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THE SPECTRAL INDICES OF THE IPEN/MB-01 REACTOR: MEASUREMENTS AND CALCULATION

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ABSTRACT

This experimental work aims to obtain the spectral indices $^{28}\rho$, $^{25}\delta$, C*, C8/F and $(C8/F)_{epith.}$ of the core of the IPEN/MB-01 nuclear reactor. The measurements were performed with high precision at the asymptotic central core region. Specifically for $^{28}\rho$ and $^{25}\delta$, this work adopts a novice approach based on the direct gamma spectrometry of the irradiated fuel rods and the traditional one based on uranium foils. The total and epithermal reaction rates were obtained from the direct gamma spectrometry of an irradiated fuel element at the maximum neutron flux position. The gamma spectrometry was performed by a fuel rod scanning equipment with a collimator of 1 cm opening size. Correction factors for the cadmium perturbations were obtained both experimentally and from a calculational approach carried out by MCNP-4B. Furthermore, this work also introduces a new spectral index namely $(C8/F)_{epith}$ for verifying the adequacy of the nuclear data at the epithermal neutron energy region. The analyses reveal that the correction factors are very sensitive to the nuclear data library used by MCNP-4B; namely ENDF/B-V and ENDF/B-VI.5 libraries. The best results are obtained when the correction factors and the spectral indices are calculated with ENDF/B-VI.5.

1. INTRODUCTION

Experiments involving determination of the reaction rates in the fuel pellets are of fundamental importance to correlate theory and experiment mainly concerning calculational methods and related nuclear data libraries. These experiments are normally performed through the irradiation of bare and cadmium covered fertile and/or fissile foils. Typical examples are the spectral indices $^{28}\rho$ and $^{25}\delta$, which provide the ratio of the epithermal to thermal neutron captures in ^{238}U and the ratio of the epithermal to thermal fission in ^{235}U respectively. The modified conversion factor C* provides the ratio of the total capture in ^{238}U to the fissions in ^{235}U. The spectral index C8/F considers basically the same ratio, but now the total fission in uranium is taken into consideration. The newly proposed spectral index $(C8/F)_{epith}$ considers the same ratio but now considering only the epithermal part (E>0.625eV) of the neutron spectrum.

For a long time, experiments involving reaction rate measurements have been carried out worldwide. The most famous spectral indices measurements are the ones performed in the TRX and BAPL critical facilities selected by the CSEWG [1] (Cross Section Evaluation Working Group) as benchmarks. Numerous researches [2, 3, 4] have assessed the adequacy of several nuclear data libraries by analyzing the CSEWG benchmarks. Historically, there has been a long-standing problem related to the over prediction of the $^{28}\rho$ predicted by several nuclear data libraries [2]. Nowadays there has been a great progress in the calculation schemes so that the main uncertainty of the calculated reactor responses are mostly credited to the nuclear data used in the process. However, the effort placed in these areas has to be followed in the same level by experiments that have uncertainties lower than that inherent in the calculation methodologies. The available experimental support for $^{28}\rho$ possesses high uncertainties and makes use of approximated methods to take into account the cadmium perturbations. Aiming to contribute in these previous aspects, the purpose of this work is to present the experiments performed at IPEN/MB-01 reactor for the determination of its spectral indices $^{28}\rho$, $^{25}\delta$, C*, C8/F, $(C8/F)_{epith}$. The procedure adopts a novice approach for $^{28}\rho$ and $^{25}\delta$ considering the direct gamma spectrometry of a specified length of an experimental fuel rod. The proposed method allows the measurements with high level of accuracy and eliminates most of the calculated corrections due to the cadmium perturbation. Also for a consistency checks $^{28}\rho$ and $^{25}\delta$ will be determined by the common approach based on uranium foil irradiations.

2. EXPERIMENT DESCRIPTION

The IPEN/MB-01 reactor is a zero power-critical facility especially designed for measurement of a wide variety of reactor physics parameters to be used as a benchmark experimental data for checking the calculation methodologies and related nuclear data libraries commonly used in the field of reactor physics. This facility consists of a array of 28 x 26 UO_2 fuel rods, 4,3% enriched and clad by stainless steel (type 304) inside a light water tank. A complete description of the IPEN/MB-01 reactor may be found elsewhere [5].

The experiments were carried out at the asymptotic region of the reactor core. An experimental fuel rod (equal to the one used in the reactor) was irradiated at the central region of the reactor. The irradiation and the subsequent data acquisition use the central region of this fuel rod alternately bare and covered with cadmium sleeves (0,5 mm thickness) of 3, 4, 5, 7 and 10 centimeter length. The total and epithermal reaction rates were obtained by using a gamma spectrometry method employing a fuel rod scanning equipment with a collimator opening size of 1 cm.

The fuel rod was irradiated for 1 hour and the gamma spectrometry was performed by a high pure germanium detector (HPGe) during a decay period of seven days in steps of 1 hour. The experimental data are the integral counting of the photo peaks located at 277.6 and 293.3 keV of the ^{239}Np and ^{143}Ce respectively. Figure.1 shows an example for ^{143}Ce. All the measurements were performed at the standard rectangular configuration (28x26) of the IPEN/MB-01 reactor core as shown in figure. 2.

The ^{238}U capture (C8) in the 1 cm length of the fuel rod is given by Nakajima [6]:

$$C8 = \frac{\lambda_{Np} C_{Np} \exp(\lambda_{Np} t_e)}{f_{\gamma_{Np}} I_{Np} \eta_{Np} \left[1 - \exp(-\lambda_{Np} t_i)\right]\left[(1 - \exp(-\lambda_{Np} t_c)\right]} \qquad (1)$$

Similarly the uranium total fission rate (F) and ^{235}U fission rate (F5) are given by:

$$F = \frac{\lambda_{Ce} C_{Ce} \exp(\lambda_{Ce} t_e)}{Y_{Ce} f_{\gamma_{Ce}} ICe \eta_{Ce} \left[1 - \exp(-\lambda_{Ce} t_i)\right]\left[(1 - \exp(-\lambda_{Ce} t_c)\right]} \qquad (2)$$

$$F5 = F.F_{25} \qquad (3)$$

where λ_{Np} is the ^{239}Np decay constant; C_{Np}, $f_{\gamma Np}$, I_{Np}, and η_{Np} are respectively the integral counts at the end of the irradiation, the fuel rod self-shielding factor, the gamma emission probability, the global counting efficiency, all for the ^{239}Np photo peak located at 277.6 keV; t_e is the counting waiting time,

t_i is the irradiation time; t_c is the counting time; λ_{Ce} is the ^{143}Ce decay constant; C_{Ce}, $f_{\gamma Ce}$,I_{Ce}, η_{Ce} are respectively the integral counts at the end of the irradiation; the self-shielding factor, the gamma emission probability; the global efficiency all for the ^{143}Ce photo peak located at 293.3 keV; F_{25} is the ^{235}U relative fission density and Y_{Ce} is the effective fission yield of ^{143}Ce.

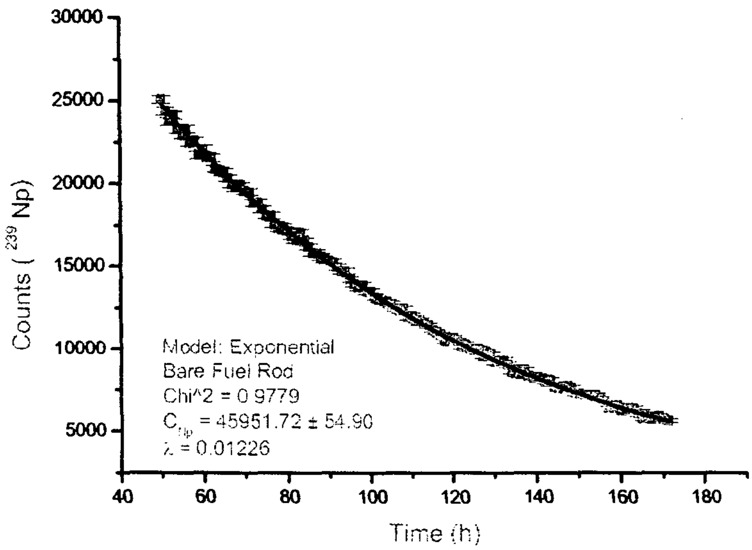

Figure 1. Counts of the ^{143}Np photo peak after irradiation measured by the HPGe.

The irradiation time (t_i) and the power level (100w) are kept identical for the irradiation of the bare and cadmium covered fuel rod. The power level was monitored by both a reactor noise method and a detector placed far away from the core. Both of these techniques indicate very consistent power levels. The waiting time (t_e) was kept equal to zero during all the acquisitions.

2.1 THE SPECTRAL INDICES $^{28}\rho$ AND $^{25}\delta$

Considering the ^{238}U neutron capture expressed by equation (1) the different factors between the bare and cadmium covered cases are only the self-shielding factor $f_{\gamma Np}$ and the ^{239}Np integral counts (C_{Np}). The remaining quantities in equation (1) are identical. Consequently, the cadmium ratio (R_{cd}) for the ^{238}U neutron capture is:

$$^{28}R_{Cd} = \frac{(C_{Np} / f_\gamma)_{bare}}{(C_{Np} / f_\gamma)_{Cd}} \tag{4}$$

Similarly, the cadmium ratio for the ^{235}U neutron fission is given by:

$$^{25}R_{Cd} = \frac{(C_{Ce} F_{25} / f_\gamma)_{bare}}{(C_{Ce} F_{25} / f_\gamma)_{Cd}} \frac{Y_{cd}}{Y_{bare}} \tag{5}$$

where the ^{235}U relative fission density and the effective yield of ^{143}Ce (Y_{cd} and Y_{bare}) have to be considered distinct for the bare and cadmium covered cases.

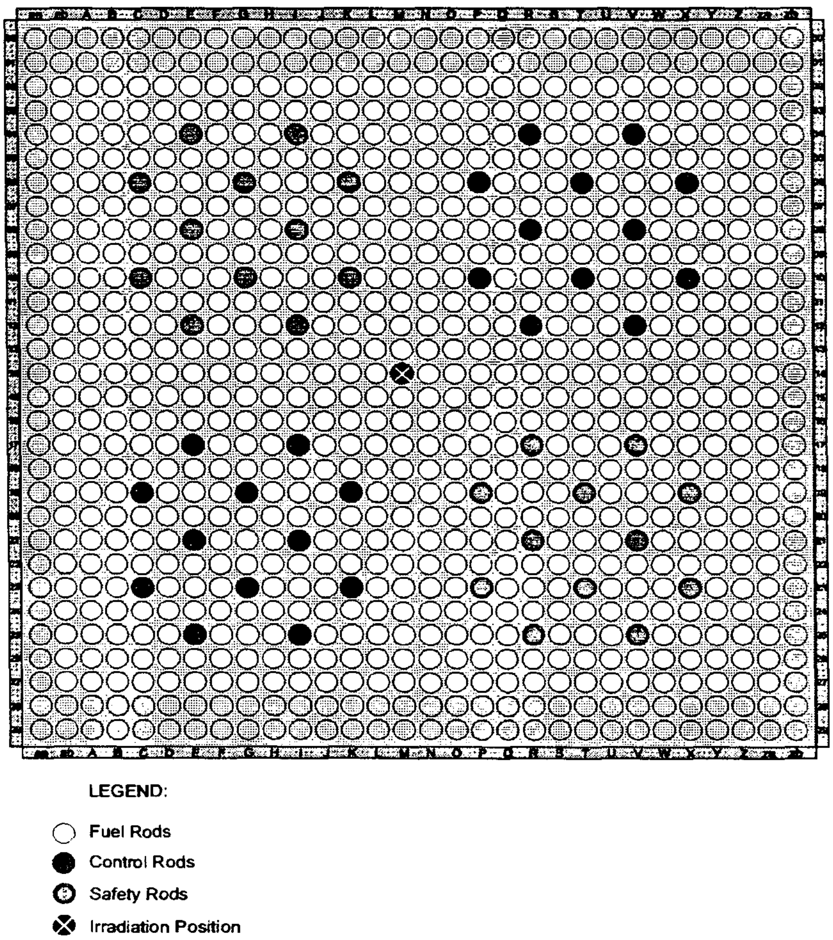

Figure 2. Rectangular configuration of the core of the IPEN/MB-01 reactor.

The integral counting for the photo peaks of ^{239}Np and ^{143}Ce during the cooling period follow an exponential law. These data were then fitted in an exponential function using the RFIT [7] code. The amplitude coefficient of the exponential function for the bare and cadmium covered fuel rod are respectively the integral counting (C_{Np} and C_{ce}) needed in equations (4) and (5). RFIT also performed a complete statistics analysis on the experimental data as well as the uncertainty analysis of the problem. The analysis considered total correlation between bare and cadmium cases.

Finally the perturbed values of $^{28}\rho$ and $^{25}\delta$ are given by:

$$^{28}\rho = \frac{1}{^{28}R_{Cd} - 1} \tag{6}$$

$$^{25}\delta = \frac{1}{^{25}R_{Cd} - 1} \tag{7}$$

2.2 THE SPECTRAL INDICES C* AND C8/F

The Modified Conversion Factor C* is defined by the following expression:

$$C^* = \frac{C8}{F5} \tag{8}$$

where C8 is given by equation (1) and F5 is given by equation (3).

The spectral index (C8/F) is given by the ratio of equations (1) and (2). In these cases only the bare fuel rod are considered to measure the fission and capture reaction rates. In both cases, the measured quantities are C_{Np} and Cce both from the RFIT fits. The ratio of the detector efficiency for the ^{239}Np and ^{143}Ce photo peaks was obtained by a standard ^{152}Eu source. Another quantities needed in equations (1) and (2) are taken from the experimental conditions and from the calculated correction factors such as the ratio of the self-shielding factors for the gamma emitted by ^{239}Np and ^{143}Ce.

2.3 THE SPECTRAL INDEX $(C8/F)_{EPITH.}$

The spectral index $(C8/F)_{epith.}$ considers the ratio of the epithermal capture in ^{238}U to the epithermal fissions in ^{235}U. The measurements of this spectral index consider the position of the fuel rod covered with cadmium. Analogously, equations (1) and (2) can be written for the cadmium covered case at the irradiation position. Thus $(C8/F)_{epith}$ is basically the ratio of these equations. Also here, it is applied the same comments as in the case of C8/F.

3. MEASUREMENTS WITH URANIUM FOILS

The new methodology for the measurements of spectral indices $^{28}\rho$ and $^{25}\delta$ was compared to the commonly one used based on the uranium foil irradiations. It was considered depleted uranium foil for the determination of $^{28}\rho$ and highly enriched foil (93.18%) for the determination of $^{25}\delta$. For this purpose, bare and cadmium covered uranium foils were irradiated at the central region of the reactor using a dismountable fuel rod. The uranium foils were also covered with aluminum foils to prevent the transference of the fission products from the surrounding fuel. A cadmium sleeve of 5cm length was used to cover the dismountable fuel rod at the uranium foil position. The procedure basically follows the same procedure as in the case of the gamma spectrometry of the fuel rod. First, the cadmium ratio is obtained for the neutron capture in ^{238}U and for neutron fission in ^{235}U. After that $^{28}\rho$ and $^{25}\delta$ from equations (5) and (6). In these cases there is no need to consider the self-shielding factor $f\gamma$ since the foils are very thin neither to consider F_{25} the uranium foil to determine $^{25}\delta$ since in this case the uranium foil is highly enriched (93.18%) and F_{25} is practically one.

4. THE CALCULATED CORRECTION FACTORS

The calculated correction factors for the perturbations due to the cadmium sleeves and also to the uranium and aluminum foils was determined employing the very powerful modeling capabilities of the MCNP-4B code [8]. The geometric model adopted for this purpose is shown in figure 3. A reflective boundary condition is used in all faces, thus simulating an infinite array of fuel rods. The experimental fuel rod is simulated in the central position of figure 3. The calculations are performed considering the fuel rod bare and covered with cadmium sleeves of various sizes. The case bare is classified as unperturbed and the case covered with cadmium and/or with uranium and aluminum foils of perturbed. From these geometric conditions several reaction rates as defined below can be calculated and from that the calculated correction factors can be inferred. The calculated corrections have a twofold functions. First to correct the measurements eliminating the perturbations in the system and second to convert the results into an specified thermal energy cutoff. A thermal energy cutoff of 0.625 eV was adopted for the unperturbed (bare) case. The calculated correction factor is defined as the ratio of the bare spectral indices to those covered with cadmium and are given by:

$$CF^{ij} = \frac{R_x1^{ij} / R_x2^{ij}}{R_x3^{ij} / \left[R_x4^{ij} - R_x3^{ij}\right]} \tag{9}$$

where,

$R_x1^{i,j} = \int_{0.625}^{20MeV} \int_V \int_{4\pi} \sigma_x^{i,j}(E)\Phi(r,E,\Omega)dVdEd\Omega$ epithermal unperturbed reaction rate for nuclide i,j;

$R_x2^{i,j} = \int_0^{0.625eV} \int_V \int_{4\pi} \sigma_x^{i,j}(E)\Phi(r,E,\Omega)dVdEd\Omega$ thermal unperturbed reaction rate for nuclide i,j;

$R_x3^{i,j} = \int_0^{20MeV} \int_V \int_{4\pi} \sigma_x^{i,j}(E)\Phi^*(r,E,\Omega)dVdEd\Omega$ epithermal perturbed reaction rate for nuclide i,j;

$R_x4^{i,j} = \int_0^{20MeV} \int_V \int_{4\pi} \sigma_x^{i,j}(E)\Phi(r,E,\Omega)dVdEd\Omega$ total reaction rate for nuclide i,j;

where

i,j = represents the nuclide (i,j=28 for ^{238}U and 25 for ^{235}U);
Φ = neutron flux without cadmium sleeves (unperturbed);
Φ^* = neutron flux with cadmium sleeves (perturbed);
V = either the volume considered of the 1 cm fuel rod length; or the uranium foil volume;
σ_x^{ij} = cross section for nuclide *i,j* and nuclear reaction (x) under consideration.

These correction factors were determined respectively for $^{28}\rho$ and $^{25}\delta$ as a function of the cadmium sleeve length for the fuel rod spectrometry case and for the cadmium sleeve length of 5.0 cm for the uranium foil cases. Specifically for the case of the uranium foil irradiation, R_x3^{ij} and R_x4^{ij} incorporates the uranium and aluminum foils inside of the fuel rod as shown in figure 3b.

The correction factor for $(C8/F)_{epith}$ is given by the following expression:

$$CF^{(C8/F)_{epith.}} = \frac{N^{28} R1_\gamma^{28} / \left(N^{25} R1_f^{25} + N^{28} R1_f^{28}\right)}{N^{28} R3_\gamma^{28} / \left(N^{25} R3_f^{25} + N^{28} R3_f^{28}\right)} \tag{10}$$

where:

$CF^{(C8/F)epith.}$ – is the correction factor for $(C8/F)_{epith.}$,
N^{28} and N^{25} – are the nuclide density concentrations for ^{238}U and ^{235}U respectively.

The MCNP-4B calculations were performed using the ENDF/B-V and ENDF/B-VI.5 libraries.

One last consideration before the discussion of the determination of $^{28}\rho$ and $^{25}\delta$ is the question of how to treat the ratio of the self-shielding factors ($f_{\gamma Np}$ and $f_{\gamma Ce}$) for the bare and cadmium covered cases needed in equations (4) and (5) and the ratio of the $f_{\gamma Np}$ and $f_{\gamma Ce}$ needed for the determination of the C*, C8/F and $(C8/F)_{epith}$. This question was addressed considering the determination of the $^{238}U(n,\gamma)$ and $^{235}U(n,f)$ reactions as a function of the position inside of the fuel pellets. The magnitude of the sources terms for the emission of the gamma radiation at 277.6 and 293.3 keV are respectively proportional to these reaction rates. The ROLAIDS and XSDRNPM modules of AMPX-II [9] and ISOSHIELD [10] were employed for such a purpose. ROLAIDS was used to calculate the self-shielded $^{238}U(n,\gamma)$ and $^{235}U(n,f)$ cross sections across the pellet in a multigroup model. Ten regions were considered for this purpose. XSDRNPM was used for the calculations of the neutron transport calculations and the subsequent reaction rates. ISOSHIELD was used to calculate the gamma transport through the uranium pellet and the subsequent reaction rate at the detector position. The calculation considered several cases: a) epithermal to thermal $f_{\gamma Np}$ needed for $^{28}\rho$, b) epithermal to thermal $f_{\gamma Ce}$ needed for $^{25}\delta$, c) $f_{\gamma Np}$ to $f_{\gamma Ce}$ needed for C8/F5 and C8/F, d) epithermal $f_{\gamma Np}$ to epithermal $f_{\gamma Ce}$ needed for $(C8/F)_{epith}$. The analyses reveal that these ratios of the self-shielding factors were essencially 1.0.

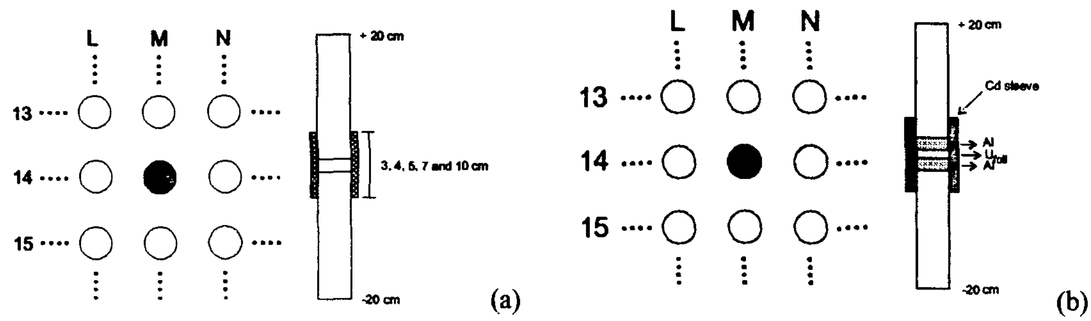

Figure 3. Geometric models for determination of correction factors needed for $^{28}\rho$, $^{25}\delta$ and $(C8/F)_{epith}$.

4. DETERMINATION OF $^{28}\rho$ BY THE DIRECT SPECTROMETRY OF THE FUEL ROD.

The results obtained for the determination of $^{28}\rho$ are shown in figure 4. This figure shows the perturbed $^{28}\rho^*$ and its calculated correction factors (^{28}CF) as a function of the cadmium sleeve length.

The unperturbed $^{28}\rho$ is obtained as the product of the extrapolated values of both curves when the cadmium sleeve length goes to zero. The extrapolated value of the experimental $^{28}\rho^*$ can be interpreted as the value in the absence of cadmium but with its thermal energy cutoff unknown. The extrapolated calculated correction factor basically makes this transposition to the thermal cutoff of 0.625 eV. The final result for the experimental determination of the spectral index $^{28}\rho$ for the IPEN/MB-01 reactor core is given below. The extrapolated calculated correction factor was obtained with the ENDF/B-VI.5 library.

$$^{28}\rho = 2.3576 \pm 0.0077$$

The experimental correction factor for $^{28}\rho$ can be defined as:

$$^{28}CF = \frac{^{28}\rho}{^{28}\rho^*} \qquad (11)$$

where $^{28}\rho^*$ is the experimental perturbed value obtained for different cadmium sleeve length. ^{28}CF can be very helpful to verify the adequacy of the methodology employed to calculate the correction factors and related nuclear data library.

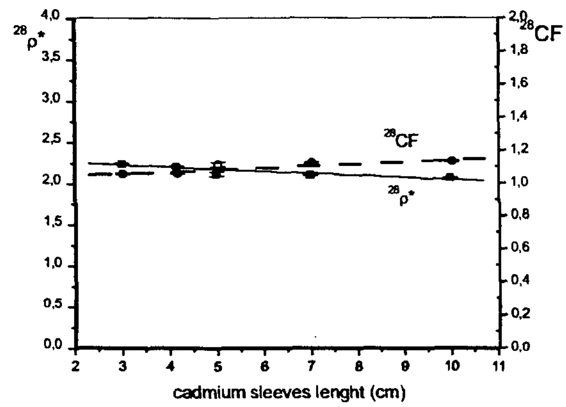

Figure 4. The experimental perturbed values of $^{28}\rho^*$ and ^{28}CF as function of cadmium sleeve length.

5. DETERMINATION OF $^{25}\delta$ FROM THE DIRECT GAMMA SPECTROMETRY OF THE FUEL ROD

In contrast to the $^{28}\rho$ case, the determination of $^{25}\delta$ requires some additional quantities that have to be determined either from another experiment or by a calculation approach. The main problems here are the determination of the ^{235}U relative fission density and the ^{143}Ce effective yield. For this purpose the MCNP-4B code was employed to estimate the relative ^{235}U fission density. The same geometry model as used for the determination of the calculated correction factors was adopted for this purpose. Thus for bare fuel rods the relative ^{235}U fission density was calculated to be 97,3 %. For the cadmium covered case considering sleeves of 3,4,5,7 and 10 cm length the relative ^{235}U fission density is 84,87%, 84,34%, 83,63 %, 83,52%, 79,40%, respectively. The effective yield of ^{143}Ce is obtained weighting its yield due to ^{235}U and ^{238}U fission by their respective fission densities.

The final results of $^{25}\delta$ are shown in figure 5. This figure shows simultaneously the perturbed values of $^{25}\delta$ along with its calculated correction factors as a function of the cadmium sleeve length. It can be observed that the perturbed value of $^{25}\delta$ reaches a minimum value when the cadmium sleeve length goes to infinite. On the other hand, the behavior of the calculated correction factor shows an inverse trend. Therefore, the final $^{25}\delta$ can be obtained considering the product of both extrapolated values. In contrast to the $^{28}\rho$ case, the physical interpretation of the extrapolated values is not so straightforward.

The final result for the experimental determination of the $^{25}\delta$ of the IPEN/MB-01 reactor core is given below.

$$^{25}\delta = 0.1215 \pm 0.0005$$

The experimental correction for $^{25}\delta$ can be defined as:

$$^{25}CF = \frac{^{25}\delta}{^{25}\delta^*} \qquad (12)$$

where $^{25}\delta$ and $^{25}\delta^*$ are the unperturbed and perturbed values respectively.

The uncertainties of spectral indices were obtained considering total statistical correlation between the bare and covered fuel.

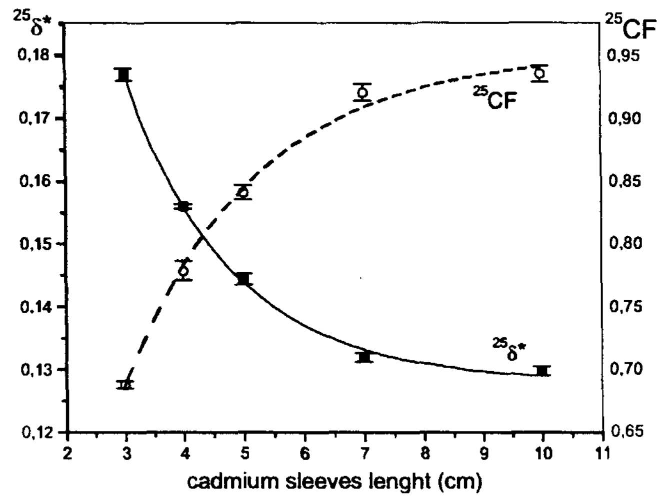

Figure 5. Experimental values of $^{25}\delta^*$ and ^{25}CF as function of cadmium sleeve length.

6. DETERMINATION OF MODIFIED CONVERSION FACTOR C*

The Modified Conversion Factor C* is defined by equation (9). Basically is defined by the ratio between the neutron capture reaction rate in ^{238}U and the fission reaction rate in ^{235}U. The measurements were made the same way that described to $^{28}\rho$ and $^{25}\delta$ spectral indices. The experimental conditions of power, control rods position and time irradiation were the same. C_{Np} and C_{Ce} were determined at the end of the irradiation and equation (1) and (3) were used to obtain C*. The factor F25 was again taken from MCNP-4B calculations. The final results is given below.

$$C^* = 0.3206 \pm 0.0028$$

7. DETERMINATION OF C8/F

The spectral index C8/F is obtained in the same way of C*, but in this case is used equations (1) and (2). The experimental results are given below.

$$C8/F = 0{,}3124 \pm 0{,}0017$$

8. DETERMINATION OF $(C8/F)_{EPITH}$

The spectral index $(C8/F)_{epit}$. also follows the same approach as in C* and C8/F, but now C_{Np} and C_{ce} (Equations 1 and 2) are taken from the cadmium covered case. Equations (1) and (2) are used to obtain $(C8/F)_{epit}$ The correction factor defined by equation (10) is used to correct for the cadmium perturbation and also to transform the experimental cutoff data into a thermal cutoff of 0.625 eV. Therefore $(C8/F)_{epit}$ is given by:

$$(C8/F)_{epit} = (C8/F)^*_{epit} \cdot CF^{(C8/F)epit} \qquad (13)$$

were $(C8/F)^*_{epit}$ is the perturbed value measured using the ratio of equations (1) and (2) and $CF^{(C8/F)epit}$ is the correction factor for $(C8/F)_{epit}$ spectral index defined by equation (10). The correction factor value obtained using the MCNP-4B and ENDF/B-VI.5 was $(C8/F)_{epit}$. $=1.0276 \pm 1.04\%$.

The final results is:

$$(C8/F)_{epit} = 1.5520 \pm 0.0045$$

9. DETERMINATION OF THE $^{28}\rho$ AND $^{25}\delta$ BY URANIUM FOIL IRRADIATIONS

The experimental determination of $^{28}\rho$ and $^{25}\delta$ basically follows the steps described in section III. The calculated correction factors applied in this case were described in section IV. The final results are:

$$^{28}\rho = 2.3575 \pm 0.0248, \text{ and}$$

$$^{25}\delta = 0.1241 \pm 0.0021$$

10. THEORY AND EXPERIMENT ANALYSES AND COMPARISONS

Table 1 shows the ratio of the calculated and experimental cadmium correction factors for $^{28}\rho$. and $^{25}\delta$ from the method based of the gamma spectrometry of the fuel rod. In general the agreement is better for longer cadmium sleeve length and for the spectral indices $^{28}\rho$. As for $^{25}\delta$, the results are sensitive to the cadmium sleeve length due to its high dependency on thermal neutron events. The comparisons also reveal that ^{28}CF is calculated better with ENDF/B-VI.5 and that ^{25}CF is not sensitive to the nuclear data library used in this work.

A comparison between calculated and measured values of spectral indices is shown in table 2. All the spectral indices of this work were calculated with MCNP-4B at the asymptotic region of the IPEN/MB-01 reactor. The geometric model considers a fully three-dimensional approach with all the details of the fuel rods, reflectors, control rods, etc. The calculations considered the nuclear data from ENDF/B-V and ENDF/B-VI.5 files. The major points illustrated in table 2 are as follow. Comparing the $^{28}\rho$ and $^{25}\delta$ experimental values from the fuel rod spectrometry and the foil activation techniques one may find that the results are consistent and inside of the experimental uncertainty. The foil activation technique shows a higher uncertainty due to the smaller uranium content. The main source of uncertainty is the counting statistics. Even so the experimental uncertainty in general is in a very good level. The ENDF/B-VI.5 shows better performance than ENDF/B-V for all the spectral indices. The longstanding problem of $^{238}U(n,\gamma)$ cross sections is now in a better position than several previous libraries/4/. This work also introduced the new spectral index $(C8/F)_{epit}$, which takes into account the $^{238}U(n,\gamma)$ reaction rates and the total fission rates above 0.625eV. A good agreement is found for C*, and C8/F. For the case of $(C8/F)_{epit}$, the agreement was considered fair because the C/E is outside of 2σ (two standard deviation).

Table 1. Ratios between calculated (C) and experimental correction factors (E).

cadmium sleeve length (cm)	C / E			
	^{28}CF [(a)]	^{28}CF [(b)]	^{25}CF [(a)]	^{25}CF [(b)]
3	1.0332	0.9888	1.1657	1.1612
4	1.0476	0.9577	1.1213	1.1275
5	1.0008	1.0124	1.0715	1.0739
7	1.0514	1.0021	1.0041	1.0027
10	(-)	1.0065	(-)	0.9958

(-)Not calculated. (a) ENDF/B-V; (b) ENDF/B-VI

Table 2. Ratios between calculated (C) and experimental (E) values of the IPEN/MB-01 reactor.

Spectral Index	Experimental Value	C/E (1)	C/E (2)
$^{28}\rho$	2.3576±0.0077	1.039 ± 0.008	1.023 ± 0.009
$^{25}\delta$	0.1215±0.0005	1.064 ± 0.007	1.035 ± 0.008
$^{28}\rho^{(F)}$	2.3575±0.0248	1.039 ± 0.013	1.023 ± 0.013
$^{25}\delta^{(F)}$	0.1241±0.0021	1.041 ± 0.018	1.013 ± 0.019
C*	0.3206±0.0028	1.030 ± 0.010	1.024 ± 0.012
C8/F	0.3124±0.0028	1.015 ± 0.008	1.009 ± 0.011
$(C8/F)_{epith.}$	1.5520±0.0045	*	0.9773 ± 0.0104

(1) ENDF/B-V; (2) ENDF/B-VI.5; (F) – Uranium Foils; (*)- Not calculated

CONCLUSIONS

This work introduces a novice approach for the determination of spectral indices $^{28}\rho$. and $^{25}\delta$ by means of a fuel rod gamma spectroscopy irradiated with and without cadmium sleeves. The results are consistent with the traditional methodology based on irradiation of uranium foils. The methodology introduces some advantages compared to the traditional one based on uranium foil irradiation because the experimental error is smaller due to the higher amount of uranium. In addition to that there is no need to assemble and disassemble the special fuel rods to remove the uranium foils after irradiation, which always induces a radiological difficulty. This work also introduces the new spectral index $(C8/F)_{epit}$ which can be of extreme importance for the nuclear data validation

The methodology used to obtain the cadmium correction factors by the monte carlo MCNP-4B code is original and showed better agreement when the ENDF/B-VI.5 library was used for the spectral index $^{28}\rho$. The same does not occur for the spectral index $^{25}\delta$, which shows very similar results for ENDF/B-V or ENDF/B-VI.5. The spectral indices C*, C8/F5, C8/F and $(C8/F)_{epit}$ could be measured with a high level of accuracy. Finally, in a general sense the ENDF/B-VI.5 shows better performance for all spectral indices of this work.

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