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"Research Note"

ANALYSIS AND OPTIMIZATION OF A FISSION CHAMBER DETECTOR USING MCNP4C AND SRIM MONTE CARLO CODES*

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Abstract – In this study, a general theoretical model to foresee and calculate the current-voltage characteristics in a plateau zone and the associated efficiency of the neutron detector (sensitivity) is presented. This study is to complete the previous studies in this field. The model also considers electric field distortion resulting from the charge collection effect. The characteristics curve is obtained as a function of fission rate, chamber geometry, and filling gas pressure. The output current at the saturation domain is calculated. The applied voltages about two phenomena, recombination and avalanche, for working the chamber in an ionization zone are an important part of the calculation. In developing the theoretical model, the MCNP code for fission rate, the SRIM code for electron-ion pair and GEANT4 for gamma sensitivity calculations were used.

Keywords – Fission chamber, MCNP, GEANT4, SRIM, optimization

1. INTRODUCTION

Fission ionization chambers are widely used as neutron detectors in irradiating environments such as nuclear reactors, accelerators, and physic laboratories. They can be used in pulse mode, current mode or Mean Square Voltage (MSV) mode [1]. Cylindrical fission chambers are made of two coaxial electrodes, which are separated by a filling gas. The filling gas that is used in ANTON TYPE 812 is a combination of argon (95%), and nitrogen (5%) [2]. The anode is usually coated with a fissile element (our model's fissile coating has 90% U-235). Under irradiation, neutrons induce fission reactions inside the fissile element (the probability is proportional to the fission reaction cross section) and two fission fragments (FF) with a range of energy of about 60 MeV to 90 MeV are emitted in opposite directions. If the energy of the incident neutron is negligible compared to 90 MeV and 60 MeV, it is accurate to say those FF emerge in opposite directions.

Thus, on average only one FF participates in the gas ionization, the other one being absorbed by the anode. The FF emitted to a gas ionizes the filling gas and as a result, generates a high number of electron-ion pairs. Of course, there is a probability that the two fragments remain in the fissile element and do not enter into the surrounding environments (gas and anode). The fissile element layer should be thin enough for fission fragments to have a chance to enter into the filling gas. When a voltage is applied, an electric field is generated between the two electrodes. The anode collects the negative charge, while the cathode collects the positive one. The collected charges are responsible for the creation of an electric current. The

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layout of this current, according to the voltage applied gives a characteristic curve, known as the calibration curve.

In the calibration curve the saturation current is proportional to the neutron flux, which is why it is important to know when the chamber works in saturation conditions.

Therefore, the main aim of this study is to determine the relevant parameters of the chamber and the optimal voltages which answer the neutron flux requirements. Also, the saturation current and sensitivity of the modeled chamber are calculated.

2. ANALYTICAL ANALYSIS

a) Fission made from neutron collision with fissile element

Suppose μ_s is the area density of a fissile element (for ANTON TYPE 812 μ_s=680 μg.cm^{-2} [2]). This parameter decreases during the life of the chamber because fissile nuclei are depleted. The fission reaction rate per unit surface is given by [3, 4]:

$$N_{fst} = \int_0^{\infty} \sigma(E) \frac{\mu_s}{M_U} N_A \phi_E(E) dE \tag{1}$$

Where *fst* stands for fission per unit surface per unit time, *σ(E)* is an effective fission cross section for the neutron of energy E, M_U is the molar mass of U-235, N_A is the Avogadro's number and $\phi_E(E)$ is the neutron flux at energy E.

Recalling that the fission rate is given by [3]:

$$\chi = \int_0^{\infty} \sigma(E) \phi_E(E) dE \tag{2}$$

To verify the accuracy of the fission rate calculation by MCNP, the neutron source was evaluated in two different methods. In the first method, a neutron source with an energy range of 0 to 2 MeV was defined and the fission rate was evaluated using MCNP. In the second method, the fission chamber was assumed to be placed in a critical nuclear reactor core, and using the KCODE option, the fission rate was evaluated.

The results of both methods were comparable and the accuracy of the fission rate evaluation was confirmed. The fission rate was found to be:

$$\chi = 1.48128 \times 10^{-15} \ fission/\mathrm{sec}$$

b) Electron-ion pair production rate calculation

After generating fission fragments nearly all entered into the filling gas and ionized the atoms of the gas, generating the ions (Ar^+ and e^-). Thus, fission fragments make an electron-ion pair. We consider $I^c(r)$ the average number of electron-ion pairs created by a fission fragment per unit of length travelled in the radius path. However, in the case of a fission chamber with small dimensions, the trajectory of the fission fragments is short enough that $I^c(r)$ can be considered constant, on average, equal to I_0^c in the electrodes space.

By using the SRIM program [5, 6] of J. F Ziegler which computes the stopping range of the ions in solids, liquid and gases, we calculate the I_0^c, considering the lightest fission fragment with an energy of 90 MeV (^{95}Mo, Molybdenum) as an incident particle in the chamber's gas.

For the ionization chamber, the energy loss by ionization computed by SRIM was obtained as 4.5469E-01 (*eV/A°.ion*) with a gas pressure of 1.01 *bar*. If the required ionization energy of the combined gas atoms is about 23 *eV* [3], we can calculate I^c_0 by dividing the ionization energy loss by the gas atoms ionization energy:

$$I_0^c \approx 454.69\times10^{-3}(eV/A^\circ.ion)/23eV = 1.976913\times10^6\, ion-pair/cm.bar$$

We need to calculate the density of the electron-ion pair created per unit time at a distance *r* from the anode axis, *N(r)*. For a fission chamber with small dimensions we could write [3]:

$$N(r) = N_0 = \frac{\pi}{2} N_{fst} p I_0^c \tag{3}$$

where *p* is the pressure of the filling gas.

c) Saturation Current, I_{sat}

The saturation current corresponding to the collection of all electrons created by the primary ionization, I_{sat}, is obtained by:

$$I_{sat} = \pi e L N_0 (r_c^2 - r_a^2) \tag{4}$$

where *L* is the sensitive length, *e* is the charge of the electron, r_c is the cathode radius, and r_a is the anode radius. The limitations of the saturation plateau zone are due to the recombination and threshold condition where the recombination modifies the saturation current. With some theoretical assumptions the beginning voltage of the saturation plateau, V_{rec}, is equal to the minimum voltage of the plateau zone.

d) Minimum Voltage, V_{min}

For a voltage less than the minimum value, the electric field is not strong enough to evacuate the charges created by the primary ionization. Below this minimum voltage a steady state condition could not exist. Minimum voltage is calculated by integrating the electric field between the anode and cathode distance [3]:

$$V_{\min}(N_0) = \int_{r_a}^{r_c} [N_0 \frac{e}{4\varepsilon_0}(\frac{(r^2-2r_a{}^2)}{\mu_+} + \frac{(r^2-2r_c{}^2)}{\mu_-}) + \frac{C_{\min}}{r^2}]^{\frac{1}{2}} dr \tag{5}$$

Where μ_+ and μ_- are the mobility of positive and negative ions respectively and C_{min} is integral constant ($\mu_+ \approx 1.3\ cm^2.bar.V^{-1}.sec^{-1}$, $\mu_- \approx 1300\ cm^2.bar.V^{-1}.sec^{-1}$).

Using equation 1 and 2 and the MCNP result for the fission rate, the fission reaction rate per unit surface is:

$$N_{fst} = \frac{\mu_s}{M_U} N_A.\chi \approx \frac{680\frac{\mu g}{cm^2}}{235.0534\frac{g}{mole}} \times 0.602\times10^{24}\frac{\#atom}{mole}\times1.48\times10^{-15}\frac{1}{\sec} \approx 2585\frac{\#atom}{cm^2.\sec}$$

and the density of the electron-ion pair created per unit time is obtained from equation 3:

$$N_0 = \frac{\pi}{2}N_{fst}pI_0^c = \frac{\pi}{2}\times2585\frac{\#atom}{cm^2.\sec}\times1.01bar\times2\times10^6\frac{ion-pair}{cm.bar} \approx 8.178\times10^9\frac{ion-pair}{cm^3.\sec}$$

By substituting $\varepsilon_0 = 8.85\times10^{-16}$ $(N.cm^2/C^2)$, e = 1.6×10^{-19} C, $r_a = 0.8595\ cm$, $r_c = 2.5695\ cm$, and calculating C_{min} to be about *15825.45* in equation 5, the minimum voltage for the fission chamber is obtained as:

$$V_{\min}(N_0) = 357.71 volts\ .$$

e) Maximum voltage, V_{max}

In the plateau zone the maximum voltage should be limited. The relationship between $\boldsymbol{V_{max}}$ and the chamber parameters is [3]:

$$V_{\max}(N_0) = \int_{r_a}^{r_c} [\frac{N_0 e}{4\varepsilon_0}(\frac{(r^2 - 2r_a^{\ 2})}{\mu_+} + \frac{(r^2 - 2r_c^{\ 2})}{\mu_-}) + \frac{E_S^2 r_a^2}{r^2} + \frac{C_{\min}}{r^2}]^{\frac{1}{2}} dr \tag{6}$$

By substituting the parameters from section 2.4 and $E_s = 0.05\times10^6$ V/m in equation 6, the maximum voltage for the fission chamber is obtained as:

$$V_{\max} = 634.81\ \ volts\,.$$

f) Sensitivity (efficiency) of fission chamber

The sensitivity is obtained by dividing the current delivered by the chamber to the thermal neutron flux:

$$S = I_{sat} / \Phi_{th} \tag{7}$$

By replacing I_{sat} from equation 4 and N_0 from equation 3, we can write S as

$$S = \frac{\pi^2}{2} eL \frac{\mu_s}{M_U} N_A p I_0^c \sigma_{th} (r_c^2 - r_a^2) \tag{8}$$

Where, σ_{th} is the effective thermal neutron cross section and its value is considered about 572 barns [7]. Therefore, substituting L =15.24 cm in Equation 8 gives:

$$S = 1.420114\ \times 10^{-13}\ {}^{ampere}\!\!\diagup_{(n / cm^2 . \sec)}$$

Having the sensitivity, the saturation current could be obtained in any neutron flux from the ANTON TYPE 812 datasheet [2]. For example, in a flux of 3×10^9 n/(cm^2.sec), using the equation 7, the current I_{sat} is obtained as 0.4260634 mA.

4. GAMMA SENSITIVITY CALCULATION USING GEANT4 CODE

The fission chamber was modeled with GEANT4 [8, 9] to estimate electron-ion pair production by γ-radiation from different sources and the gamma sensitivity.

The gamma sensitivity threshold energy to produce the electron-ion pair was obtained as 12.451 *KeV* in GEANT modeling. Therefore, taking into account the range of energies of γ-rays in a thermal reactor, the gamma threshold energy is negligible and could be considered as noise.

5. THE OPTIMIZATION PROCESS

a) The Gas Pressure

The inner-electrodes gas pressure was varied to analyze the electron-ion pair generation. Ionization energy at each pressure was computed by SRIM program.

Increasing the gas pressure results in an increase in electron-ion pair generation. Figures 1 and 2 illustrate the effects of pressure variation in electron-ion pair generation and the detector's operating voltage plateau, respectively.

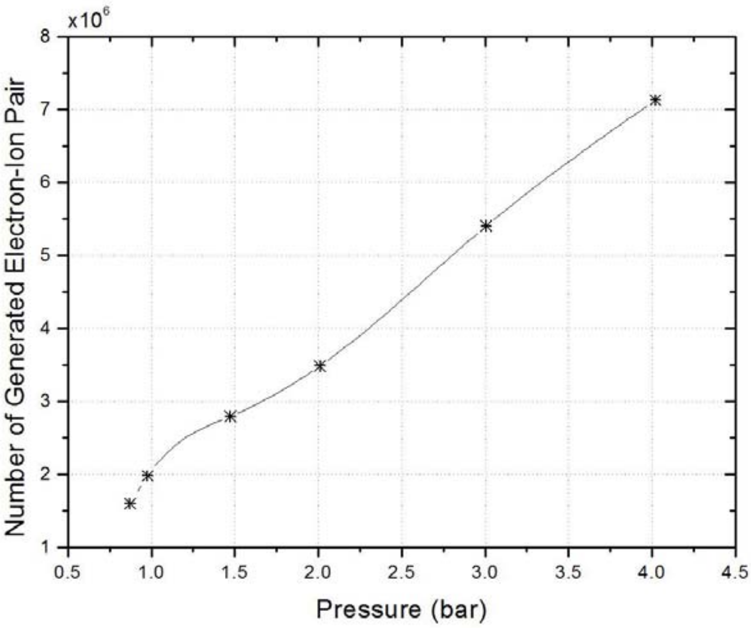

Fig. 1. The variation of electron-ion pair production vs. pressure

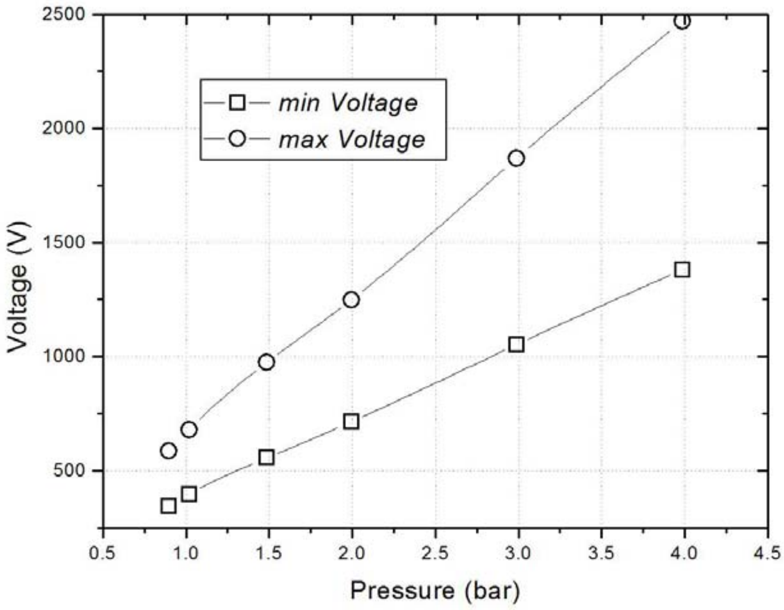

Fig. 2. The variation of Vmin- Vmax plateau voltage vs. internal gas pressure

b) Area density and enrichment variation of Fissile Element

The area density variation increases min-max plateau voltages. The results are shown in Fig. 3.

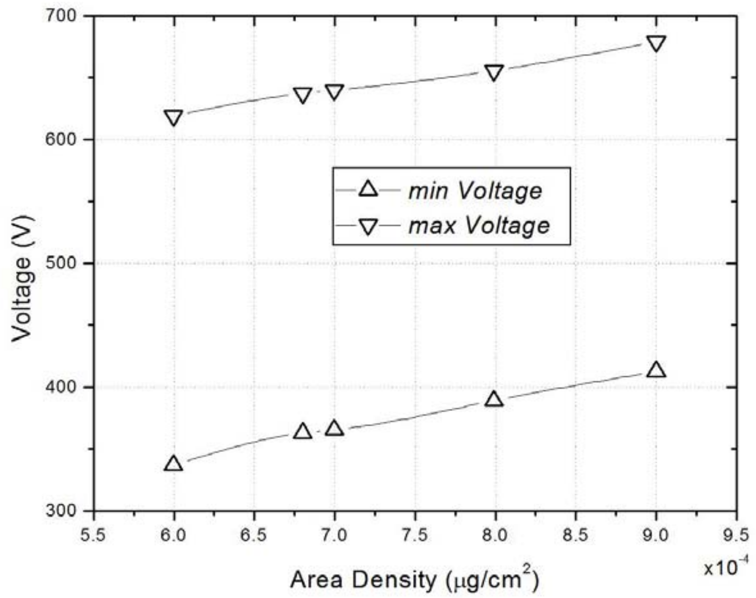

Fig. 3. The variation of Vmin-Vmax plateau voltage vs. surface mass

Besides the original enrichment used in analysis (90% for U-235), two different enrichments (95% and 85%) were used to investigate their effect on the fission rate and min-max voltages. Figures 4 and 5 illustrate these variations, respectively.

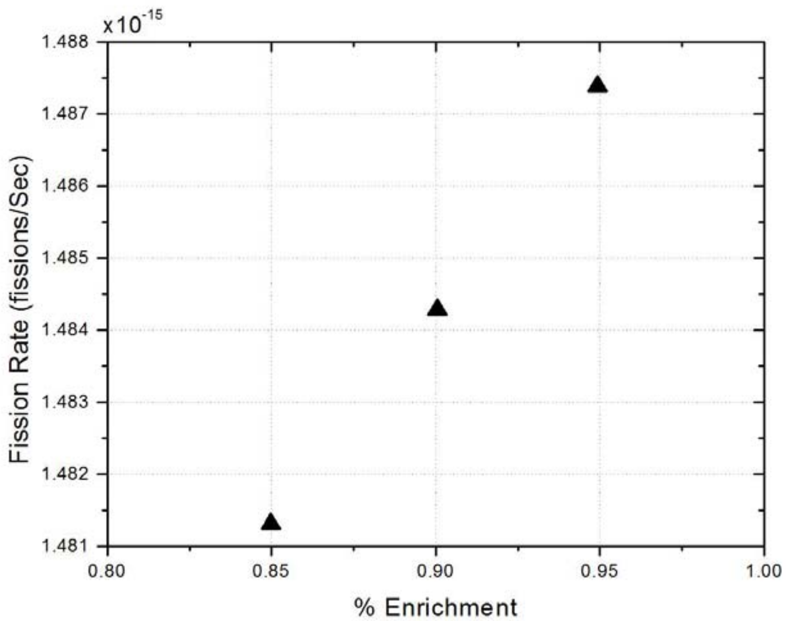

Fig. 4. The variation of fission rate vs. enrichment

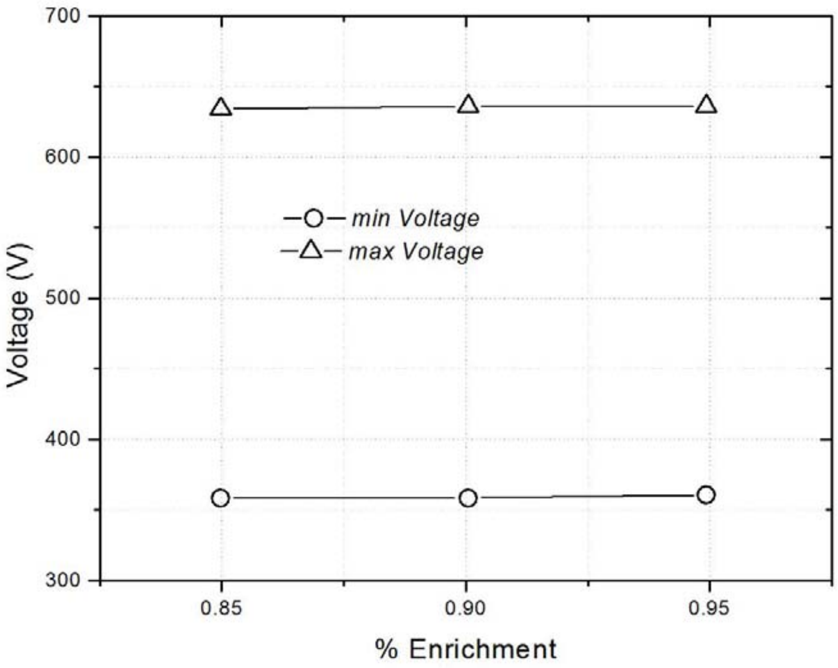

Fig. 5. The variation of min-max plateau voltage vs. enrichment

c) The Inter-Electrodes Gap

Anode radius varied with the fixed cathode radius. The major effect appears in the numerical calculation and has an ignorable effect on the fission rate resulting from the MCNP code. Figure 6 shows the voltage variation for different inter-electrode gaps.

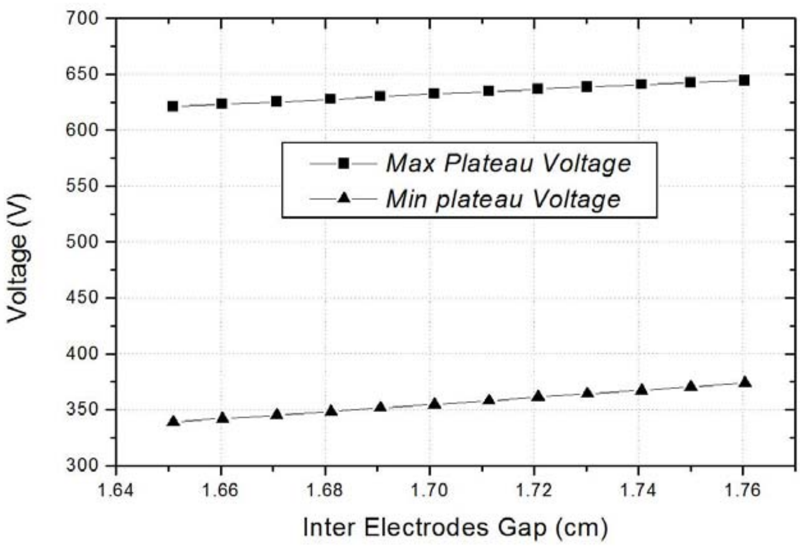

Fig. 6. The variation of min and max plateau voltages vs. inter-electrodes gap

6. CONCLUSION

This study revealed three important results about the fission chamber.

Firstly, the best approach for decreasing the minimum voltage in the plateau zone and retaining the chamber in the ionization zone is to reduce the pressure of the filling gas in the chamber. However, by reducing the chamber gas pressure we decrease the filling gas density whose net effect is electron-ion pair rate reduction. This electron-ion pair reduction would also affect the sensitivity (sec 3.4).

It was noted that at high pressure, the plateau zone width would extend. This extension would force a higher electric field requirement and a distortion of the electric field due to the space charge effect.

Secondly, by changing the area density and enrichment of the fissile element we deduce that increasing the fissile element enrichment can be useful in a high flux neutron surrounding (Fig. 4) where the applied voltage and plateau zone width did not change (Fig. 5). Increasing the fissile element area density has no useful effect, and it requires higher voltage (Fig. 3).

Thirdly, by decreasing the inter-electrodes space, the detection sensitivity of the neutron flux would decrease, which increases the width of the plateau zone (Figs 6 and 7), improving the chamber performance for high neutron flux and decreasing the resulting errors.

Furthermore, by decreasing or increasing the inter-electrode gap, the fission chamber could be used either in a high flux or low flux neutron surrounding respectively, providing a high resolution of neutron detection.

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