZPR cores. Since the fuel regions of ZPR-3/53 and ZPR-3/54 include Pu and C in common, the sensitivities and contributions of Pu and C are similar between these cores as shown in Fig. 1, and therefore, the uncertainties of criticality due to Pu and C vanish in the replacement reactivity. Thus, it indicates that the replacement reactivity from blanket to iron reflector is affected mainly by ^{238}U and Fe, and the overestimations of the replacement reactivity shown in Table III are attributed mainly to them. Although the σ_{inela} of ^{238}U and σ_{ela} of ^{56}Fe have contributions of $-0.1\%\Delta k/k$ for ZPR-3/53 and -3/54, respectively, they cancel out in the total difference in k_{eff}.

Fig. 2 shows the difference in k_{eff} by changing JENDL-4.0 to ENDF/B-VII.1 for the FCA cores. Since the fuel regions of FCA X-1 and X-2 include ^{235}U, Pu, O and Al in common, their contributions are also similar between the FCA cores. From the same reason as the ZPR cores,