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Study of Neutron Fluxes Before and After the Change HEU to LEU Fuel for TRIGA Mark III Reactor of Mexico

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ABSTRACT

In the operation of the TRIGA Mark III reactor, is very important to know the neutron flux profile to perform tasks such as radioisotope production, research on neutron physics, burning fuel and neutron dosimetry. With neutron profile we can also calculate the average flux in the reactor core, which is directly proportional to reactor power. In this work, due to the conversion of fuel from HEU to LEU, the new profiles of neutron flux are shown and compared with the previous values of fluxes with the mixed core. It is explained how we to carry out the measurements (in various irradiation facilities of the reactor core) of the subcadmic neutron flux with energies less than 0.4 eV (the cutoff energy of cadmium is about 0.4 eV), and the epicádmico flux with higher energies of 0.4 eV. The distributions of radial and axial fluxes were determinated, the power factor per ring also were calculated.

1. Introduction

Due to change from high to low-enriched fuel is necessary to know the new fluxes in the different irradiation facilities of TRIGA Mark III Reactor of Mexico, with this purpose the foil activation method is used, which it consists of irradiate pairs of foils with neutrons, one covered with cadmium and the other uncovered, measuring the activity of the irradiated foils and with the irradiation parameters , chemical and physical properties of the irradiated element it is possible to determine the subcadmic flux (neutrons with energies less than 0.4 eV, cadmium cutoff energy) and epicádmico flux (neutrons with energies greater than 0.4 eV).

2. Theory

The subcadmic flux is defined as the neutron flux with energies less tan the cadmium cutoff energy E_{Cd} (Energy threshold = 0.4 eV) and is given by:

$$\varphi_{cd} = \frac{P_a}{kN_A\sigma_c(1-e^{-\lambda(t_i+T)})\varepsilon_T PPD}\left[n_d(t_d)e^{\lambda t_d} - n_{cd}(t_d)e^{\lambda t_d}\right] \qquad (1)$$

And the epicadmic flux is defined as the neutron flux with energies greater than $E_{Cd.}$ We can write as:

$$\phi_{epi} = \frac{P_a n_{cd}(t_d)}{kN_A ERI(1-e^{-\lambda(t_i+T)})\varepsilon_T PPD} \qquad (2)$$

The above fluxes must be corrected with correction factors [1], which consider the losses in the activity induced by neutrons, such as:

- **Epicadmic Factor F_{cd}** - This factor corrects the decrease of activity in the covered foil with cadmium, due to the presence of resonances in cadmium at higher energies of greater than 0.4 eV. F value depends on the thickness of the foil and the cadmium plates used.

- **Termal correction factor F_P** – This factor corrects two effects:

  1. *Self – shielding* (*fs*): This type of factor is used to compensate the loss of neutrons due to the neutron absorption by the foil material.

  2. *Flux depression* (*fd*): Due to the presence of the absorbering foil in the neutron flux, the flux produces a depression in the vicinity of the foil.

Including the previous correction factors in equations (1) and (2), remains:

- Subcadmic Flux:

$$\phi_{cd} = \frac{F_p P_a}{kN_A \sigma_c (1-e^{-\lambda(t_i+T)})\varepsilon_T PPD}\left[n_d(t_d)e^{\lambda t_d} - F_{cd} n_{cd}(t_d)e^{\lambda t_d}\right] \qquad (3)$$

- Epicadmic Flux:

$$\phi_{epi} = \frac{F_p P_a F_{cd} n_{cd}(t_d)}{kN_A ERI(1-e^{-\lambda(t_i+T)})\varepsilon_T PPD} \qquad (4)$$

Where, the parameters involved in the above equations are:

k : Isotopic abundance of material.
P_a: Atomic weight of element
λ : Decay constant
t_i: Irradiation time
T: Reactor period (Step correction factor).
N_A: Avogadro`s number.
σ_c: Activation cross section.
ERI: Effective resonance integral.
PPD: Percentage by disintegration of gammas detected
ε_T: Total efficiency of the detection system for gammas of interest.

We define specific count after delay time t_d *as*:

$N(t_d) = N(t_d)e^{\lambda td}/t_c\, m$ (5)

Where:

t_c: Counting time.

m; mass of foil.

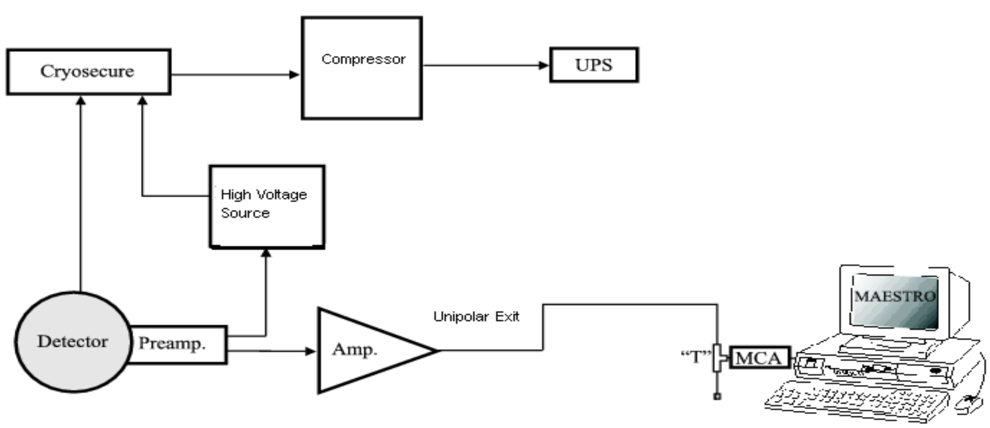
Once the material is chosen to use, the foils are weighed and irradiated and subsequently counted, for in this way to have all the parameters involved in the equations (3) and (4). The calculations of activities, epicadmics and subcadmics fluxes, efficiencies in the energies of interest, all of this is performed with the computer program CAFLU [2], which gives a list of the mentioned fluxes, the activities of the foils and the reason cadmium for each pair of foils.

3. Equipment and materials

The equipment and materials used were:

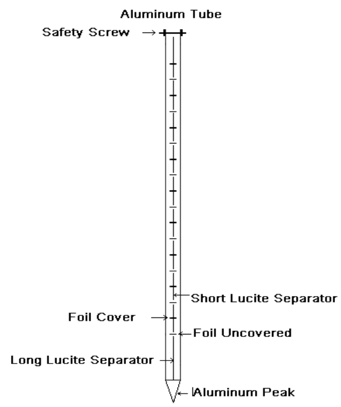
- TRIGA Mark III Reactor.
- Foil containers, which consist of aluminum tubes and pointed plugs.
- Foils of an Al-AU (99.9 OF Al and 0.1 % of Au) alloy with a diameter of 3 mm and 0.0508 mm thick).
- Cadmium foils (3.4 mm in diameter and 0,508 cm thick).
- Lucite separators of two different lengths, 2.54 cm and 5.4 cm and 3 mm in diameter.
- **Gamma spectrometry system:**
  - Hyperpure germanium detector (HPGe) with glass of 56.5 mm in diameter and 57.4 mm length, nominal resolution of 1.9 keV for energy of Co 1332.49 keV and 30% relative intrinsic efficiency.
  - Preamplifier integrated to the detector, Mat. ORTEC, Model 232N.
  - Linear amplifier, Mar. OTEC, Model 571.
  - High voltage source, Mar. ORTEC, Model 659.
  - Computer, Mar. Compaq Deskpro with a card for multichannel analyzer, Mar. ORTEC, Model TRUMP with 4000 channels.
  - Cabinet NIM, Mar. ORTEC, Model 4001M.
  - Coaxial cables with BNC terminals

Figure 1. Schematic representation of the spectrometry system



4. Experimental and theoretical methodology.

The measurement of the subcadmics and epicadmics fluxes was realized by the method known as foil activation, which consists of irradiating pairs of foils of the same material, one uncovered and the other covered whit cadmium in order that from the difference of activities of the foils the subcadmic flux is determined and with the activity induced in the uncovered, the epicadmic flux can be calculated.
Because of above it is necessary to form arrangements with one or several pairs of foils. In the case of DC (Central thimble), C1, S1, S2, S3, and S4, it was necessary to form the arrangements as shown in the figure below.

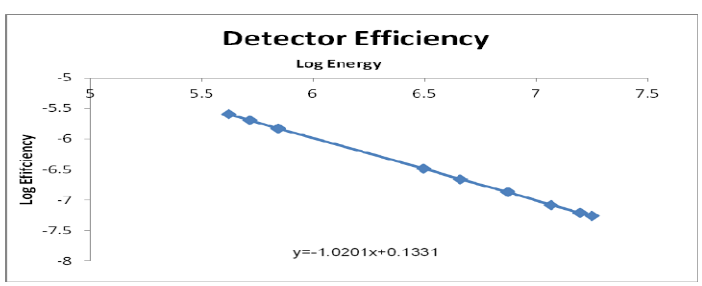


- The foils are placed within an aluminum tube with inner diameter of 0.632 cm and 0.635 cm outer diameter, alternating a foil covered with plates of cadmium and the other uncovered. Each foil is separated from the next with lucite separator which haves a length of 2.54 cm.
- In cases of SINCA and SIRCA, the arrangements were formed by placing a couple of foils, separated by a container with a height of 1.5 cm to avoid the presence of the absorbering foil does not affect the other foil.

5. Results

Efficiency calibration

The values in efficiency were obtained for the different energy sources ^{152}Eu, ^{137}Cs, ^{133}Ba, and ^{60}Co with a source-detector distance of 10.5 cm (7 lucite separators) [1]. The measurement data obtained for the core LEU are giving in a log-log scale graph. Resulting then the graph Log (energy) vs Log (efficiency). This data are presented in Graphic 1.

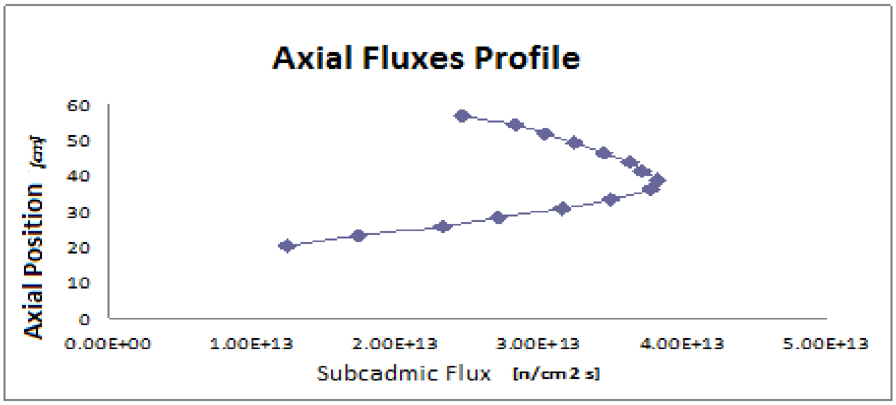


Graphic 1. Log Efficiency vs. Log Energy

The previous graph was adjusted with least squares, and we obtained the following parameters for the straight m = -1.02 y b = 0.133, then for the gold energy 411.8 keV corresponds an efficiency $\varepsilon = 2.45 \times 10^{-3} \pm 1.76 \times 10^{-5}$.

Determination of axial flux profile in the mixed core

The data obtained are plotted in a graph position vs. Subcadmic flux giving us the axial flux profile (Graphic 2), which is a cosinusoidal curve where it can be seen a maximun value for the subcadmic flux of 3.82×10^{13} n/cm^2-s. The maximum epicádmico flux turns out to be 3.83×10^{13} n/cm^2-s.

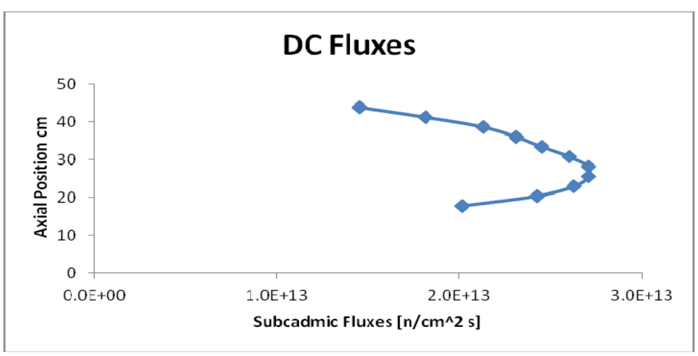


Graphic 2. Axial fluxes for mixed core

The position, where the subcadmic flux is maximum, is the place of the arrangement at 38.6 cm plus the height that was rose from the bottom of the DC, 41.0 cm, which gives 79.6 cm. Measured from the bottom of the DC.

Determination of axial flux profile in the core LEU

The data obtained with LEU fuels are plotted in a graph Position vs. Subcadmic flux giving us the new axial flux profile (Graphic 3), which is a cosinusoidal curve where it can be seen a maximum value for the subcadmic flux of 2.71×10^{13} n/cm^2-s. Regarding the maximum epicádmico flux turn out to be 3.67×10^{13} n/cm^2-s.



Graphic 3. Axial flux profile for the core LEU.

The position where the maximum subcadmic flux is, resulted in 33.0 cm plus the height rose from the bottom of the Central Thimble of 38.0 cm, which gives 71.0 cm measured from the bottom of the DC.

Radial flux profile of the mixed core

Regarding the radial flux profile (Figure 4), the results of the arrangements irradiated in the positions, DC, C1, S1, S2, S3 and S4, average flux values are taken from each arrangement and these values are given in table 1.

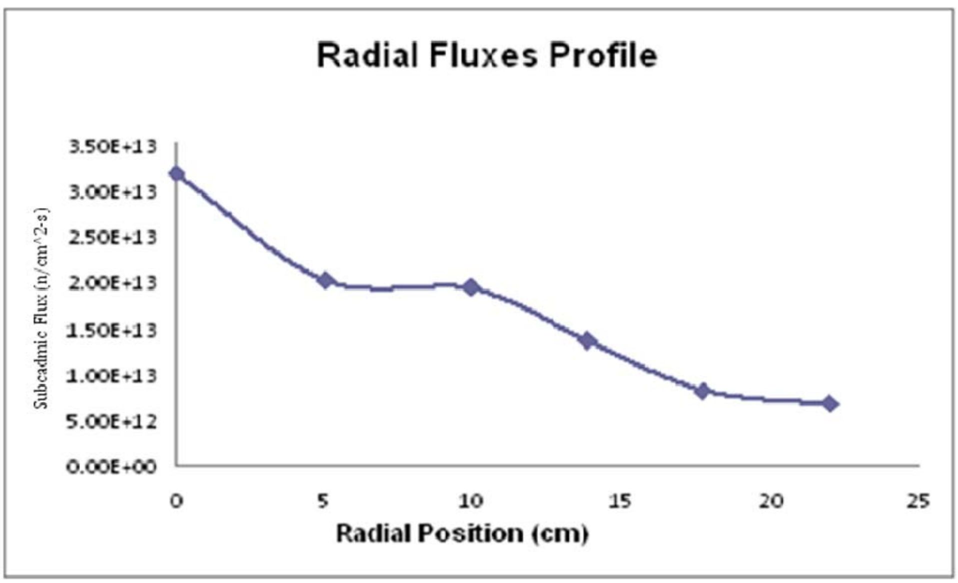
The average subcadmic flux in all over core was approximately:

$\Phi \approx 8.9E+12$ [n/cm^2-s]

Position	**Distance** (cm)	**Average Flux**
DC	0.0	3.17E+13
C1	4.98	1.66E+13
S1	9.9	1.6E+13
S2	13.8	1.12E+13
S3	17.7	6.55E+12
S4	21.96	5.6E+12

Table 1.

Graphic 4. Radial Fluxes Profile in mixed core

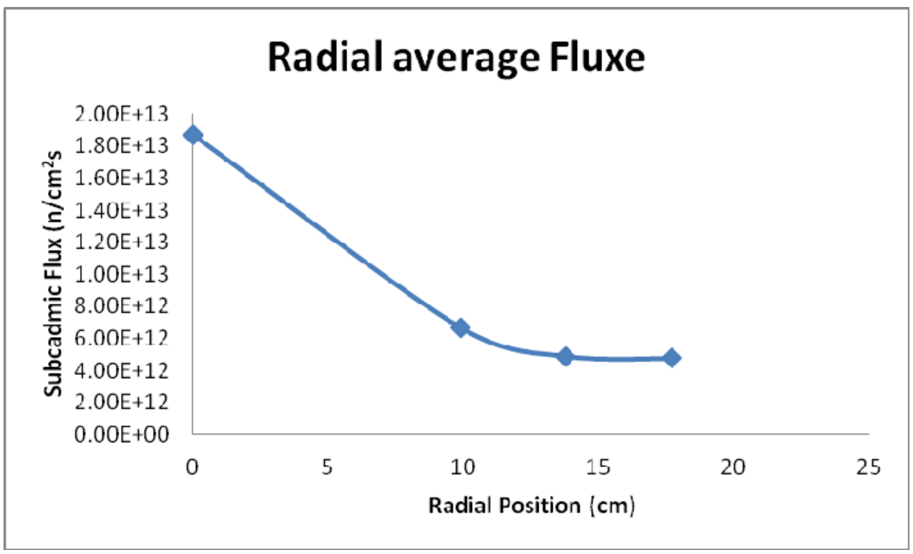


Radial flux profile of the core LEU

Respect to the radial flow profile (Graphic 5), the results of irradiated arrangements in positions DC, S1, S2, S3 and S4 (in progress), average values are taken from each array fluxes and these values are given in table 2.

Table 2

Position	Distance (cm)	Average Flux
DC	0.0	1.87×10^{13}
S1	9.9	6.67×10^{12}
S2	13.8	4.88×10^{12}
S3	17.7	4.75×10^{12}



Graphic 5. Radial average flux in the core LEU

Power factors by ring

The power factor by ring defined as [2], [3], the division between the average flux in each rings and the average flux in all over the core:

$$F_p = \Phi_{pa} / \Phi_{pn}$$

Where:

Φ_{pa}; is the average flux in the ring.

Φ_{pn}; is the average flux throughout the core.

From the values given in table 3 for the mixed core and interpolating the flux for each distances of the rings, we obtain the values of the power factors by ring in the core.

Table 3.

Ring	**Position** (cm)	**Average Flux**	**Power Factor**
B	8.0	1.52E+13	2.03
C	12.0	1.27E+13	1.69
D	16.0	8.32E+12	1.11
E	20.0	5.7E+12	0.76
F	24.0	4.77E+12	0.64

Table 4. Contains the value of the measured fluxes in the following facilities [4]; DC (maximum value) rotating SIRCA (average of the 4 fluxes measured at points 2, 12, 22, and 32), fixed SIRCA (average of the 10 fluxes measured at positions 1, 2, 3,4, 5, 6, 7, 8, 9 and 10) and SINCA (single measurement).

The measured fluxes for the mixed core in the irradiation facilities were:

Position	**Subcadmic flux**	**Epicadmic flux**
DC	3.643×10^{13}	3.715×10^{13}
Rotating SIRCA	4.35×10^{13}	2.68×10^{13}
Fixed SIRCA	2.66×10^{12}	6.313×10^{11}
SINCA	1.12×10^{13}	6.401×10^{12}

Table 4. Subcadmic fluxes in the main irradiation facilities for the mixed core.

The following table 5, contains the value of the measured fluxes in the following facilities[4]: DC (maximum value), B-4, E-4, E-22, SINCA (single measurement), rotating SIRCA (average of the flux measured at positions 2, 12, 22, and 32), fixed SIRCA (average of the 10 measured positions 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10).

The measured fluxes for the core LEU in the irradiation facilities were:

Position	Subcadmic flux	Epicadmic flux
Dedal Central	2.65×10^{13}	3.67×10^{13}
B-4	3.28×10^{13}	3.47×10^{13}
E-4	2.42×10^{13}	1.95×10^{13}
E-22	2.12×10^{13}	2.6×10^{13}
SINCA	7.41×10^{12}	5.42×10^{12}

Table 5. Subcadmic fluxes in the main irradiation facilities for the core LEU.

6. Conclusions

The fluxes obtained in the mixed core are slightly higher than those reported by the manufacturer for a core loaded with standard fuels, this is because power is directly proportional to the product of the flux by the density atoms of fissile material in the fuel, therefore when the atoms of the fuel decreases then the flux must increases to maintain constant the power. The opposite happens in the core LEU, the flux is less because there is a greater density of atoms in the fissile material.

In the radial profile it shows that for the mixed core there are two prominences corresponding to C and D rings, where the fuels is loaded into the HEU; and de core LEU profile is a very acute prominence at the center, due to traps of neutron thermal, which exist in the central thimble, B-1 and B-4 irradiation positions.

7. References

[1] Román, Mojica Irianelly, "Determinación de los parámetros alfa, f y Q_o en las instalaciones de irradiación del reactor TRIGA Mark III para la aplicación de la técnica k_o" Tesis profesional, Fac. Ciencias UAEMEX-ININ, México 2012.

[2] F. de Corte *et al*, Journal of Radioanalytical Chemistry, Vol. **52**, No 2 (1979) 295-304.

[3] Aguilar, Hernández Fortunato, et al, "Informe de Seguridad del Reactor TRIGA Mark III, del ININ", México 2012.

[4] TRIGA Mark III Reactor Mechanical maintenance and operating manual for CNEN of Mexico, GA-6610, USA 1966.