USE OF ENDF/B-VI.5 AND JEF-2.2 EVALUATIONS FOR THE 3-D VENUS-2 BENCHMARK

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ABSTRACT

The OECD/NEA launched a benchmark based on three-dimensional VENUS-2 experimental results. In the previous two-dimensional benchmark, even though the results were generally in good agreement with the experimental data, all the calculations overestimated pin powers of MOX rods and slightly underestimated those of UO_2 rods. Therefore, the objective of this benchmark is to investigate more thoroughly calculation methods (codes and nuclear data) for MOX-fuelled core. For this purpose, SCK•CEN (the Belgian nuclear research centre, at Mol) released to the OECD/NEA the three-dimensional VENUS-2 MOX core experimental data in October 2000. The experimental results for this benchmark mainly consist of the measured fission rate distributions (by γ-scanning) of six fuel rods at 21 different axial points and the multiplication factor.

This paper presents the results obtained by using the Monte Carlo code MCNP (version 4C) with two different nuclear data evaluations: ENDF/B-VI (release 5) and JEF-2.2. The sensitivity of some requested results (K_∞ of the 3 different VENUS-2 fuel cells, axial pin power distributions of six fuel rods, and K_{eff}) to the nuclear data used is analysed.

1. INTRODUCTION

The VENUS (***V****ulcain* ***E****xperimental* ***Nu****clear* ***S****tudy*) criticality facility is a water moderated zero power reactor located at SCK•CEN, Mol (Belgium), built in 1963-1964. Since then, many modifications and improvements have been undertaken in order to study LWR core designs and to provide experimental data for nuclear data and code validation.

In a series of experiments in the VENUS facility, the VENUS 2 core configuration was obtained by replacing the peripheral UO_2 fuel by MOX fuel. Even though the VENUS-2 experiments (October 1986 - December 1987) were carried out originally for studies on lead factor reduction at the pressure vessel, the measured results contain very useful data for MOX-fuelled system benchmarks for both reactor physics and dosimetry calculations.

The following measured data are available from the VENUS-2 experiments: (1) pin power (fission rate) distribution for 128 fuels rods at the mid-plane of the core, axial buckling measurement, reaction rate measurement at several important positions in the reactor using $^{58}Ni(n,p)$, $^{115}In(n,n')$, $^{103}Rh(n,n')$, $^{64}Zn(n,p)$, $^{237}Np(n,f)$, $^{238}U(n,f)$ and $^{27}Al(n,\alpha)$ detectors, and (2) axial pin power distribution of 6 fuel rods at 21 axial levels and the axial reaction rates at different positions using $^{237}Np(n,f)$, $^{235}U(n,f)$ and $^{64}Zn(n,p)$ detectors

The measured results of pin power (fission rate) distribution for 128 fuels rods at the mid-plane of the core were used for the previous OECD/NEA international benchmark on two-dimensional MOX core calculations. This was the first experimental result based MOX core benchmark and completed in 2000 [1]. The results of the 2-D benchmark were generally in good agreement with the experimental data. However, all the calculations overestimated pin powers of MOX rods and slightly underestimated those of UO_2 rods. Therefore, a need was felt for a more thorough investigation into calculation methods (codes and nuclear data) for MOX-fuelled core and, for this purpose, SCK•CEN (the Belgian nuclear research centre at Mol) released to the OECD/NEA the three-dimensional VENUS-2 MOX core experiment data in October 2000 [2]. Based on these 3-D results, the benchmark specification was issued to the participants [3].

This paper presents the results of SCK•CEN for the 3-D VENUS-2 MOX core benchmark exercise. The calculations were performed by using the Monte Carlo code MCNP (version 4C) with two different nuclear data evaluations: ENDF/B-VI (release 5) and JEF-2.2. The sensitivity of some requested results (K_∞ of the 3 different VENUS-2 fuel cells, axial pin power distributions of six fuel rods, and K_{eff}) to the nuclear data used is analysed.

2. VENUS-2 CORE DESCRIPTION

A schematic horizontal cross-section of the VENUS-2 core is shown in Figure 1 in which the positions of 6 fuel rods measured are also marked. The VENUS-2 core comprises, in the central part, four assemblies 15×15 of UO_2 fuel pin enriched with 3.3 wt. % in ^{235}U. Of the eight assemblies on the periphery of the core, all of which contain fuel pins 4.0 wt.% enriched in ^{235}U (called UO_2 4/0 pins), eight rows of the most external fuel pins have been replaced by MOX fuel pins (UO_2-PuO_2) enriched with 2.0 wt.% in ^{235}U and 2.7 wt.% in high grade plutonium. There are 5 Pyrex pins in 1/8 of the core. The fuel cell pitch is 1.26 cm. More details about the VENUS-2 geometry and fuel and Pyrex cell description/composition can be found in reference 3.

Figure 2 shows a vertical cross-section of the core with corresponding axial co-ordinates. Vertically the core may be divided, from bottom to top, in 10 parts: (1) the *reactor vessel* (stainless steel), (2) the *lower filling* (water), (3) the *reactor support* (water and stainless steel, not shown in the figure), (4) the *bottom grid* (32.8 vol % water and 67.2 vol % stainless steel), (5) the *lower reflector* (mainly water and Plexiglas); the reflector composition changes a little from one fuel region to another, depending on the structure of the corresponding fuel pins, (6) the *active height* (fuel and stainless steel), (7) the *upper reflector* (mainly water and Plexiglas), including the *intermediate grid* (63.4 vol % water and 36.6 vol % Plexiglas); the reflector composition changes a little from one fuel region to another, depending on the structure of the corresponding fuel pins, (8) the *upper grid* (63.4 vol % water and 36.6 vol % stainless steel), (9) the *upper filling* (water), and (10) the VENUS room environment (air).

The material of interest (i.e. fuel or stainless steel) is located from level 105 cm to level 155 cm (50 cm length). To ensure proper axial buckling conditions, both lower and upper axial reflectors are "quasi" infinite for all the regions (the effective extrapolation length is about 7 cm); where necessary water is replaced by Plexiglas.

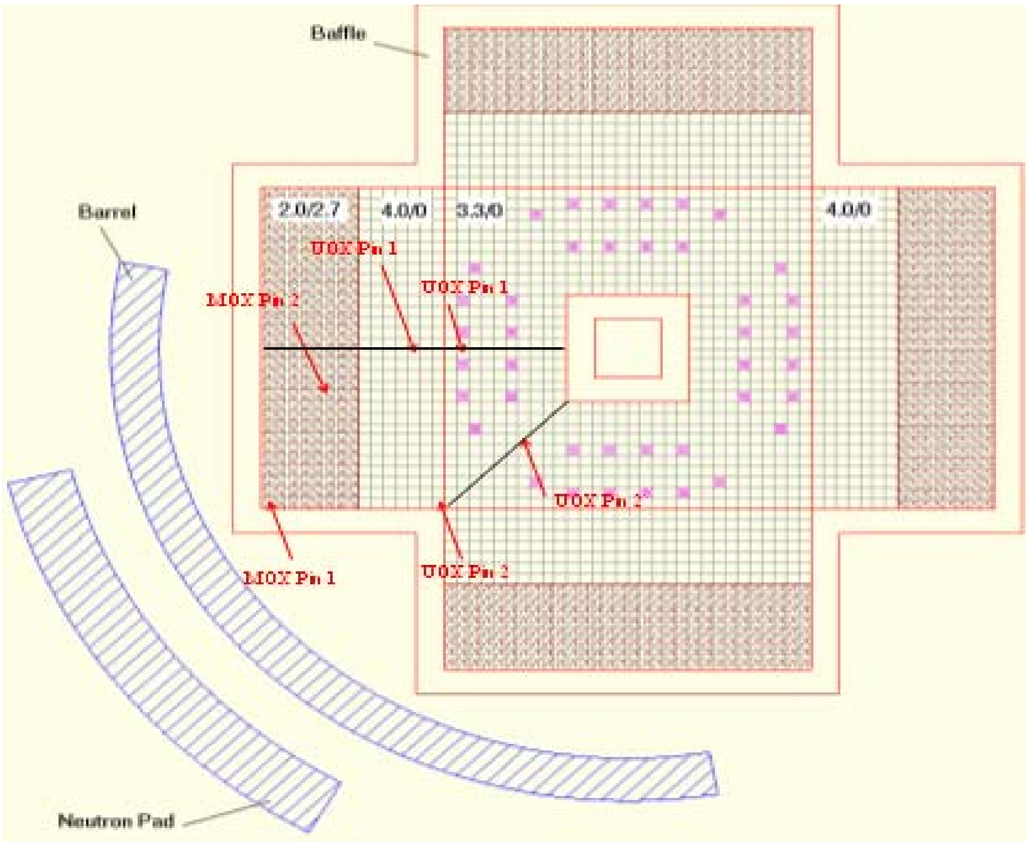

Figure 1. VENUS-2 core geometry and positions of measured fuel pins

The fission rate distributions of six fuel pins (two UO_2 3.3/0, two UO_2 4/0 and two MOX 2/2.7 pins) were measured axially by γ scanning after an irradiation of 8h at 90% of the VENUS maximum power. The reported uncertainty of the measured data (1σ) is ±2.2% in UO_2 and ±3.4% in MOX pins [2].

A complete description of the benchmark model, including all geometry and material data required to develop the detailed computational model of the 1/4 fraction of the VENUS-2 core can be found in [3].

The results to be reported were the following: from each fuel cell calculation (UO_2 3.3%, UO_2 4.0%, 2/2.7 MOX), K_∞, absorption and fission reaction rates per isotope (energy integrated and in 3 groups involving the 5 keV and 4 eV boundaries).

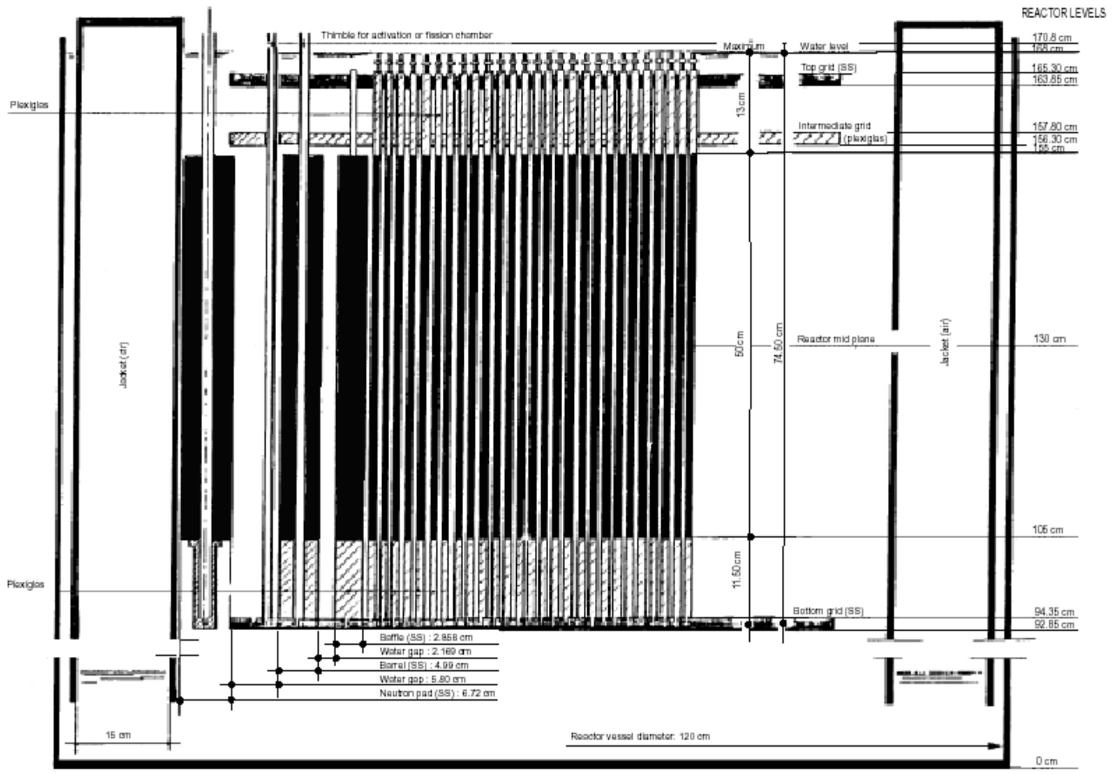

Figure 2. Vertical cross-section of the VENUS-2 reactor configuration

From core calculations, it was requested to report K_{eff}, normalized radial fission rates on 1/8 of the core which consists of 325 fuel pins (normalization should be made to a core average fission rate = 1 fission/sec/fuel cell) and normalized axial fission rates of the six fuel pins. The results of radial fission rate distribution of 325 fuel pins are not presented in this paper. This paper will mainly discuss the results of axial pin powers of 6 fuel rods.

3. CALCULATION METHODOLOGY AND NUCLEAR DATA

All the cell and core calculations for the 3-D VENUS-2 benchmark were performed by using the Monte Carlo code MCNP (version 4C) [4]. Self-shielding effects in the unresolved resonance range were taken into account by a probability-table treatment for some isotopes. 1/4 of the core was modelled in 3 dimensions, respecting all the details including the structure materials: barrel, neutron pad, vessel, grids, etc. An important number of histories were used to get more confident results: 500000 particles per cycle (700 cycles with 80 inactive ones).
To calculate the axial pin power distribution at a specific position, we estimated the results inside a volume of (1 cm^3) in which the specified position was the centre.

With regard to the nuclear data used, mainly two sets of nuclear data evaluations were used: ENDF/B-VI.5 from the MCNP-4C package [4] and a locally generated library based on JEF-2.2 [5, 6]. The latter was prepared based on the JEF-2.2 with the nuclear data processing code system NJOY-97.99 except for ^{239}Pu cross sections. For this isotope, the "JEF-CEA-corr. ^{239}Pu" file was used. Compared to the original JEF-2.2 officially released version, some modifications were made: they included corrections concerning the distribution of the neutron width of ^{239}Pu for L=1/J=1 and the removal of the partial fission channels because there was an inconsistency regarding the partial fission channels which did not give an exact sum of the total fission channel in the JEF-2.2 evaluation [7, 8].

4. RESULTS AND DISCUSSIONS

4.1. CELL CALCULATIONS

Infinite multiplication factor (K_∞) and reaction rates

As shown in Table 1, from cell calculations, K_∞ values are much higher in the JEF-2.2 based results than in the ENDF/B-VI based ones. The differences in K_∞ values are more pronounced for the UO_2 cells (862 pcm and 727 pcm as differences for the UO_2 3.3% and UO_2 4.0% cells, respectively) than for the MOX 2/2.7 cell (284 pcm). The ^{238}U energy integrated absorption rate is higher by 1.6% in the ENDF/B-VI library than in the JEF-2.2 library for UO_2 cell and its absorption contribution is more than 30% of the total absorption. However, the ^{235}U energy integrated fission rates do not show an important discrepancy between the two basic libraries. Indeed, in the energy range E<5 keV, where the ^{235}U fission contribution to the total fissions is more than 92%, the ^{235}U fission rates are almost the same (the difference is less than 0.33%) between ENDF/B-VI and JEF-2.2 evaluations. This could explain the difference obtained for K_∞ values for UO_2 cells.

Concerning the MOX cell, ^{238}U contribution to the total absorption rate is less important (less than 25%), and the ^{239}Pu fission rate is slightly higher (about +0.35%) in the JEF-2.2 library than in the ENDF/B-VI library, in the thermal energy range where its fission contribution is about 52% of the total fission. Therefore, the discrepancy between both evaluations is less pronounced in the MOX cell than in the UO_2 cells.

Table 1. K_∞ values with different nuclear data

Cells / Library	ENDF/B-VI	JEF-2.2
UO_2 3.3%	1.40382 ± 0.00056	1.41244 ± 0.00052
UO_2 4.0%	1.33572 ± 0.00055	1.34299 ± 0.00056
MOX	1.25555 ± 0.00061	1.25839 ± 0.00063

4.2. CORE CALCULATIONS

Effective multiplication factor (K_{eff})

The calculated K_{eff} values obtained from MCNP-4C calculations with ENDF/B-VI and JEF-2.2 are reported in Table 2. The corresponding statistical errors of MCNP calculations and the differences compared to the experimental value (=1.0) are also presented.

Table 2. K_{eff} values with different nuclear data

Library	K_{eff}	Difference (pcm)
ENDF/B-VI	1.00073 ± 0.00006	+73
JEF-2.2	1.00666 ± 0.00006	+666

ENDF/B-VI based result shows a good agreement with the experimental value (=1.0) with an over prediction of 73 pcm. However, the JEF-2.2 evaluation overestimates the K_{eff} value by more than 660 pcm. The same trend with JEF-2.2 was observed in calculated K_{∞} values for the 3 fuel pin cells. However, for the both evaluations, the maximum discrepancies of K_{eff} do not exceed 1%.

For both core calculations, the statistical errors (1σ) in calculated K_{eff} values are 6 pcm. The uncertainty of the K_{eff} measurement is about 32 pcm.

Axial pin power results

The positions of six measured fuel pins are shown in Figure 1. With respect to the core centre, their locations are (-37.17, +18.27), (-30.87, +5.67), (-22.05, +0.63), (-19.53, +18.27), (-17.01, +0.63) and (-10.71, +10.71) in cm. They correspond to: two MOX 2/2.7, two UO_2 4/0 and two UO_2 3.3/0 pins. The axial measurements were carried out at 21 different vertical planes along 50 cm of the fuel pin length (from 105 cm to 155 cm): starting from 110 cm, and at every 2 cm upwards to 150 cm.

The axial pin power distribution of the measured 6 fuel pins are calculated and compared with the measured values as C/E. In the following analysis of calculated results, the uncertainty of the measured data (1σ) should be taken into account: they are ±2.2% in UO_2 and ±3.4% in MOX pins [2].

For the UO_2 4/0 and UO_2 3.3/0 pins, as shown in Figures 3 and 4, most of the calculated axial pin power results (based on JEF-2.2 and ENDF/B-VI cross-sections) fit the experimental values sufficiently well, especially for the positions in the central part of the fuel pin. Indeed, most of the calculated results show discrepancies within ±1.5%. Only a few axial positions (located at both edges of the pins (top and bottom parts near the Plexiglas region) show discrepancies by up to 3 or 4%.

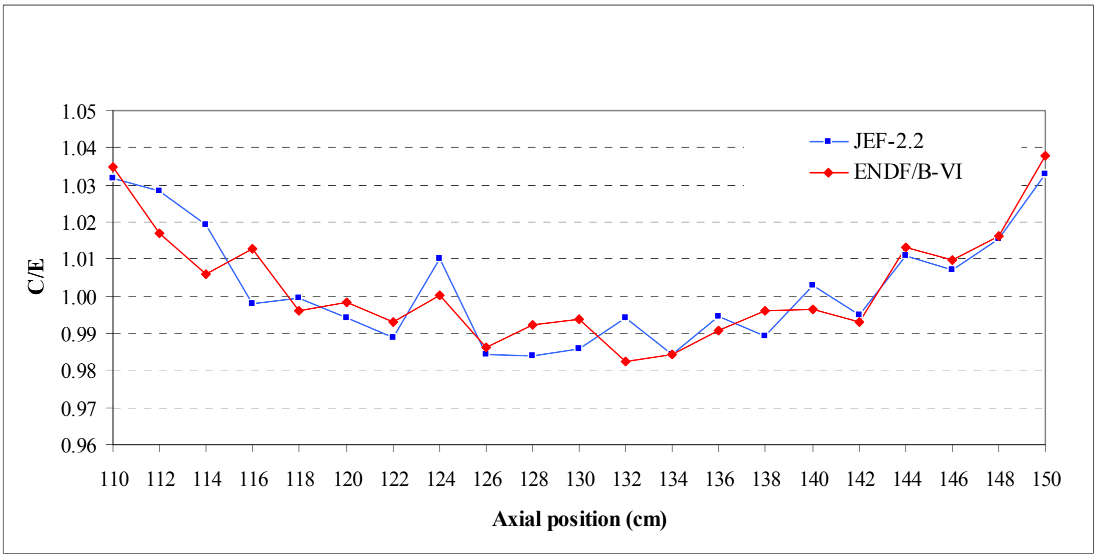

Figure 3. Axial pin power distribution for UO_2 3.3/0 pin 2

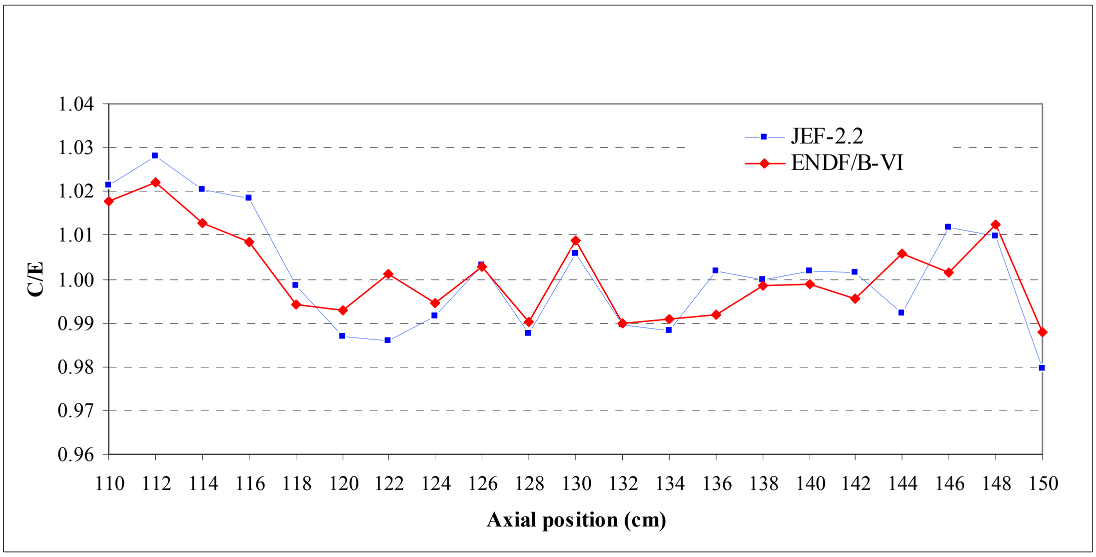

Figure 4. Axial pin power distribution for UO_2 4/0 pin 1

The C/E comparison for the axial pin power distribution of the two MOX 2/2.7 pins are shown in Figures 5 and 6.

In general, the discrepancies compared to the experimental values are larger for the MOX pins than for the UO_2 pins, but for most of the axial pin positions, the discrepancies are still within ±2%. The effect of the proximity to the Plexiglas region is more pronounced: some positions located near the two edges of the pin show deviations up to 5%.

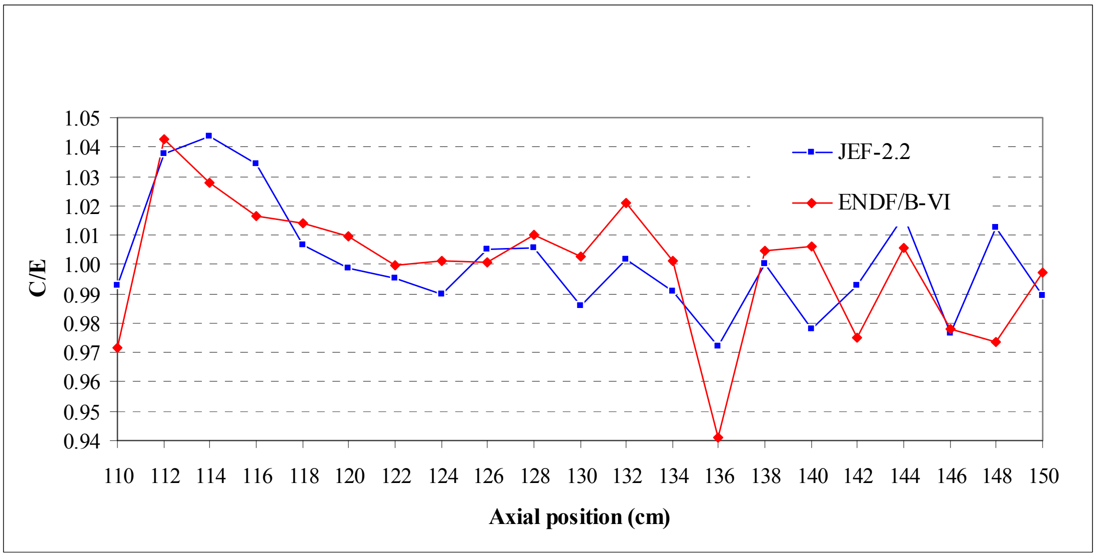

Figure 5. Axial pin power distribution for MOX 2/2.7 pin 1

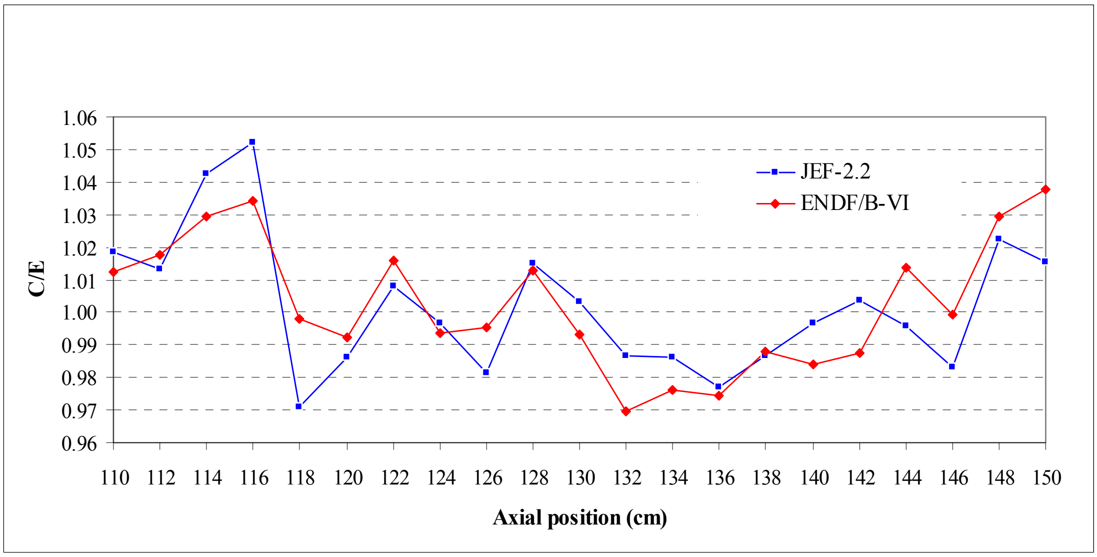

Figure 6. Axial pin power distribution for MOX 2/2.7 pin 2

The relative errors (1σ) concerning MCNP calculation results are small for most of the calculated power positions. For the UO_2 pins (UO_2 4/0 and UO_2 3.3/0 pins), the average of the relative error is less than 0.7% whereas for the MOX 2/2.7 pins, this value is about 1.5%. Table 3 summarises the average deviations (%) for each pin and the sensitivity to the nuclear data used.

Table 3. Deviation (%) from the average value of the results

	2/2.7 MOX Fuel		UO_2 4/0% Fuel		UO_2 3.3% Fuel	
Library/Pin	Pin 1	Pin 2	Pin 1	Pin 2	Pin 1	Pin2
ENDF/B-VI	2.23	2.01	0.98	1.57	1.74	1.51
JEF-2.2	1.93	2.10	1.34	1.18	1.68	1.58

Based on the above comparison, we cannot conclude which evaluation gives better results. Both evaluations give very similar pin power distribution results. However, taking into account the reported uncertainties of ±2.2% in UO_2 and ±3.4% in MOX pin power measurements, both MCNP calculation results are reasonably good compared with experimental data.

5. CONCLUSIONS

With a view to a thorough investigation into calculation methods (codes and nuclear data) for MOX-fuelled core, the OECD/NEA launched a benchmark based on three-dimensional VENUS-2 MOX core experimental results. In this benchmark, measured fission rate distributions of six fuel rods at 21 different axial points and the multiplication factor were mainly investigated.

Full three-dimensional Monte Carlo calculations using MCNP (version 4C) were carried out with two different nuclear data evaluations: ENDF/B-VI (release 5) and JEF-2.2. The sensitivity of some requested results (K_∞ of the 3 different VENUS-2 fuel cells, axial pin power distributions of six fuel rods, and K_{eff}) to the nuclear data used is analysed.

To summarise, concerning the K_{eff} value, the ENDF/B-VI based K_{eff} value is in good agreement with the experimental values (the discrepancy is less than 73 pcm), whereas the JEF-2.2 evaluation with the "JEF-CEA-corr. ^{239}Pu" file overestimates this value by more than 660 pcm.

For the axial pin power prediction, both evaluations (ENDF/B-VI and JEF-2.2) are fitting sufficiently well the experimental values. Discrepancies are less than ±2% for most of the pin positions. They are much closer to the experimental values when positions are located in the central part of the fuel pins. Near the two axial edges of the pins, the deviation becomes larger. For the UO_2 pins, most of the calculated results show discrepancies within ±1.5%. Only a few axial positions (located at both edges of the pins (top and bottom parts near the Plexiglas region) show discrepancies by up to 3 or 4%. The discrepancies compared to the experimental values are larger for the MOX pins than for the UO_2 pins, but for most of the axial pin positions, the discrepancies are still within ±2%. The effect of the proximity to the Plexiglas region is more pronounced, some positions located near the two edges of the pin show deviation up to 5%.

Taking into account the reported uncertainties of ±2.2% in UO_2 and ±3.4% in MOX pin power measurements, MCNP calculation results with both ENDF/B-VI and JEF-2.2 are reasonably good compared with experimental data.

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