

Development of Neutron Detector Using the PIN Photodiode With Polyethylene (n, p) Converter

Carlos H. Mesquita, Tufic Madi Filho, and Margarida M. Hamada

Abstract—A Si photodiode detector PIN-type 10×10 mm, with a slim film of a converter material capable of producing charged particles, was used as sensor of neutrons and it was projected to be used in an environment of a zero power reactor. Polyethylene $n(\text{CH}_2)$, which produces recoil protons from the (n, p) interaction, was used to improve the detection efficiency. A mathematical model was applied to fit the experimental data and the optimal thickness of the converters was determined by the maximum point of the function. For an AmBe source, the optimum polyethylene layer thickness was of 0.105 cm ($96.6 \text{ mg} \cdot \text{cm}^{-2}$). The converter of polyethylene was capable to improve the detection efficiency to a factor of 16.4 compared to measurement without converter. The detector shows a good response ($r = 0.999372$) to estimate the power variation during the operation of the zero power-type reactor (IPEN/MB-01).

Index Terms—Neutron detector, photodiode, polyethylene converter, recoil protons.

I. INTRODUCTION

IN the fission nuclear reactors, neutrons generated in the primary process have energies around 1 MeV, which are classified as fast neutrons [1]. Other devices, such as the particle accelerators and sources of AmBe, also produce fast neutrons. The development of neutron detectors is essential in the nuclear reactors technology due to their capability for monitoring the reactor environment and its workers (personal dosimeters). As the neutron sources are associated to gamma radiation, it is necessary that the neutron detecting system be capable to discriminate the gamma interference. Several techniques have been used to meet this purpose such as: 1) pulse height analysis applying threshold electronic discriminator and 2) pulse-shape discrimination [2], [3].

Due to the absence of charge in the neutron it is necessary to use a material converter that generates radiations capable to produce signals in the detector. Materials constituted of small atoms, mainly hydrogen, are capable to produce ionization because the interaction with fast neutrons (n, p) is similar to a billiard ball interaction and gives to the proton enough kinetic energy, creating secondary ions in its pathway.

Plastic scintillators like the CR39 and gaseous mixtures can be used to detect neutrons using basically this effect. The high noise/signal ratio for the plastic scintillator and the high level

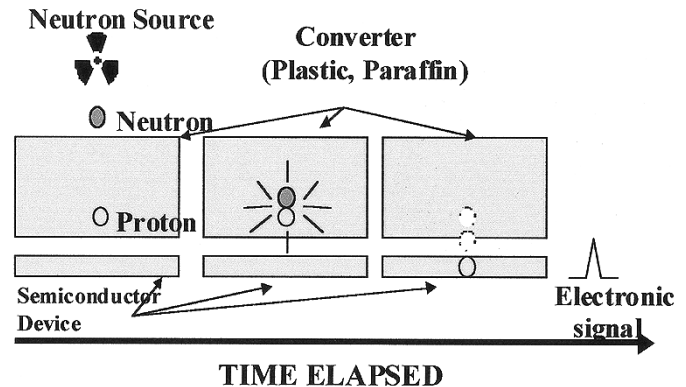


Fig. 1. Semiconductor associated with a (n, p) converter to detect a source of neutrons.

of energy necessary to produce ionization in gaseous mixtures restricts the sensitivity of these detectors [3]–[6].

Semiconductor detectors such as Si, Ge, and others are traditionally used for detecting ionization radiation due to their low noise/signal ratio and their high energetic resolution performance. But, these semiconductors are made with height atomic numbers that are not efficient to produce useful interactions with neutrons. This limitation can be overcome by using a converter material on its sensitive surface, transferring the kinetic energy from neutron to proton, as shown in Fig. 1.

The silicon has high sensitivity for proton detection. Additionally, the range of the proton in the silicon varies approximately from 0.09 to 1 mm for particles ranging from 3 to 12 MeV [7], which makes possible to construct thin surface detectors. Besides, the silicon detector has high mobility of electrons and holes. This characteristic and the small dimension of the detector allow the charge collection in a short time (nanoseconds) and, therefore, a high resolution can be reached [8].

It is known that detectors with small dimension avoid interferences or deformations in the neutron flux [8]. The Si semiconductors is a good alternative for neutron flux measurements because the Si-detector system can be designed in small dimensions, keeping desirable counting efficiency. Particularly, the Si photodiode PIN type meets technically the prescriptions to be used as a proton recoil detector and it is easily available at a low cost.

In this work, a neutron detector using PIN type silicon photodiode with polyethylene as (n, p) recoil protons generation was studied. In such design, the optimum thickness of the converter is an important parameter to be established. The optimal thickness was determined experimentally and theoretically. The de-

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C. H. Mesquita and M. M. Hamada are with the IPEN/CNEN-SP, Cidade Universitária, 05508-900 São Paulo, Brazil (e-mail: mmhamada@net.ipen.br).

T. M. Filho is with the IPEN/CNEN-SP, Cidade Universitária, 05508-900 São Paulo, Brazil, and also with UNICSUL, 08060-070 São Paulo, Brazil.

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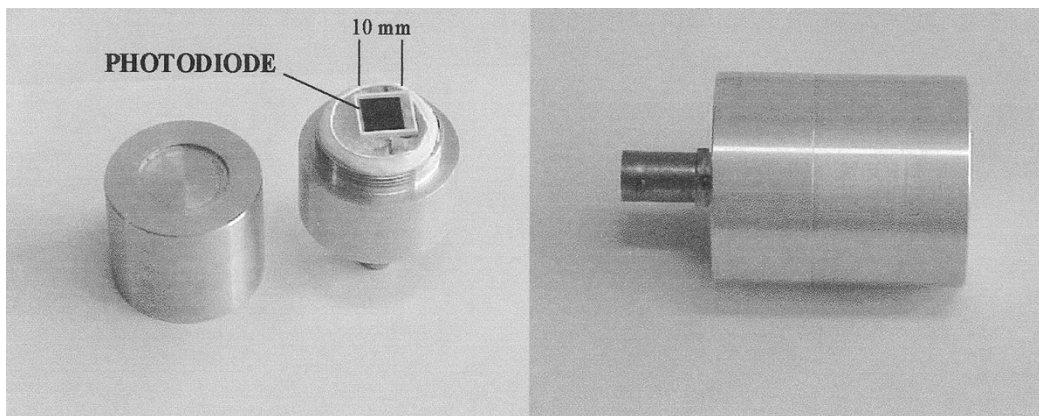


Fig. 2. Illustration of the developed detector.

detector ability to act as a controller of a zero-power type reactor was evaluated.

II. MATERIAL AND METHODS

The sensor consists of the PIN silicon photodiode Hamamatsu S3590-09 windowless type, sensitive area of 10×10 mm covered with foils of polyethylene. The polyethylene converter was used as a recoil proton generator.

To determine the optimal thickness of the polyethylene, the photodiode sensitive surface was covered with polyethylene foils ranging from 0 to 120 mm thickness. Details of the experimental procedures and the fitting model were described in our previous work [8]. Fig. 2 shows the picture of the assembled detector.

The model is defined as

$$R(c/s) = \varepsilon_P \cdot N_0 \cdot (1 - e^{-\mu \cdot X}) \cdot e^{-\Sigma \cdot X} + \varepsilon_n \cdot N_0 \cdot e^{-\Sigma \cdot X} \quad (1)$$

where ε_P is the proton detection efficiency; ε_n is the PIN Si photodiode neutron efficiency detection (without polyethylene converter, i.e., $X = 0$); and N_0 is the AmBe neutron rate in the detector for the experimental arrangement used. This was previously estimated by the gold foil activation technique ($9638 \text{ n} \cdot \text{s}^{-1}$). N_0 value depends on: 1) the solid angle between the neutron source and the detector geometry [9] and 2) the AmBe source activity and its geometry. $\Sigma(\text{cm}^{-1})$ is the mean macroscopic cross section to the incident neutrons in the converter and μ is the proton absorption coefficient in the polyethylene converter with energy E_P in MeV [10], which is defined as being the reciprocal of the range

$$\mu = \frac{1}{0.00235 \cdot E_P^{1.8}} \quad ((\text{cm}^{-1})). \quad (2)$$

The detector was studied in two different situations: 1) in the laboratory, using an AmBe source and 2) in the zero power nuclear reactor (IPEN-MB-01) at a radial distance of 360 mm and half height from the reactor core.

The detector with (n, p) converter, was placed around the reactor core, then the reactor IPEN/MB 01 was operated at different powers. The slope and interception of the experimental points: power (W) versus counting rate (c/s) were determined by the least square method.

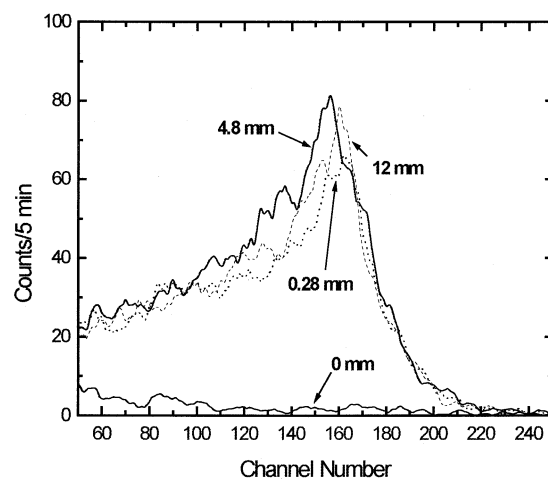


Fig. 3. AmBe spectra of the Si PIN photodiode with different thickness polyethylene and without converter.

III. RESULTS AND DISCUSSION

Fig. 3 shows three spectra of the PIN photodiode detectors with converter thickness of 0.28, 4.8, and 12 mm and a photodiode detector without converter.

As observed in Fig. 3, the neutrons could generate small signals in the detector even without converter, as already described by Filho *et al.* [8]. Fast neutrons can produce charged particles elastically scattered. The neutron energy fraction transferred to the recoil atom can be predicted by $x = (4 \cdot A / (1 + A)^2)$ [3], [11], where $A =$ ratio of target nucleus mass/neutron mass. For silicon ($A = 28$), the fraction $x \cong 0.133$ and for 6 MeV neutron, which is a representative mean of the AmBe energy, then the maximum proton recoil energy becomes $0.133 \times 6 = 0.798$ MeV. Therefore, small intensity of the signals in the photodiode without converter, shown in Fig. 3 (curve 0 mm), may be explained. On the other hand, same considerations applied to hydrogen atom gives $x = 1$ then it is possible that hydrogen recoil proton could have the same energy of the incident neutron. However, the recoil proton energy also depends on the angle of (n, p) interaction and consequently for neutrons with energy E_n the hydrogen recoil proton has a mean energy of $E_p = E_n/2$. Thus, the use of a hydrogenated film is capable to convert neutron energy in ionizing radiation, increasing the efficiency of the detection significantly, with the advantage of generating high

TABLE I
FITTED PARAMETERS FROM (1) AND CORRELATED PARAMETERS

FITTED PARAMETERS	Value	SD
ε_p (Proton efficiency)	0.00216	-
ε_n (Neutron efficiency without converter)	0.00015	-
N_0 (Source activity) ($n.s^{-1}$)	8968*	± 1250
Σ (Macroscopic cross-section) (cm^{-1})	0.1345	± 0.0075
μ (Proton absorption coefficient) (cm^{-1})	56.7	± 1.9
CORRELATED PARAMETERS		
Mean AmBe neutron energy (MeV)	6.0	[5.7 – 6.3]
Mean recoil proton in polyethylene (MeV)	3.1	[3.0–3.2]
Optimal thickness (cm)	0.105	-
Counting Efficiency (%)	0.25	± 0.06

*The value determined experimentally by the gold foil activation technique was of $9638 \pm 1348 n.s^{-1}$.

signals and far from interference of the noise and the gamma radiation.

The first part of (1) " $\varepsilon_P \cdot N_0 \cdot (1 - e^{-\mu \cdot X})$," represents the growth of the proton flux on the surface of the photodiode in function of the converter thickness. In counterpart, recoil protons have a range in the medium predicted by $Range(cm) = 0.00235 \cdot E_P^{1.8}$, which is the reciprocal of the μ parameter. Part of the neutrons interacts with the atoms of the converter generating recoil protons in an intensity, which depends on the microscopic cross section σ (in barn units). However, the converter is constituted by two kinds of atoms: hydrogen and carbon, so it is necessary to know an average effect of these two atoms in the cross section parameter. The appropriated procedure is to use the macroscopic cross section Σ in (cm^{-1}), combining each σ microscopic cross section and the number of their atoms per cm^3 in order to define the $\Sigma(cm^{-1})$ parameter. So, in (1) the first factor $e^{\Sigma \cdot X}$ represents the fraction of the neutrons absorbed in the converter. Finally, the remaining fraction of the neutrons that is capable to cross the converter foil and to interact with the photodiode is represented by the term " $\varepsilon_n \cdot N_0 \cdot e^{-\Sigma \cdot X}$ " in (1).

A suitable selection of the converter thickness is a decisive factor in the detector performance due to the self-absorption effect of the energy inside the converter material. Very slim converter foils are not efficient, because small amount of atoms capable to interact with the incident neutrons are available. Otherwise, for thicker films, the interaction probability increases and a larger amount of charged particles is produced [8]. However, the generated recoil protons have little range in the material and then they are absorbed in the converter itself. This suggests that a foil converter with approximately 0.1 cm ($92 mg \cdot cm^{-2}$) is enough to be used for neutrons detection up to 12 MeV [7].

Only a thin thickness is responsible to generate protons that hit the detector. Otherwise, broad thicknesses worsen the neutron scattering geometry and they do not contribute with the improvement of the efficiency of the detector.

Table I shows the regression parameters from the fitting data presented in Fig. 4. The function of (1) has a maximum at $X_{max} = 0.105$ cm ($96.6 mg \cdot cm^{-2}$) and $R_{max} = 22.11$ c/s. X_{max} is the optimal thickness and R_{max} is the maximum count rate.

The maximum neutron energy for AmBe is $\cong 12$ MeV (top of Fig. 5), as a consequence the mean energy of the recoil pro-

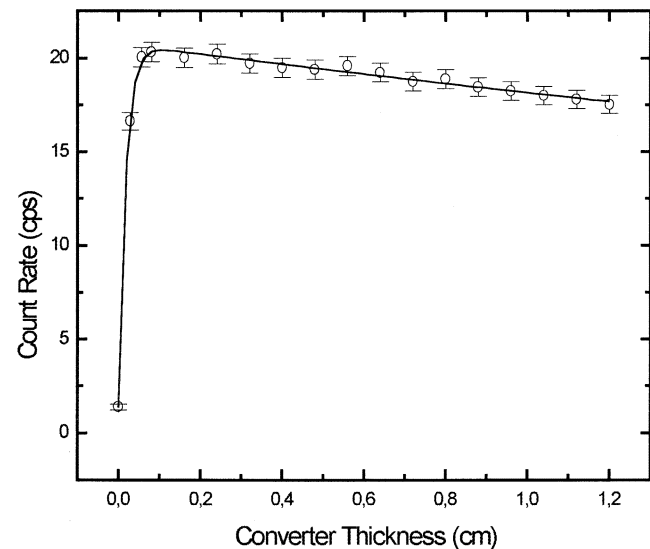


Fig. 4. Detection efficiency of Si detector as a function of the converter thickness of polyethylene (n, p). The error bar corresponds to 2σ .

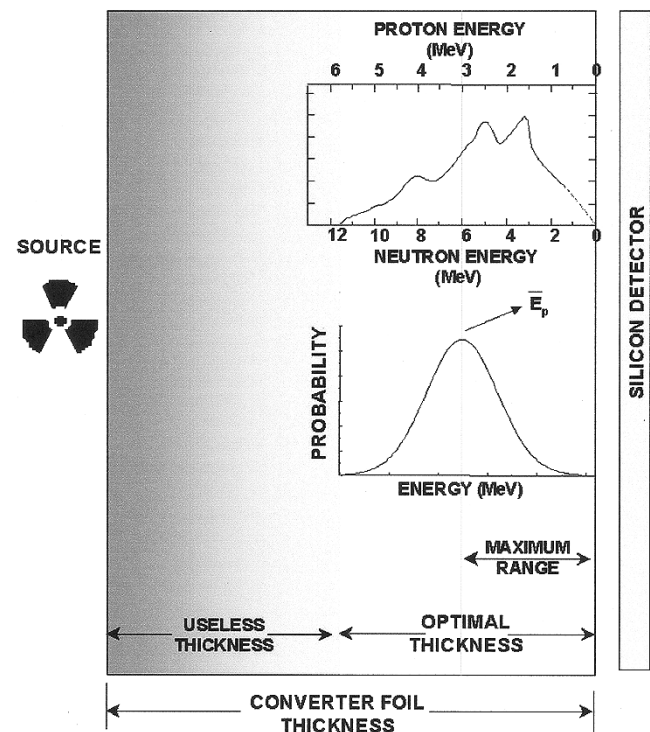


Fig. 5. Schematic diagram explaining the relations between converter thickness and AmBe neutron energy spectrum.

tons is $\cong 6$ MeV [6]. Then, according to the reciprocal of (2), it has a range of 0.0591 cm in polyethylene, i.e., the range is approximately half of the optimized thickness $X_{max} = 0.105$ cm. Thus, only a thin layer in the end of the converter is effectively capable to generate protons that reach the Si detector. In fact, neutrons with any energy can generate recoil protons. However, low-energy neutrons only generate signals in the detector if the interaction occurs in a very thin layer in the boundary of the interface converter detector. Otherwise, neutrons with high or low energies can produce the same pulse-height, thus, the experi-

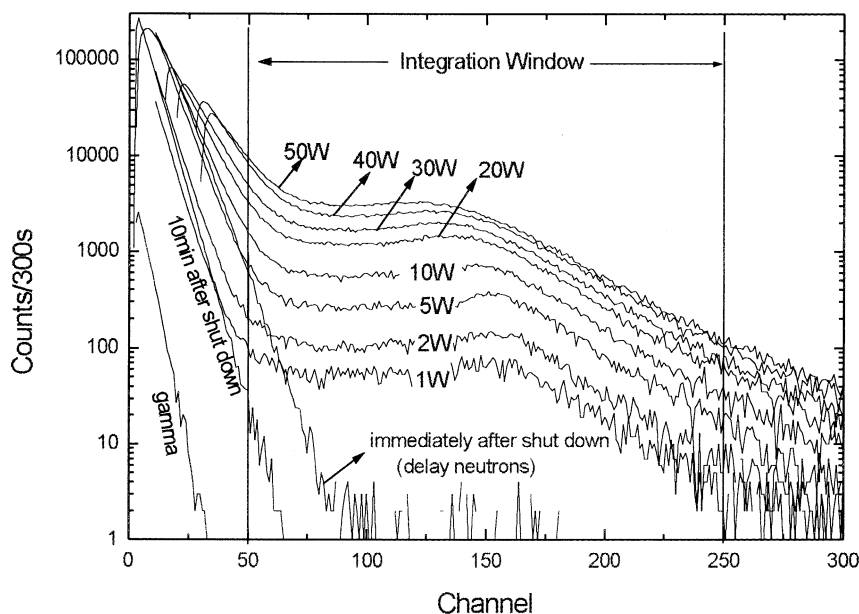


Fig. 6. Spectra of the developed detector in the reactor environment.

mental spectrum (Fig. 5) obtained with the recoil proton converter and sensor system depends on probabilistic factors and the neutron energy profile. These conceptions are summarized in Fig. 5.

Table I summarizes the parameters concerned to the model of (1) and their correlated parameters.

Using that optimal thickness for the converters (0.105 cm), the detection efficiency increased 16.4 times for the polyethylene compared to that measured without converter.

The microscopic cross section values (barn) of hydrogen and carbon were obtained from Japan Atomic Energy Research Institute (JAERI) data [12], in the energy range of 1 to 10 MeV.

In this work, the microscopic cross section of hydrogen in function of the energy was fitted to sixth-order polynomial

$$\begin{aligned} \sigma_H(\text{barn}) = & 6.94 - 4.48 \cdot E + 1.60 \cdot E^2 - 0.313 \cdot E^3 \\ & + 0.0332 \cdot E^4 - 0.00179 \cdot E^5 + 0.0000385 \cdot E^6 \quad (3) \end{aligned}$$

($r = 0.9996$ in the range of $1 \leq E$ (MeV) ≤ 10).

Similarly, for carbon, σ_C was estimated by the following polynomial:

$$\begin{aligned} \sigma_C(\text{barn}) = & 9.70 - 13.5 \cdot E + 8.22 \cdot E^2 - 2.33 \cdot E^3 \\ & + 0.330 \cdot E^4 + -0.0228 \cdot E^5 + 0.00061 \cdot E^6 \quad (4) \end{aligned}$$

($r = 0.9355$, in the range of $1 \leq E$ (MeV) ≤ 10).

As polyethylene has a density of $0.92 \text{ g} \cdot \text{cm}^{-3}$ and its primary formula CH_2 has a molecular mass of 14 g, the $-\text{CH}_2-$ molecule number in one cm^3 is estimated to be $0.92/14 \cdot 6.02 \cdot 10^{23} \approx 3.96 \cdot 10^{22}$. Therefore, in polyethylene, the number of H and C atoms is $n_H = 7.91 \cdot 10^{22} \text{ atoms} \cdot \text{cm}^{-3}$ and $n_C = 3.96 \cdot 10^{22} \text{ atoms} \cdot \text{cm}^{-3}$, respectively. The polyethylene macroscopic cross section is defined by

$$\Sigma_{\text{polyethylene}}(\text{cm}^{-1}) = (n_H \cdot \sigma_H + n_C \cdot \sigma_C) \cdot 10^{-24} \quad (5)$$

where 10^{-24} is the conversion factor: $1 \text{ barn} = 10^{-24} \text{ cm}^2$.

By combining (3)–(5), the polyethylene macroscopic cross section, in the range of $1 \leq E$ (MeV) ≤ 10 , can be estimated as

$$\begin{aligned} \Sigma_{\text{polyethylene}}(\text{cm}^{-1}) = & 0.933 - 0.889 \cdot E + 0.452 \cdot E^2 - 0.117 \cdot E^3 \\ & + 0.0157 \cdot E^4 - 0.00104 \cdot E^5 + 0.0000273 \cdot E^6. \quad (6) \end{aligned}$$

Applying $\Sigma = 0.135 \text{ cm}^{-1}$ (Table I) in (6), it was obtained two real roots, $E_1 = 5.7$ and $E_2 = 6.3$ MeV. Both energy levels are in agreement with the AmBe neutron energy range, described by Thompson and Taylor [13]. Therefore, recoil protons for these energies are 2.85 and 3.15 MeV, respectively. On the other hand, the representative recoil proton energy, inferred from (2), using $\mu = 56.7 \pm 1.9$, gives $E_P = 3.1$ [3.0–3.2]. These values are also in accordance with the range from 1.5 to 6.0 MeV, described by Salgir and Walker [6]. In conclusion, both calculations, using Σ and μ , give close and realistic values to represent the incident neutron mean energy and the recoil proton mean energy in polyethylene.

Fig. 6 shows spectra of the detector for recoil protons, for measurements carried out in the IPEN/MB-01 zero power-type reactor, operated at 1, 2, 5, 10, 20, 30, 40, and 50 W. As shown in Figs. 6 and 7, the detector with polyethylene showed a good response to the power variation in the operation of the IPEN-MB01 reactor. The linear correlation between the reactor operation power versus the detector count rate (counts/s) was $r = 0.999072$. The count rate values used in the linear adjustment were obtained discounting the gamma interference using the pulse rate threshold technique. This was possible due to the difference between the pulse height generated by the gamma radiation and the recoil protons.

The characterization of the converter thickness is of great importance in the projects and construction of neutron detectors. In most scientific approaches, the first step is to establish the experimental expectations in function of the available theoretical studies. In the interactions of the neutrons with the converter material, two items should be considered: 1) the neutron ability

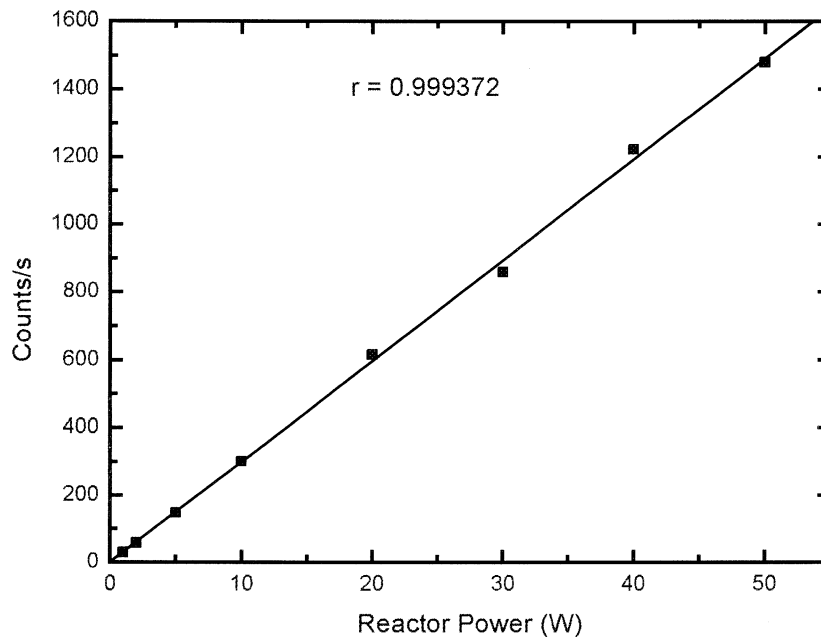


Fig. 7. Correlation between the reactor power and the counting rate.

to generate the ionizing particles (protons) and 2) the self-absorption process.

The detection efficiency depends on the size, format and intrinsic efficiency of the detector [3].

The intrinsic efficiency (ε) of detection is defined as the ratio between the detected value and the amount of incident neutrons in the converter detector, i.e.,

$$\varepsilon = \frac{\text{Protons Counting Rate (counts/s)}}{N_0 = \text{Incident Neutrons } \left(\frac{n}{s}\right)} \quad (7)$$

The incident neutrons (N_0) were estimated previously using the gold foil activation technique [8], [14], which found $N_0 = (9638 \pm 1348)n \cdot s^{-1} \cdot \text{cm}^{-2}$. This same parameter determined by fitting experimental data to (1) was $N_0 = (8968 \pm 1250)n \cdot s^{-1} \cdot \text{cm}^{-2}$ and there are no significant differences between them. For the optimized thickness (0.105 cm), the count rate was $\cong 22.11$ counts/s, therefore the count efficiency was $\varepsilon \cong 0.25\%$ for an AmBe neutron source.

IV. CONCLUSION

It could be shown, experimentally, that the polyethylene is capable to increase the neutron detection efficiency by a factor of 16.4.

The results show the capacity of the detector to act as a controller of the small zero power-type reactor.

The mathematical model was able to estimate several physical parameters realistically such as: (E_n) the mean energy of an AmBe source, (μ) the recoil proton linear absorption coefficient and its range in the converter (Σ) the macroscopic cross section for the polyethylene, (N_0) the neutron source rate ($n \cdot s^{-1}$) in the detector surface, (ε_p) and (ε_n) the efficiencies of the sensor to measure neutrons with and without the converter, respectively. The mathematical model was useful to determine the optimized converter thickness and the mean values that represent: (E_n) the neutrons emitted from AmBe source and (E_P) the respective recoil protons in polyethylene. This model could be used for other neutron sources and converters with minor adaptations.

V. FUTURE WORK

The pilot detector will be redesigned in an optimized small configuration to be used as personal neutron dosimeter. Another application for this detector is the development of a neutron position sensitive detector, for example, to be used as a neutron telescope in a cosmic neutron imaging system.

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