Neutronics and H*(10) in a Nuclear Chicago 9000 Subcritical Nuclear Reactor with polyethylene moderator and reflector

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Abstract

Subcritical Nuclear Reactor, also known as Subcritical assembly or Exponential pile, is the combination of nuclear fuel and moderator where neutrons are multiplied through nuclear fission without become critical, regardless the type of extraneous neutron source. Subcritical reactors have been designed and built with different purposes, using different fuel and moderators. Its use as pedagogical device has the advantage of being inherently safe where reactor physics can be learned. The subcritical reactor Nuclear Chicago model 9000 is a heterogeneous combination of natural uranium, in hexagonal lattice, and light water (moderator and reflector) that uses a ^{239}PuBe neutron source. Several of these reactors are still in use since the 60s. In this work a detailed Monte Carlo model was built changing the moderator by polyethylene. The k_{eff} was calculated as the amount of hexagon rings were increased and was compared with the k_{eff} obtained when the water was the moderator. Using 282 fuel tubes (case 10a) the neutron fluence and H*(10) distribution were estimated, as well as the source amplification factor and the reactor power.

Keywords: *Subcritical reactor; Nuclear Chicago 9000; Monte Carlo; k_{eff}, Neutron fluence; Ambient dose equivalent.*

1.- INTRODUCTION

A subcritical nuclear reactor, also named Subcritical assembly, Exponential assembly or Exponential pile, is a homogeneous or heterogeneous combination of fuel and moderator where neutrons are multiplied through nuclear fission without become critical.

To start and operate, these reactors need an extraneous source of neutrons, like those that produce neutrons through; (α, n) and (γ, n) reactions (isotopic neutron sources); spontaneous fission, like ^{252}Cf; D-D or D-T nuclear reactions produced in neutron generators or (γ, n) or (e, n) reactions in linear accelerators. Regardless the extraneous neutron source the sub criticality condition ($k_{eff} < 1$) is maintained. The subcritical reactors power depends upon the neutron source strength [Xoubi, 2016] while, regardless the extraneous source, the k_{eff} is ruled by the amount and type of fissionable material in the fuel, the lattice array, and the material used as moderator and reflector.

Subcritical reactors have been designed and built to generate energy [Jarrah et al., 2018], to transmute spent nuclear fuel [Rubbia et al., 1995; Salvatore 1999], and as neutron source [Shahbunder et al., 2010]. Among subcritical reactors are the Yalina-Booster subcritical assembly [Persson et al. 2005; Talamo et al. 2011; Bécares et al. 2013], the subcritical assembly at Dubna [Polanski et al. 2006; Shvetsov et al. 2006], the subcritical reactor at the University of Cincinnati [Maldonado, Xoubi and Zhao, 2008] the Delphi subcritical assembly [Szieberth et al. 2015], the BRAHMMA subcritical reactor [Sinha et al., 2015], the Nuclear Chicago model 9000 [Papastefanou 2004; Maldonado, Xoubi and Zhao, 2008; Sinha et al. 2015; Vega-Carrillo et al. 2015], the Jordan subcritical assembly [Xoubi, 2016; Jarrah et al., 2018; Radaideh et al., 2018], and the Esfahan subcritical reactor [Arkani, 2021].

Because a subcritical reactor is inherently safe it is used as a teaching tool to learn the main reactor physics parameters [Kamalpour, Khalafi and Mirvakili, 2014]. With this purpose the "Pickle barrel" subcritical reactor was designed and built at the New York University. Later, the subcritical reactor Nuclear Chicago model 9000 [Dietrich, 1960; Borst, 1961; Kimel, 1961; Lurie, 1961] was produced with commercial purposes. In these reactors cylindrical natural uranium rods (slugs) were used as fuel while light water (tap) was used as moderator and reflector. Fuel slugs are in aluminum tubes (fuel tubes) that are distributed in concentric hexagons [Papastefanou, 2004; Maldonado, Xoubi and Zhao, 2008; Vega-Carrillo et al., 2015]. Changes in the fuel, the extraneous neutron source, fuel lattice, or moderator requires to determine the neutron distribution, the effective multiplication factor (k_{eff}), the neutron amplification (μ) and the dose around the reactor. Thus, through experiments and Monte Carlo calculations Maldonado, Xoubi and Zhao [2008] determined the k_{eff}, the neutron fluence rate distribution changing the fuel load and did explore the impact of changing the moderator.

The aim of this work was to estimate, with Monte Carlo methods, the k_{eff} and μ as the fuel load was increased for the Subcritical nuclear reactor Nuclear Chicago model 9000 with water and polyethylene moderator. Also, for the reactor with polyethylene moderator the neutron spectra were estimated along the radial and axial axis and the H*(10) at two sites outside the reactor tank were calculated.

2.- MATERIALS AND METHODS

2.1.- Subcritical reactor Nuclear Chicago model 9000

In Figure 1 is shown the radial cross sectional upper view of Nuclear Chicago model 9000 subcritical reactor (NChSR), while in Figure 2 is shown the vertical cross section view of reactor´s midplane. To start the reactor, in the central tube in inserted a 0.185 TBq (5 Ci) ^{239}PuBe radioisotopic neutron source. The source is handled with a Lucite rod that is kept in place during the reactor operation [Vega-Carrillo, 2012]. To have the hexagonal lattice there are two circular aluminum plates with holes (grids) where the fuel tubes are inserted. The fuel in the NChSR is metallic natural uranium (U_3O_8) made at the Savannah River

Plant in United States. The fuel is 3.05 Ø × 21.3 cm cylindrical slugs with a 1.25 Ø × 21.3 cm hollow. These dimensions include the 0.11 cm aluminum cladding [IAEA, 1967].

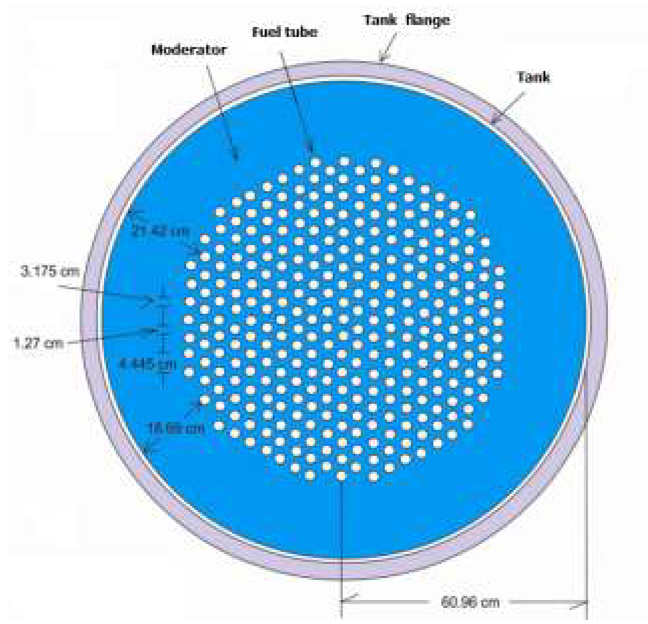

Figure 1.- Upper radial cross sectional view of NChSR.

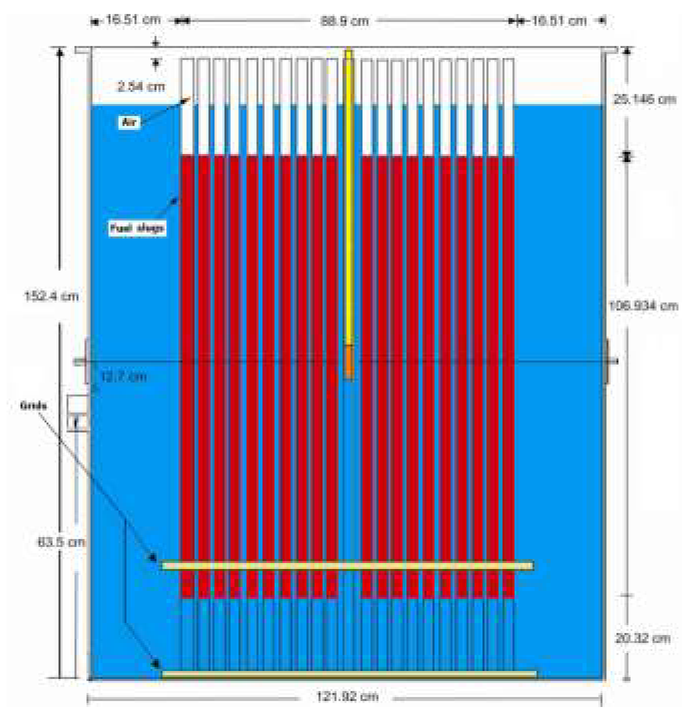

Figure 2.- Vertical cross sectional view at the midplane of the NChSR.

Five fuel slugs inserted in 3.5 Ø × 149.8 cm aluminum tube (0.10 cm-thick) is a fuel tube that has three sections: The upper part is empty (25.1 cm-long), the middle part (106.9 cm-long) is filled with the fuel slugs, and the bottom section (17.8 cm-long) that is filled with the reflector. Reactor tank (122 Ø × 152 cm) is 7.92 g/cm^3 stainless steel (SS304).

A model of the NChSR was built with the Monte Carlo code MCNP5 [X-5 Monte Carlo team, 2003] using water and 0.95 g/cm^3 polyethylene as moderator and reflector, for both materials the S(α, β) treatment was included. In the simulations the ENDF66 cross-section libraries [Frankle *et al.*, 2003] were used. All calculations were analog Monte Carlo, i.e. in the transport simulations were not used any variance reduction techniques. The amount of histories was large enough to have less than 5% uncertainties.

2.2.- k_{eff}(T) and μ(T)

The grids have 12 hexagonal rings, for both moderators, reactors models having fuel tubes from the first to the twelfth ring were built and for each case the k_{eff} was estimated. As an approach-to-critical experiment the k_{eff} and the $1/k_{eff}$ in function of the amount of fuel tubes (T) were fitted to functions shown in equations 1 and 2 respectively.

$$k_{eff}(T) = C_1\left(\frac{T}{C_2+T}\right) + C_3\left(\frac{T}{C_4+T}\right) \quad (1)$$

$$k_{eff}^{-1}(T) = a\, e^{\left(\frac{b}{c+T}\right)} \quad (2)$$

The parameters C_1, C_2, C_3, C_4, a, b, and c were obtained by fitting the Monte Carlo results and the limits of k_{eff} and $1/k_{eff}$ were calculated as the amount of fuel tubes tends to infinite, aiming to have the evidence that this reactor will never be critical.n When a neutron source, with a source strength Q n/s, is inserted in the subcritical reactor neutrons, neutrons are multiplied, the Amplification factor (μ) [Papastefanou, 2004], also named Source multiplication factor (M) [Kersten et al., 1964], depends on the k_{eff} as is shown in equation 3.

$$\mu = \frac{Q + Q\,k_{eff} + Q\,k_{eff}^2 + \cdots + Q\,k_{eff}^n}{Q} \tag{3}$$

Cancelling out the source strength (Q), the k_{eff} series in equation 3 is,

$$\mu = \frac{1}{1 - k_{eff}} \tag{4}$$

The Amplification factor was calculated as the amount of fuel tubes was increased, the $\mu(T)$ was fitted to the function shown in equation 5, and the $\mu(T)$ limit was calculated as $T \rightarrow \infty$.

$$\mu(T) = \alpha\left(\frac{T}{\beta + T}\right) + \gamma\left(\frac{T}{\delta + T}\right) \tag{5}$$

For the subcritical reactor the reactor power (P) depend of μ and the k_{eff} [Vega-Carrillo, 2012], as is shown in equation 6.

$$P = \frac{Q\ \mu\ k_{eff}\ E_R}{\nu} \tag{6}$$

Here, Q is the extraneous neutron source strength, ν is the mean value of neutrons emitted per fission (2.44), E_R is the thermal energy recovered per fission 3.12425E(-11) W-s/f [Lewis, 2008]. For the reactor with 282 fuel tubes (case 10a) with water and polyethylene moderators the power was calculated.

2.3.- Neutron and H*(10) distribution

The NChSR lattice grids have 11 hexagonal rings, filling up to the 10^{th} ring the reactor can be loaded with 282 fuel tubes (case 10a) or with 324 (case 10b). Filling up the 11^{th} hexagonal ring the amount of fuel tubes is 348 (case 11). For both moderators the neutron fluence and the Ambient dose equivalent (H*(10)) distribution per history were estimated at midplane shown in Figure 2, for the case 10a.

3.- RESULTS AND DISCUSSION

3.1.- k_{eff}(T) and μ(T)

For the NChSR with water and polyethylene moderators in Figure 3 the effective multiplication factors, in function of the amount of fuel tubes, are shown. Here, is included the fitted functions whose parameters are shown in Table 1, where in the last column is included the $k_{eff}(T)$ value as the amount of fuel tubes (T) tends to infinite.

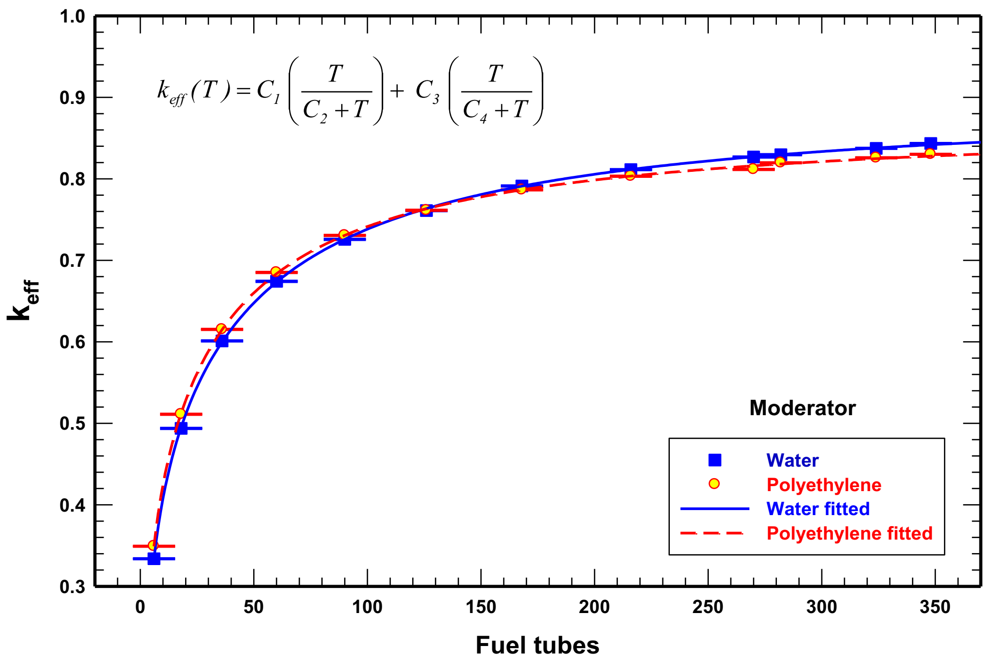

Figure 3.- k_{eff} of the NChSR in terms of the fuel load.

Table 1.- Equation 1 parameters for the $k_{eff}(T)$ of using water or polyethylene as moderator.

Moderator	C_1	C_2	C_3	C_4	k_{eff} limit $T \rightarrow \infty$
Water	0.4207±0.0160	3.0896±0.2313	0.4803±0.0146	45.5±2.3	0.9010
Polyethylene	0.4086±0.0330	2.7020±0.4269	0.4654±0.0311	35.4±3.3	0.8740

The ^{235}U nucleus is fissile, thus when it absorbs a neutron the nucleus will experience nuclear fission emitting between 2 to 3 fast neutrons depending on the energy of the incident neutron. As the amount of fuel tubes increases the amount on neutrons also increases at each generation that is characterized by the k_{eff} as is shown in Figure 3, which looks similar to calculations and measurements reported by Maldonado, Xoubi and Zhao [2008] in a similar subcritical reactor moderated with water. In the subcritical reactor the fuel is uranium having 0.72% of ^{235}U. To increase the probability of having nuclear fission in ^{235}U fast fission neutrons must be moderated to reduce its energy. Along the neutron moderation there is a probability of being absorbed by the moderator, the aluminum nuclei in the fuel tube and slugs cladding, as well as in the ^{238}U nuclei. Also, neutrons can escape through the reactor boundaries. Thus the amounts of neutrons available to induce more fission are reduced and the reactor remains subcritical. Water or polyethylene moderators combined with the lattice and fuel used in the NChSR never can be critical, even if the amount of nuclear fuel were infinite (Table 1). The k_{eff} of water-moderated reactor is 3.09% larger than the effective multiplication factor obtained when the reactor use polyethylene as moderator.

The inverse of $k_{eff}(T)$ values are shown in Figure 4, as well as the fitted functions.

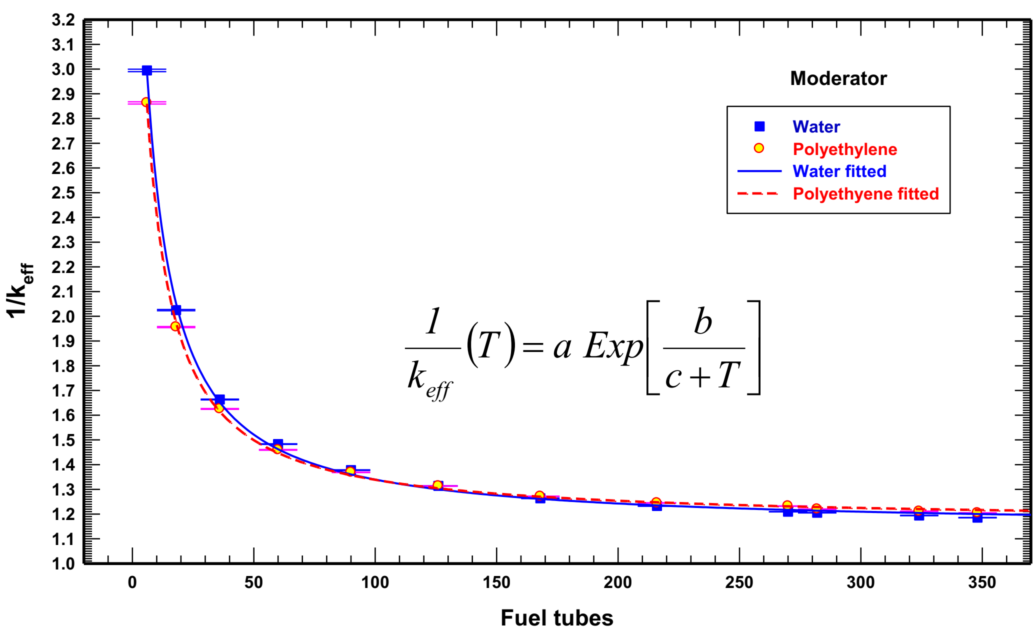

Figure 4.- $1/k_{eff}(T)$ of the NChSR in terms of the fuel load.

The $k_{eff}(T)^{-1}$ diminish as the fuel load is increased, the $1/k_{eff}(T)$ is alike to calculations and measurements reported by Maldonado, Xoubi and Zhao [2008]. For both moderators the fitted functions are asymptotic tending to being constant as the amount of fuel tubes is increased.

In Table 2 are the parameters of Equation 2, the limit of $1/k_{eff}(T)$ was obtained and with this the $k_{eff}(T)$ was calculated and shown in last column of Table 2.

Table 2.- Equation 2 parameters for the $1/k_{eff}(T)$ for water or polyethylene moderator.

Moderator	*a*	*b*	*c*	k_{eff} limit $T \rightarrow \infty$
Water	1.1420±0.0075	17.98±0.69	12.68±0.65	0.8757
Polyethylene	1.1656±0.0054	15.37±0.47	11.12±0.47	0.8579

The $k_{eff}(T)$ when $T \rightarrow \infty$ using Equation 1 is 2.89% larger than the value obtained through Equation 2 for water-moderated reactor, and 1.88% larger when the moderator is polyethylene. However, regardless the moderator the reactor will remain subcritical. For water-moderated reactor the $k_{eff}(T)$ when $T \rightarrow \infty$ using Equation 1 3.09% larger than value obtained in the reactor with polyethylene as moderator. On the other hand, the $k_{eff}(T)$ when $T \rightarrow \infty$ obtained through Equation 2 is 2.07% larger when water is the moderator in comparison with the reactor moderated with polyethylene.

In Figure 5 the Amplification factors of neutrons emitted by the extraneous source in terms of fuel load $\mu(T)$ are shown. The $\mu(T)$ is larger when the first to fifth hexagonal ring are loaded in the polyethylene-moderated reactor is loaded. When the sixth ring is loaded the amplification factor is the same for both moderators. Loading the seventh to the eleventh hexagonal ring in the reactor moderated with water increases the amplification factor in comparison to the reactor moderated with polyethylene. This is probable due to the combination of the efficiency to reflect neutrons and the low neutron absorption of water in comparison to polyethylene.

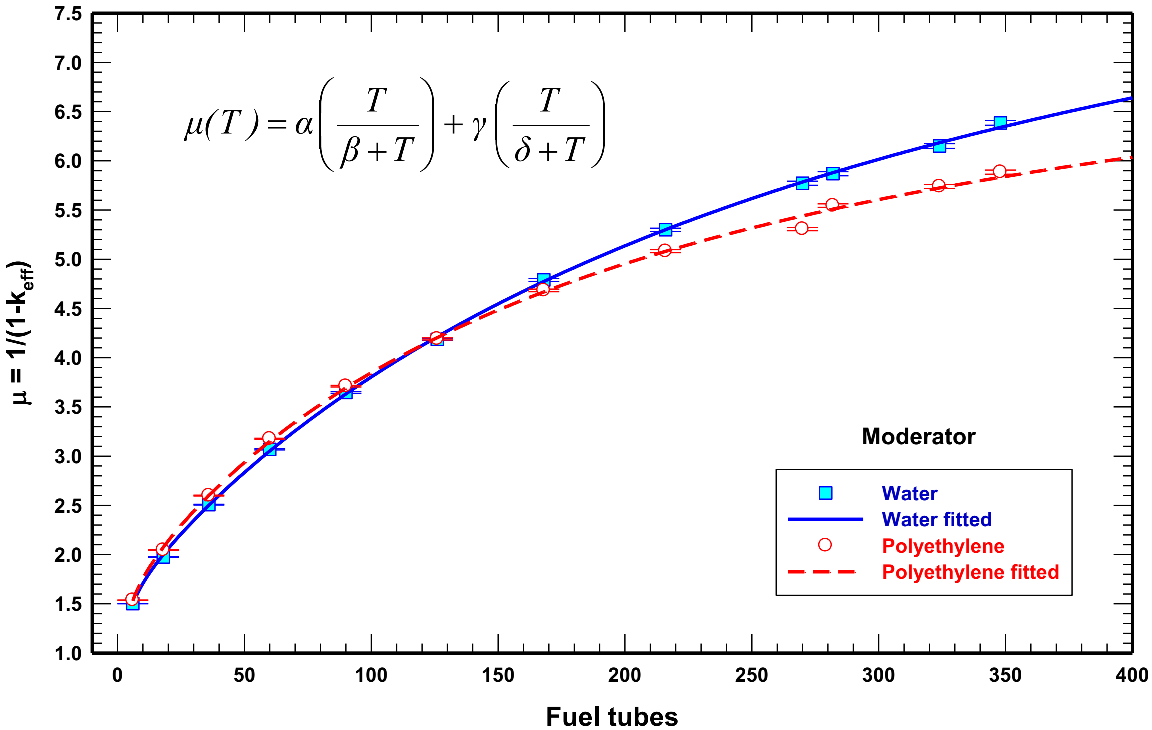

Figure 5.- $\mu(T)$ of NChSR.

In Table 3 are the parameters of Equation 3 for the NChSR with water and polyethylene moderators, as well as the $\mu(T)$ values as the T tends to infinite.

Table 3.- Equation 5 parameters of the NChSR with water and polyethylene moderators.

Moderator	α	β	γ	δ	μ(T) limit $T \rightarrow \infty$
Water	1.5967±0.0579	1.2610±0.3106	8.7350±0.1654	292.2±16.5	10.33
Polyethylene	1.6127±0.1471	1.2812±0.7204	6.5242±0.1635	189.3±23.1	8.14

The neutron source amplification in the water-moderated reactor, loaded with an infinite amount of fuel tubes is 26.9% larger than the μ obtained with the polyethylene-moderated reactor.

For the reactor with 282 fuel tubes (case 10a), using the 5 Ci ^{239}PuBe source (Q = 1.01E(7) n/s) the reactor power when water is used as moderator is 0.63 mW, and 0.59 mW when the moderator is polyethylene. With water as moderator the power is 6.8% larger than the power of the reactor with polyethylene as moderator.

3.2.- Neutron fluence and H*(10) distribution

The neutron fluence and the H*(10) distribution in the reactor loaded with 282 fuel tubes (case 10a) were estimated for both moderators. For water-moderated reactor Figure 6 shows the neutron fluence distribution per history in the plane shown in Figure 2 while in Figure 7 is shown the H*(10) distribution per history.

Figure 8 and 9 shows the neutron fluence and H*(10) distribution per history for the case 10a reactor moderated with polyethylene.

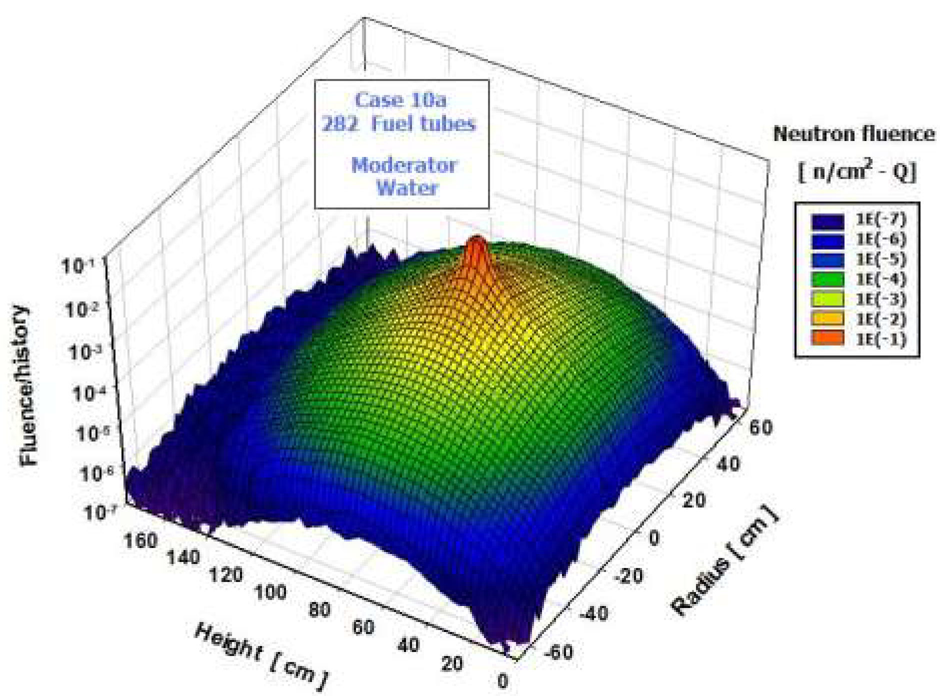

Figure 6.- Neutron fluence per history in the NChSR moderated with water.

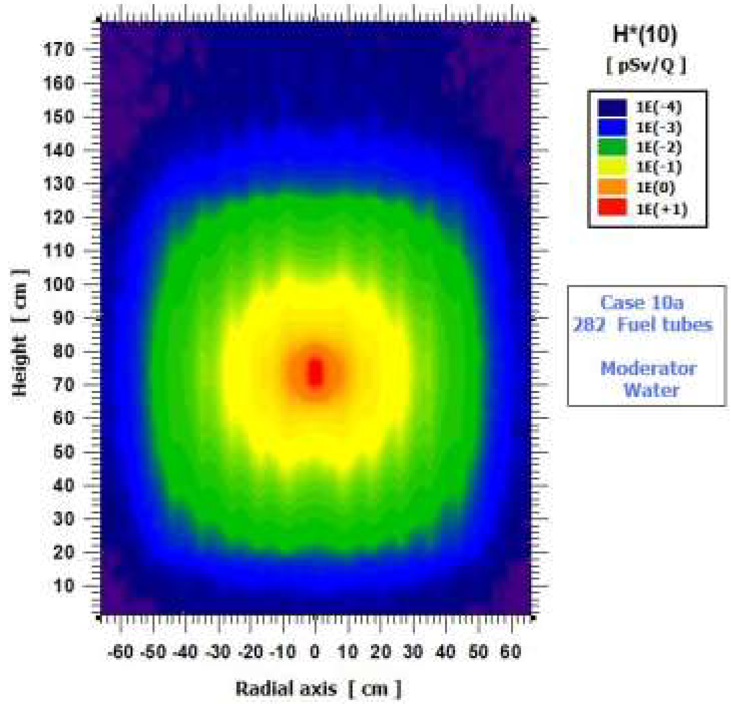

Figure 7.- H*(10) per history due to neutrons in the NChSR moderated with water.

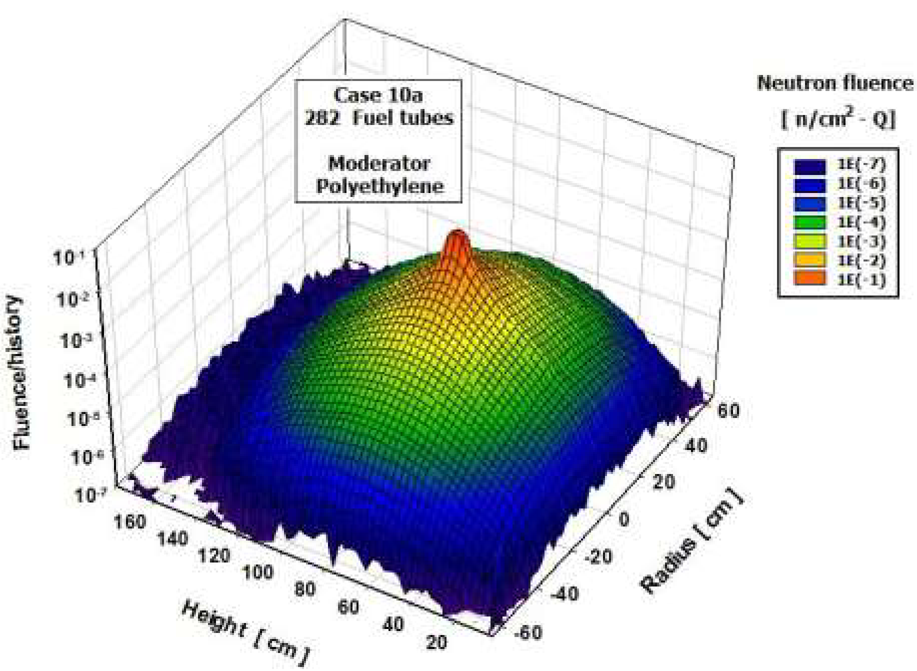

Figure 8.- Neutron fluence per history in the NChSR moderated with polyethylene.

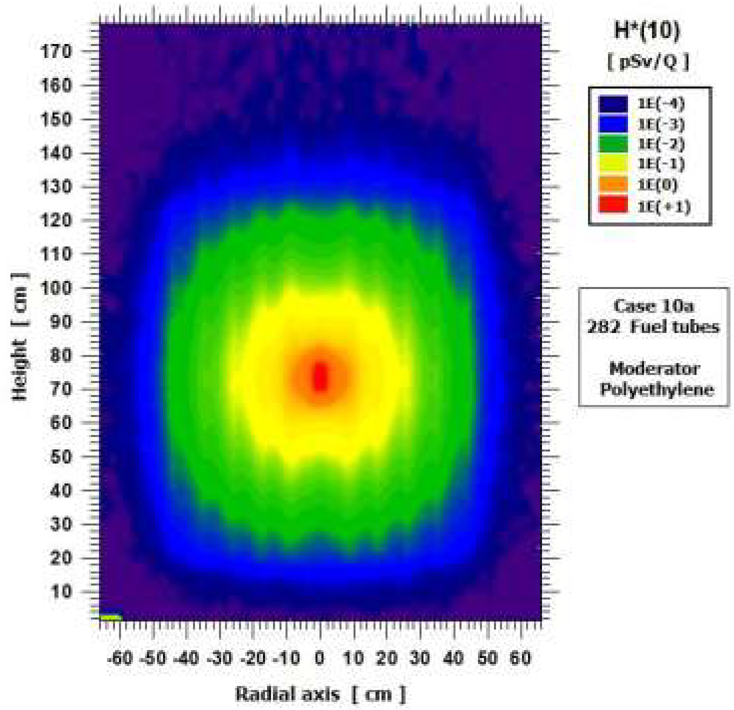

Figure 9.- H*(10) per history due to neutrons in the NChSR moderated with polyethylene.

Regardless the moderator the largest neutron fluence and H*(10) is larger where is the ^{239}PuBe neutron source. As the radial and axial distance in reference to the source increases fluence and dose diminish; however this decrement is smaller for the reactor moderated with water.

At the upper section of the reactor (z > 150 cm), there are less neutrons at and the H*(10) is smaller for the reactor moderated with polyethylene in comparison to the water-moderated reactor. The same is noticed outside the reactor, particularly along the radial axis and at the bottom.

Water-moderated reactor has larger k_{eff} and m therefore there are more neutrons. During moderation neutrons are slowed down reducing their kinetic energy and the dosimetric features of neutrons depend on the neutron energy and in combination of having less neutrons when polyethylene is used as moderator explain the dose distribution noticed in the reactor in comparison with the reactor moderated with water.

4.- CONCLUSIONS

The k_{eff} and μ of a Nuclear Chicago model 9000 subcritical reactor in function of the fuel load using Monte Carlo methods. Calculations were carried out using water and polyethylene as moderator. Calculated values were fitted to two functions $k_{eff}(T)$ and $\mu(T)$ and the limit as T $\rightarrow \infty$ were obtained. Also, the $1/k_{eff}$ were calculated and the data were fitted $1/k_{eff}(T)$ and the limit was obtained and the $k_{eff}(T)$ in the limit was obtained.

The Nuclear Chicago model 9000 is subcritical, with water or polyethylene as moderator. regardless the amount for fuel tubes loaded.

The maximum $k_{eff}(T)$ for the reactor moderated with water is 0.9010, and 0.8740 if the moderator is polyethylene.

For the reactor with 292 fuel tubes (case 10a) moderated with water and the 5 Ci ^{239}PuBe source, the neutron source amplification factor (μ) and the reactor power are 5.869 and 0.63 mW respectively. Using polyethylene as moderator the m is 5.5451 and the power is 0.59 mW.

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