SUBCRITICAL NUCLEAR ASSEMBLY

Hector Rene Vega-Carrillo

Unidad Academica de Estudios Nucleares
Universidad Autonoma de Zacatecas
C. Cipres 10, Fracc. La Peñuela 98068 Zacatecas, Zac. Mexico.

E-mail: fermineutron@yahoo.com

Abstract

A Subcritical Nuclear Assembly is a device where the nuclear-fission chain reaction is initiated and maintained using an external neutron source. It is a valuable educational and research tool where in a safe way many reactor parameters can be measured. Here, we have used the Wigner-Seitz method in the six-factor formula to calculate the effective multiplication factor of a subcritical nuclear reactor Nuclear Chicago model 9000. This reactor has approximately 2500 kg of natural uranium heterogeneously distributed in slugs. The reactor uses a ^{239}PuBe neutron source that is located in the center of and hexagonal array. Using Monte Carlo methods, with the MCNP5 code, a three-dimensional model of the subcritical reactor was designed to estimate the effective multiplication factor, the neutron spectra, the total and thermal neutron fluences along the radial and axial axis. With the neutron spectra in two locations outside the reactor the ambient dose equivalent were estimated.

Keywords: Subcritical Nuclear reactor; Monte Carlo

1.- INTRODUCTION

A nuclear reactor is a system where the nuclear fission chain reaction is started, maintained and controlled. An important parameter in the design of a nuclear reactor is the multiplicaton factor, k, that is the amount on neutrons in any generation-to-the amount of neutrons in the previous generation ratio. If the multiplication factor is less than one ($k < 1$) the nuclear reactor is Subcritical, that is also known as Subcritical Assembly. If the reactor is infinite the k is named infinite multiplication factor, if the reactor is finite the k is known as effective multiplication factor, k_{eff} [Lamarsh 1977].

For any nuclear system, like a nuclear reactor, array of nuclear fuel during transport or storage, or even a nuclear war head, containing nuclear materials must be analyzed to determine their criticality in order to verify the proper safety conditions to avoid critical excursions [Abderrahim *et al*., 2010; Pyeon *et al*., 2007].

Accelerator-driven subcritical reactors have been developed and used as neutron sources, for energy production and for spent fuel transmutation [Shahbunder *et al*., 2010].

The Universidad Autonoma de Zacatecas has a subcritical reactor, UAZSNR, Nuclear Chicago model 9000. This is a heterogeneous reactor, fueled with natural uranium with light water as moderator and reflector [Papastefanou 2004]. Probably, the design of this reactor was based on the “pickle barrel reactor” built at the New York University [Dietrich 1960].

To run the reactor a 0.185 GBq ^{239}PuBe isotopic neutron [Vega-Carrillo *et al*., 2009] is inserted in the center of a series of rings or hexagonal layers of aluminum tubes. In each tube there are five hollow rods of fuel or slugs. The main application of this type of reactor is for teaching, training and research.

The value of the k_{eff} depends upon de amount and type of nuclear fuel as well as the fuel geometry array and it is important to determine its value to avoid criticality accidents [Endo 2011]. The k_{eff} is the key parameter in the design or characterization of subcritical assemblies [Papastefanou 2004; Talamo *et al*., 2011].

The aim of this work was to calculate the effective multiplication factor using the six-factor formula; as well as, to estimate the neutron spectra along the reactor diameter and the k_{eff} using Monte Carlo methods.

2.- MATERIALS AND METHODS

The UAZSNR has 280 aluminum tubes which are arranged in a hexagonal pattern. Each tube contains 5 metallic natural uranium 3 Ø × 21.3 cm^2 cylinders, or slugs, with 0.1 cm-thick aluminum cladding. The reactor uses natural water as moderator and reflector, in the center of the fuel array there is a tube that is used to hold the isotopic neutron source. The fuel and the moderator are contained in a 1.22 Ø × 1.52 m^2 stainless steel tank. In the figure 1 is shown the subcritical reactor.

Figure 1.- View of the UAZSNR showing the lattice arrangement.

In this work, two methods were used to determine the k_{eff}. In the first method, the six-factor formula was used and Monte Carlo calculations were carried for the second method. Also Monte Carlo calculations were used to estimate the neutron spectra in several points along the diameter in the middle plane of the reactor. With the neutron spectra the total neutron fluence and the thermal neutron fluence ($E \leq 0.414$ eV) were also estimated.

2.1.- Using the Six-factor Formula to Calculate the k_{eff}

The UAZSNR has 1400 fuel slugs that can be loaded in 10 rings of hexagonal arrays, thus the k_{eff} was calculated for the reactor loaded from 1 up to 10 hexagonal rings. The effective multiplication factor, k_{eff}, was calculated using the six factors formula [Papastefanou 2004; Lamarsh 1977; Vega-Carrillo 2012] shown in equation 1. The calculations were performed under Mathcad® [Mathsoft 1994].

$$k_{eff} = \eta \; \varepsilon \; p \; f \; P_{NL,th} \; P_{NL,f} \qquad (1)$$

Here, η is the reproduction factor, ε is the fast fission factor, p is the resonance escape probability, f is the thermal utilization factor, $P_{NL,th}$ and $P_{NL,f}$ are the thermal and the fast no leakage probabilities respectively [Papastefanou 2004; Lamarsh 1977; Vega-Carrillo 2012].

The reactor equation, shown in equation 2, for cylindrical geometry, was solved using, the Wigner-Seitz method [Lamarsh 1977], through equivalent unit cells.

$$\nabla^2 \Phi + B^2 \Phi = 0 \qquad (2)$$

In this equation, $\Phi = f(r,z)$ is the neutron distribution along the radius, r, and the reactor axial axis, z, and B^2 is the Buckling. The non- leakage factors were obtained using the two-group approximation [Papastefanou 2004; Lamarsh 1977; Vega-Carrillo 2012].

In the assembly, neutrons are increased by the amplification factor, μ, that is calculated using equation 3.

$$\mu = \frac{1}{1 - k_{eff}} \tag{3}$$

The subcritical reactor power, P, was calculated using equation 4 [Shahbunder *et al*., 2010; Papastefanou 2004] where ν is the average neutrons produced during the ^{235}U fission and w is 3.201E(10) fission/Watt, and Q is the neutron source strength.

$$P = \frac{Q}{\nu\, w} \frac{k_{eff}}{1 - k_{eff}} \tag{4}$$

2.2.- Monte Carlo calculations

A detailed model of the subcritical reactor loaded from 1 up to 10 hexgonal fuel rings was designed, in figure 2 is shown the case with 1350 slugs, 270 tubes in 8 hexagonal rings. This case was used with the MCNP 5 code [Forster 2004] to estimate the neutron spectra and total neutron fluence along the reactor radial and axial axis; also the ambient dose equivalent at two locations around the reactor were estimated. This model was also used to estimate the k_{eff}.

The calculation of the k_{eff} also calculated for fuel arrays since 1 hexagonal ring up to 10 hexagonal rings and these values were compared with the results obtained with six-factor formula.

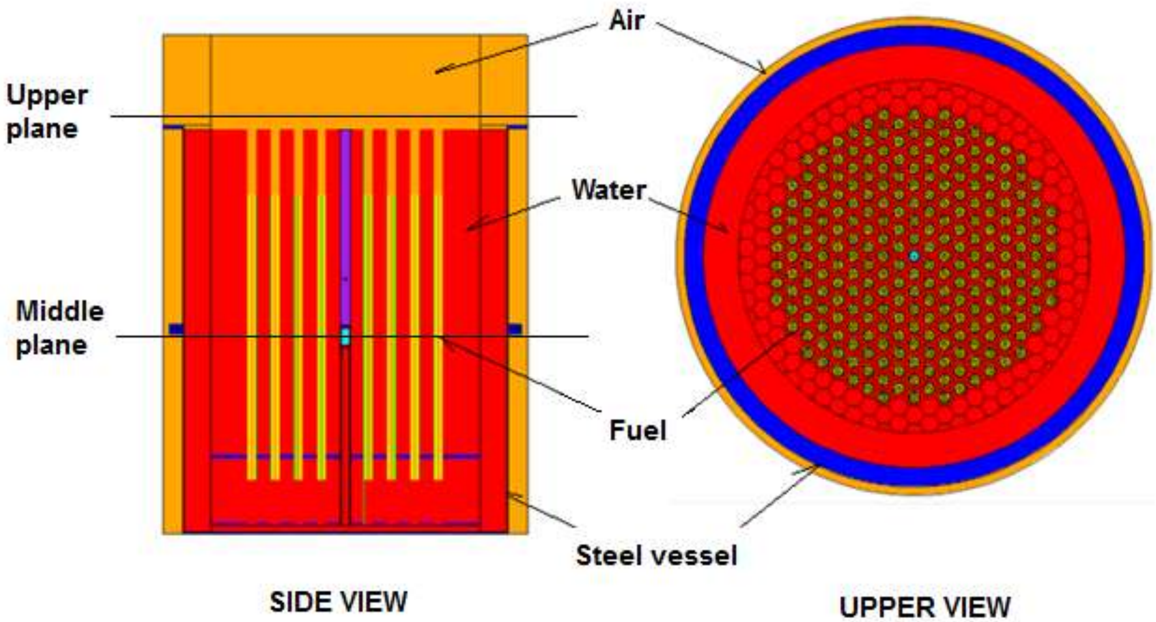

Figure 2.- Monte Carlo model of the subcritical reactor.

3.- RESULTS

In the table 1 are shown the k_{eff} values calculated for the three cases using the six-factor formula and the Monte Carlo methods.

Table 1.- Values of the k_{eff} calculated using three different amounts of fuel slugs using the six factor formula and the Monte Carlo calculations.

Fuel slugs	k_{eff} calculated with the six-factor formula	k_{eff} calculated with the MCNP5 code
1350	0.8498±0.02549	0.8268±0.0007
1410	0.8537±0.02561	0.8296±0.0006
1620	0.8653±0.02596	0.8374±0.0006

The six-factor formula overestimates the k_{eff} probably due the simplifications of the method and the quality of the data.

The relative difference between the k_{eff} values calculated by both procedures is approximately 3%. If a 2% error is assigned to k_{eff} obtained with the six-factor formula and using 3σ in the k_{eff} estimated with the MCNP5 code, the differences are not significant.

In the figure 3 are shown the correlation between the k_{eff} values, calculated with both methods.

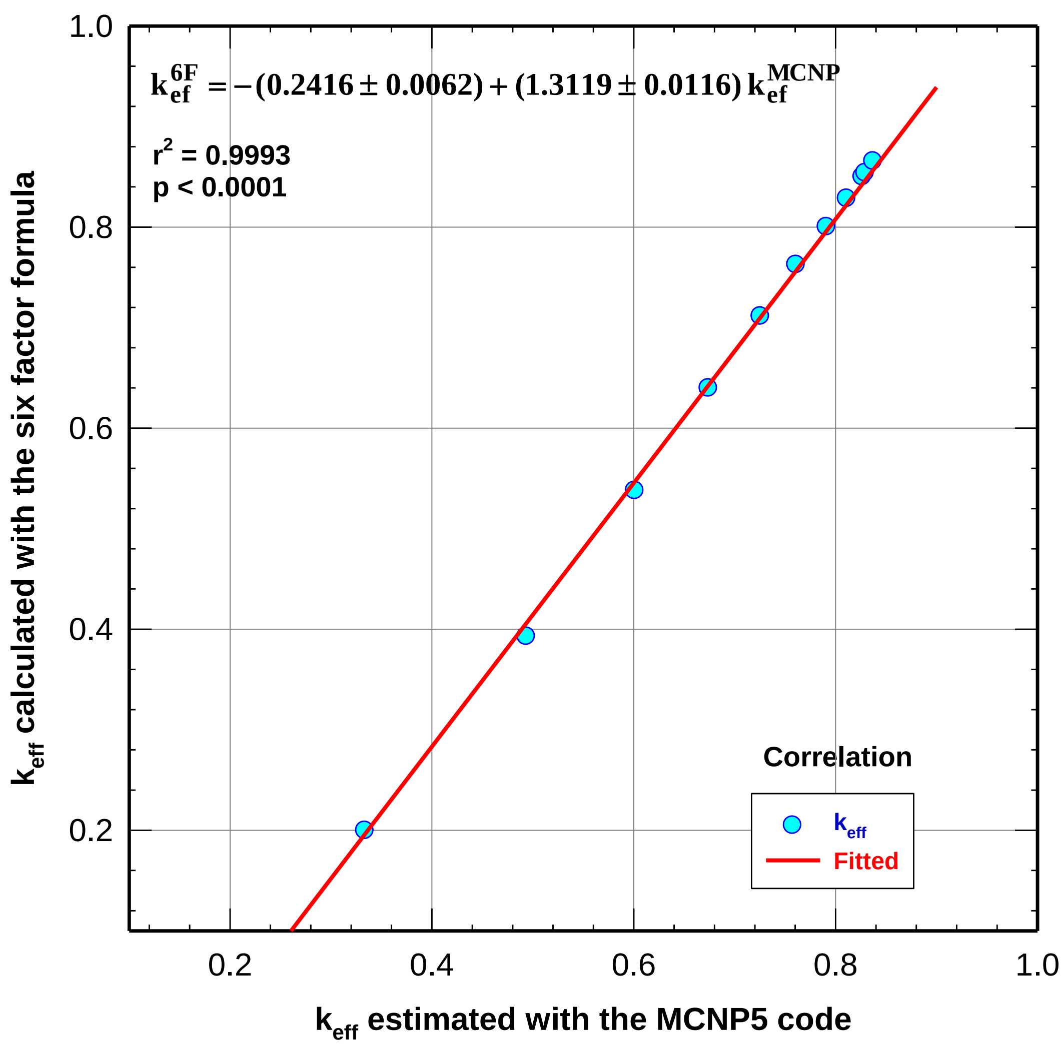

Figure 3.- Correlation between k_{eff} calculated by both methods

There is a correlation between the keff calculated through both methods. It can be noticed that regardless the method used in the calculations, as the amount of fuel is increased the criticality increases; however, even with the maximum fuel load the assembly remains subcritical.

Using the case with 1350 fuel slugs the reactor amplification factor is 5.77 and the reactor power is 61.11 pW per neutron emitted by the ^{239}PuBe source.

In the figure 4 are shown the neutron spectra in 3 points in the middle plane along the radius of the reactor with 1350 slugs. Here, is also included the neutron spectrum outside the reactor and the relative ^{239}PuBe neutron spectrum used as source term.

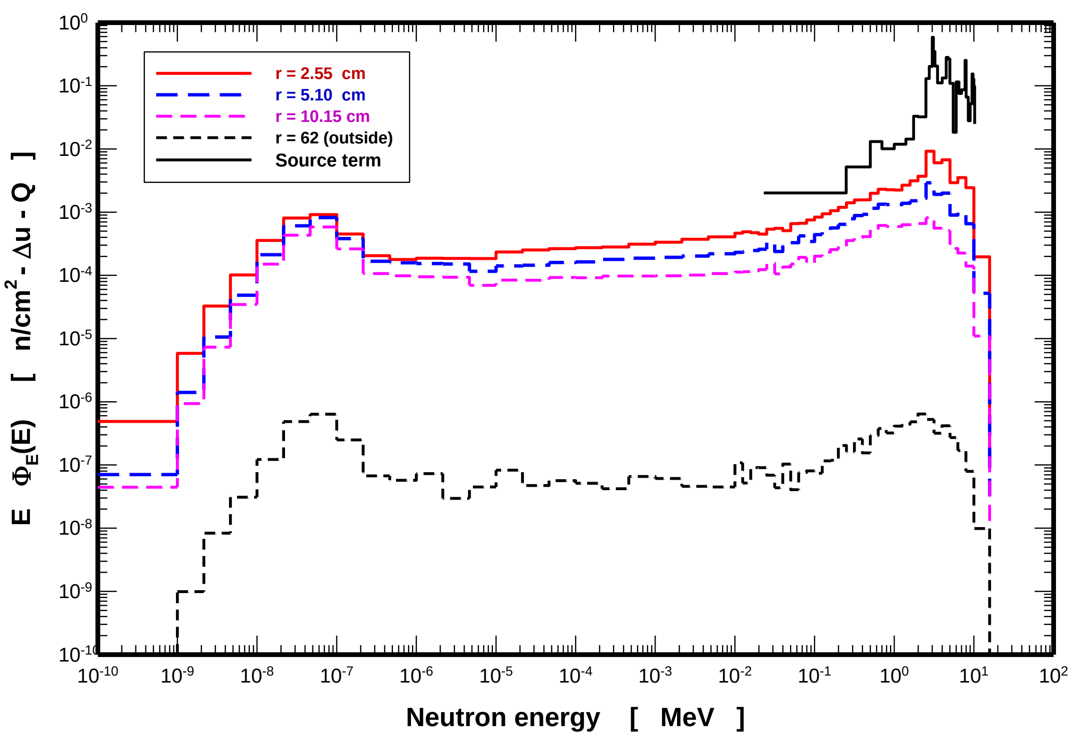

Figure 4.- Nuclear spectra in the middle plane along the UAZSNR radius.

For the point closest to the source the spectrum keeps the shape of source term neutrons, as the distance is increased, from 0.1 up to 15 MeV the fission spectrum is more clearly defined. In the spectra can be noticed the thermal neutron spectrum, these spectra have approximately the same shape as those reported for subcritical assemblies [Talamo *et al*., 2011].

The total and the thermal neutron fluencies along the reactor radius are shown in figure 5.

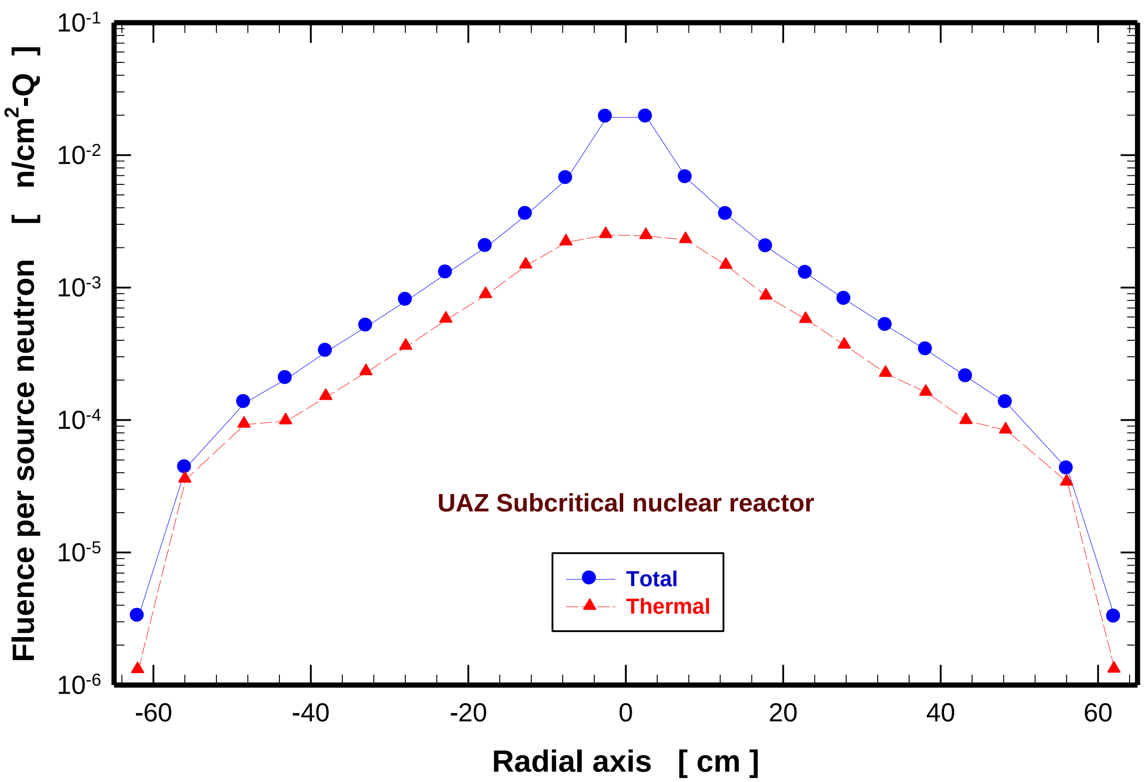

Figure 5.- Total and thermal fluencies along the reactor radial axis.

Here, the last hexagonal rings of fuel ends at 44.5 cm, thus the next two points beyond are in the moderator and that beyond 60 cm is outside the reactor. Both radial distributions are in agreement with measurements reported in literature [Papastefanou 2004].

The total neutron fluence distribution in the middle plane of the reactor is shown in figure 6, while in the figure 7 is shown the total neutron fluence distributions in the upper plane of the reactor.

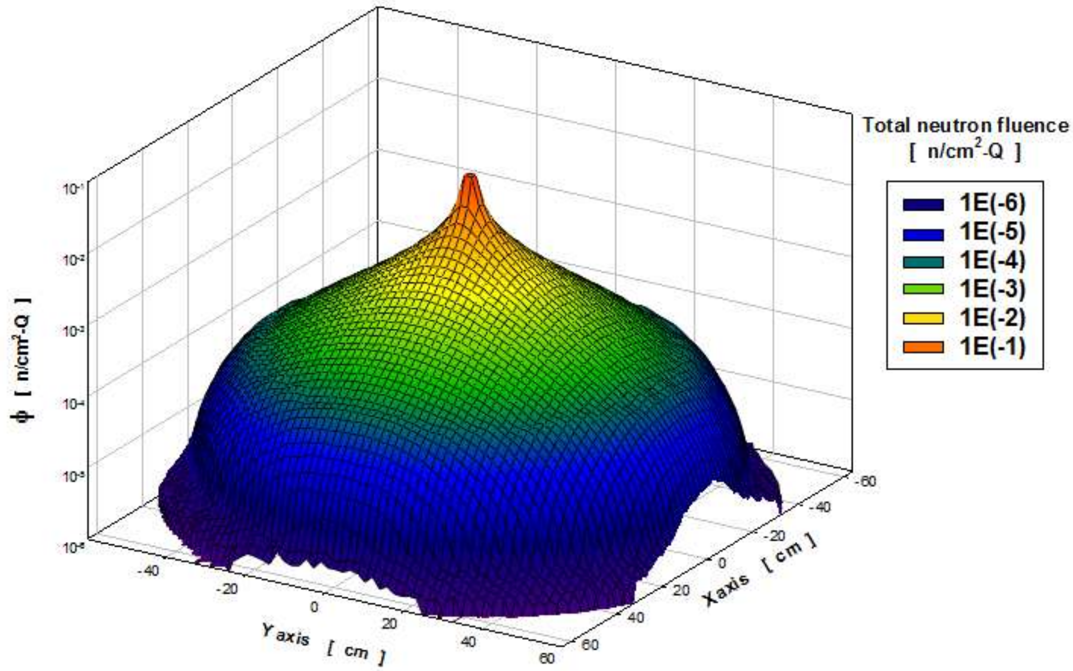

Figure 6.- Spatial distribution of neutrons in the reactor middle plane with 1350 fuel slugs.

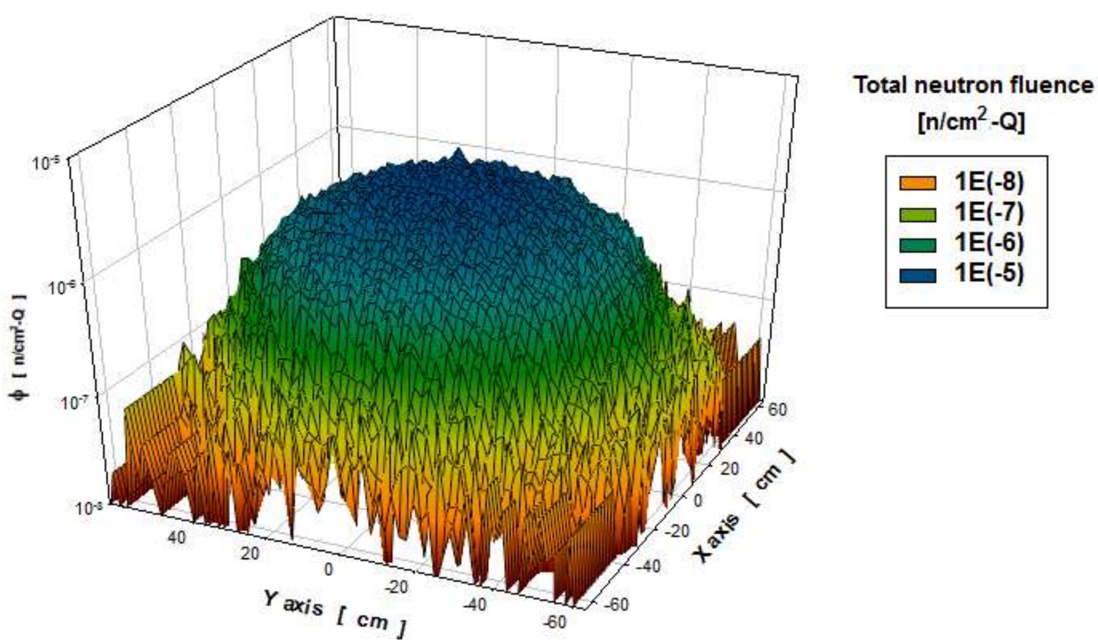

Figure 7.- Spatial distribution of neutrons in the reactor upper plane with 1350 fuel slugs.

The sharp peak in figure 6 are the neutrons inside the neutron source, this distribution is different to the distribution in the upper plane, which is outside the reactor. The Ambient dose equivalent a r = 65 cm (outside the reactor container) in the middle plane is 2.576E(-4) pSv/Q while at r = 55 cm (inside the reactor container) in the upper plane is 1.324E(-5) pSv/Q. Scaling these values using Q = 8E(6) n/s, the neutron ambient dose equivalent rate in the middle plane is 7.4 μSv/h while in the upper plane is 0.4 μSv/h thus is safe to be around during reactor operation.

4.- CONCLUSIONS

The k_{eff} of the UAZSNR was calculated using the six-factor formula and the Monte Carlo methods. With the Monte Carlo methods the neutron features of the reactor were estimated; also the ambient dose equivalents, at two locations, were calculated. From these calculations the main conclusions are:

1. The six-factor formula tends to overestimate the k_{eff} in comparison to use Monte Carlo methods when the fuel is less than 750 kg. When the amount of fuel is larger than 2500 kg the six factor formula tends to underestimate the k_{eff} in comparison to Monte Carlo calculations.

2. Using 1350 fuel slugs, that is the total fuel load, the k_{eff} is 0.8267 ± 3%, μ is 5.77. For a ^{239}PuBe source with 8E(6) n/s the reactor power is 489 μW. Conservatively, the H*(10) values are 7.4 μSv/h and 0.4 μSv/h in the middle and upper planes respectively.

3. As the distance, respect to the reactor center, increases the amount of fast, epithermal and thermal neutrons decreases. In sites near the reactor center the spectrum is strongly affected by the source neutron spectrum, this feature tends to vanish as the radius increases.

4. The neutron distribution in the reactor middle plane is symmetric along the radius.

REFERENCES

Abderrahim HA; Baeten P; De Bruyn D; Heyse J; Schuumans P; Wagemans J. (2010). *MYRRA, a multipurpose hybrid research reactor for high-end applications*. Nuclear Physics News **20**: 24-28.

Pyeon CH; Hirano Y; Misawa T; Unesaki H; Ichihara Ch; Iwasaki T; Shiroya S. (2007). *Preliminary experiments on accelerator-driven subcritical reactor with pulsed neutron generator in Kyoto University critical assembly*. Journal of Nuclear Science and Technology **44**: 1368-1378.

Shahbunder H; Ho Pyeon Ch; Misawa T; Lim J-Y; Shiroya S. (2010). *Subcritical multiplication factor and source efficiency in accelerator-driven system*. Annals of Nuclear Energy **37**: 1214-1222.

Dietrich FS. (1960). *Subcritical reactor as a College facility*. American Journal of Physics **28**: 309-314.

Endo T; Yamamoto A; Yamane Y. (2011). *Detected-neutron multiplication factor measured by neutron source multiplication method*. Annals of Nuclear Energy **38**: 2417-2427.

Papastefanou C. (2004). *Measurement of neutron flux and albedo of water for thermal neutrons with foils of indium in a subcritical nuclear reactor*. Journal of Radioanalytical and Nuclear Chemistry **261**: 671-678.

Talamo A; Gohar Y; Aliberti G; Cao Y; Smith D; Zhong Z; Kiyavitskaya H; Bournos V; Fokov Y; Routkovskaya C; Serafimovich I. (2011). *MCNPX, MONK, and ERANOS analyses of the YALINA Booster subcritical assembly*. Nuclear Engineering and Design **241**: 1606-1615.

Lamarsh JR. *INTRODUCTION TO NUCLEAR ENGINEERING*. Reading Mass. USA, Addison-Wesley. (1977).

Vega-Carrillo HR; Manzanares E; Hernandez-Davila VM; Ramirez-Gonzalez; Hernandez-Villasana J; Ruiz-Chacon A. (2009). Spectrometry and dosimetry of a neutron source. Radiation Effects and Defects in Solids **164**: 218-223.

Vega-Carrillo HR. *TEORÍA DE REACTORES NUCLEARES*. Saarbrucken Germany, Editorial Académica Española. (2012).

MathSoft. *MATHCAD PLUS 5.0 USER´S GUIDE*. Cambridge Mass. USA. MathSoft Inc. (1994).

Forster, R.A.; Cox, L.J.; Barrett, R.F.; Booth, T.E.; Briesmeister, J.F.; Brown, F.B.; Bull, J.S.; Geisler, G.C.; Goorley, J.T.; Mosteller, R.D.; Post, S.E.; Prael, R.E.; Selcow, E.C.; Sood, A. (2004). *MCNP^{TM} Version 5*. *Nuclear Instruments and Methods in Physics Research B* **213**: 82-86.