Preliminary results of a dosimetric system to be applied in microdosimetry as a support instrument in operational routines in nuclear medicine and radiotherapy

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Abstract: Most of the radiation effects (in particular biological effects) depend on the microscopic pattern of energy deposition. This fact become apparent if one observes that, although the average energy expended to produce el[1]ementary units of physical damage (ionizations) is fairly independent of particle type and energy, the biological effectiveness of otherwise equal doses of different radiation types may be quite dissimilar.

Microdosimetry, the study of the fluctuations of energy deposition and the associated stochastic quantities, was developed to provide a comprehensive description of the spatial and temporal distribution of absorbed energy in irradiated matter.

An important step in understanding the radiobiology quality of therapeutic beams is the development of a microdosimeter based on the measurement of deposited energies at a cellular level.

Microdosimetry deals with the problem of identifying radiosensitive targets and obtaining the probability of energy deposition therein. Models of radiation action, biological or otherwise, may then be used to convert this information in observable quantities.

The aim of this work is the development of a dosimetric prototype system using semiconductors as sensitive material for microdosimetric measurements to determine equivalent doses and energies of incident beams in order to be applied as a support tool in operational routines in radiobiology, radiotherapy, microelectronic and radiation protection.

The radiation response of silicon components to neutron fields from nuclear research reactors, IEA-R1 and IPEN-MB1 (thermal, epithermal and fast neutrons), from beam holes, experiments halls, AmBe neutrons source and in the BNCT (Boron Neutron Capture Therapy) Research facility at the IEA-R1 reactor of IPEN/CNEN-SP was investigated.

KEYWORDS: Dosimetry, Radiotherapy, Nuclear Reactors Facilities

1. Introduction

Microdosimetry

When the first papers about microdosimetry were published in the fifties or sixties by Rossi and others [1-3] the relevance of this new approach was immediately apparent: in fundamental radiobiology, for the better understanding of primary mechanism of radiation action and in radiation protection, where one deals with low doses, a small number of events and with different types of radiation.

In radiation therapy where the doses are relatively high, the relevance of microdosimetry appeared, at first, to be limited. However, with the development of neutron therapy (and high LET therapy), the possible application of microdosimetry became more evident [4].

One of the ways in which microdosimetry has evolved in the past decade has been its increasing application in practical fields such as health physics and medical physics. With this increased dissemination of microdosimetry to other fields, many new practitioners of microdosimetry are being engendered who may not always be familiar with the experimental techniques [5].

Microdosimetry is the area that deals with the distributions of energy deposition events at the microscopic level and their correlation to the effects of radiation on biological targets. Microdosimetry is formally defined by Rossi and Zaider [6] as “the systematic study and quantification of the spatial and temporal distribution of absorbed energy in irradiated matter” [7].

Microdosimetry, as stated by the ICRU Report 36 [8], is a conceptual framework (with corresponding experimental methods) for the systematic analysis of the microscopic distribution of energy deposition in irradiated matter, being its objective to develop concepts which relate some of the principal features

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of the absorption of ionizing radiation in matter to the size and perhaps the nature of the structures being affected in order to improve the understanding of radiation effects.

The fields of radiation protection, radiobiology, radiotherapy and radiation effects on electronics require microdosimetry methods for measuring the pattern of energy deposition in small cellsized volumes.

The scale of measurements in microdosimetry is typically at the micron level. At such small dimensions, the primary tool of experimental microdosimetry has been the low pressure proportional counter known as TEPC or Tissue Equivalent Proportional Counter.

Although generally considered the best currently available detector, the proportional gas counter has several shortcomings. These include a relatively large physical size which limits spatial resolution and increases vulnerability to pileup effects, the use of gas in the detection volume which leads to phase effects and wall effect errors, and an inability to simulate an array of cells. In many applications silicon based detectors offer significant advantages particularly with regard to spatial resolution. McNulty [9] proposed the use of arrays of silicon reverse-biased p-n junctions for characterizing complex radiation environments inside spacecraft and aircraft primarily. Such a detector removes several of the previously mentioned problems associated with proportional gas counters [10].

An ‘ideal’ microdosemeter should have the following characteristics: (a) to be tissue equivalent, (b) to have several micrometers of active thickness, (c) to have a noise level that allows the detection of signals as low as 100 $eV.\mu m^{-1}$, and (d) to be capable of detecting (with good energy resolution) individual particle tracks [11].

Tissue Equivalence

Silicon microdosimetry requires a tissue equivalent converter on top of the device. Ideally, detected interactions should arise exclusively from events originating in the medium surrounding the detector.

Therefore, the device should have a small overlayer thickness and the sensitive volume should be as small as possible to enhance crosser particles and reduce direct nuclear interactions with silicon. A brief study comparing tissue and silicon neutron interactions in FNT (Fast Neutron Therapy) was described by Bradley et al [12].

For neutron energies less than 5 MeV, microdosimetric measurements in silicon volumes with dimensions of the order of 1 micron will not be significantly affected by events generated within the silicon. At higher neutron energies, the spectrum at high lineal energies may be affected by silicon elastic and inelastic reactions [11].

Semiconductors in Microdosimetry

The first comparison of microdosimetric measurements between a spherical proportional counter and a single junction solid state detector was made by Dicello et al in 1980 [13]. They found that the silicon detector was capable of measurements at full therapeutic beam intensity whilst the proportional counter measurements were complicated by a need to reduce beam intensity. Orlic in 1989 [14] and Kadachi et al in 1994 [15] worked on radiation protection applications. Orlic used a silicon photodiode biased at zero voltage, to give an estimated sensitive thickness of 5 microns and with a thick polyethylene converter mounted in front of the detector. Kadachi extended this work by comparing the response of a silicon PIN photodiode with sensitive depth of 8 microns at zero voltage and 13 mm^2 area and a tissue equivalent proportional counter (TEPC) of 1 micron simulated diameter.

Additional comparisons were later made by Kadachi et al [16] using a variety of silicon photodiodes (p-n, PIN, and pnn) and depletion depths in bulk silicon (1, 3, 5 and 8 microns).

The concept of simultaneous macro and microdosimetry was introduced by Rosenfeld in 1996 [17]. For macrodosimetry, the total dose was measured using threshold voltage changes arising from radiation induced build-up of gate oxide charge. Microdosimetric methods are especially useful for high-LET radiation therapy due to the requirement of quantitative specification of radiation quality [10].

Microdosimetry Application in BNCT

Radiotherapy is very effective for a number of tumors, however, several tumors are resistant to standard radiotherapy. Several laboratories in Europe, USA, Asia, Australia and Argentina have been working intensively on a radiotherapy called Boron Neutron Capture Therapy (BNCT).
The ^{10}B(n,p) capture reaction is a thermal reaction. In cases of superficial tumors a beam of thermal neutrons (energy less than 0.8 eV) is required to treat the tumor by BNCT. Beams of epithermal neutrons (energy between 0.8 eV and 0.1 MeV) are used to treat deep seated tumors. Adequate fluence rates of epithermal neutrons can presently only be provided with special facilities at nuclear reactors. The radiation field from a reactor core is a mixture of γ-rays, fast, epithermal, and thermal neutrons, then to develop epithermal neutron beams special filters have to be used. Microdosimetry can be a viable technique for determining absorbed dose and radiation quality [18].

2.- Objectives

The aim of this work is the development of a dosimetric prototype system using semiconductors as sensitive material for microdosimetric measurements to determine equivalent doses and energies of incident beams in order to be applied as a support tool in operational routines in radiobiology, radiotherapy, microelectronic and radiation protection.
The radiation response of silicon components to neutron fields from nuclear research reactors, IEA-R1 (epithermal neutrons) and IPEN-MB1 (thermal, epithermal and fast neutrons), from beam holes, experiments halls and AmBe neutrons source (Laboratory) are being investigated.

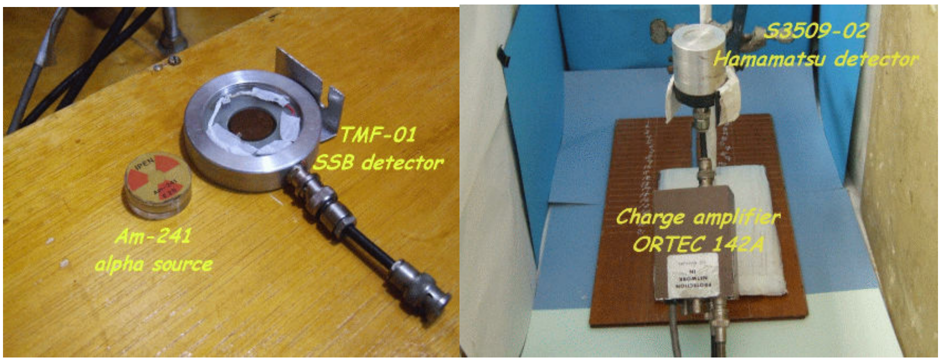
3.- Materials and Methods

3.1 Experiments facilities description

3.1.1 Laboratory CENF

Measurements using an AmBe neutrons and reaction (a,n), acquire from Amersham in 1970 with a nominal activity of $3.7\text{x}10^9$ Bq (100 mCi) of Am and neutrons emission rates of $3.1\text{x}10^5$ n.s^{-1} were carried out in this Laboratory. By calculations we obtained 2, $9\text{x}10^5$ n.s^{-1} for the actual emission rate. Fig. 1 shows the detectors used and the charge sensitive preamplifier [19].

Figure 1: SSB TMF-1 (left) and S3509-02 detectors with the ORTEC 142A preamplifier (right)



Radiological protection requirements were implemented to work with the AmBe source bench through a biological shielding structure made by 10 cm paraffin blocks.

3.1.2 The IEA-R1 BNCT facility.

The IEA-R1 reactor is an open pool 2 MW reactor design and modified to operate at 5 MW with forced circulation and 200 KW in natural circulation (first criticality at September 16th of 1957).
The reactor operates on three shifts, 24 hours/day from Monday to Wednesday resulting in about 64 hours each week. Following shutdown on Wednesday at midnight, reactor maintenance is conducted on Thursday and Friday.

A facility for research in Boron Neutron Capture Therapy – BNCT – in the IEA-R1 reactor was constructed in IPEN-CNEN/SP. This experimental facility, is comprised of a 20,32 cm beam port (Beam Hole #3, IEA-R1 reactor). Moderators and filters, sample holder and shielding were placed inside BH#3 and, externally, in the experimental room, a biological shielding was built to provide a proper isolation from one facility to another as well to fulfill the radiation protection requirements to allow people circulation in the area, Fig. 2 shows the assembly for experiments [20].

Figure 2: Beam-hole #3 assembly in close (left) and open (right) position

Due to its size limit, the facility is not suited to carry out any treatment. However, neutrons fluxes attained at the sample irradiation position is high enough to reproduce adequate conditions to perform experiments in neutron capture therapy.

A 15 Gy/h dose rate due to thermal neutrons is observed at the sample position. Experiments such as: neutron irradiation biological damage, neutron dosimetry and neutrons detectors have been carried out in the facility [21].

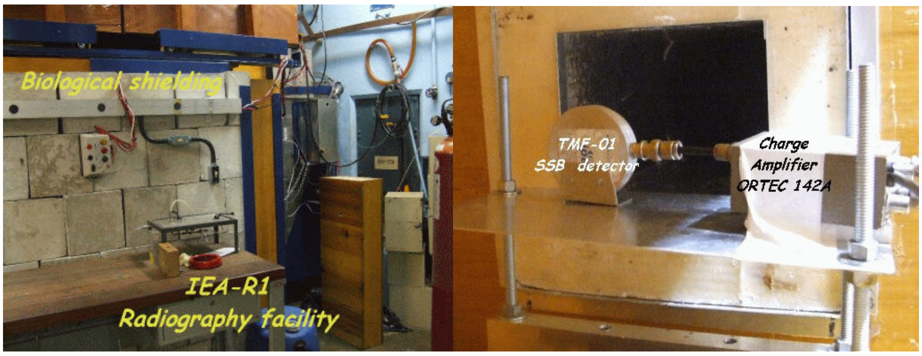
3.1.3 The IEA-R1 Neutrongraphy facility

In the experiment hall of the IEA-R1 there is another facility built around of Beam Hole #8 in order to be used for Neutrongraphy experiments. This irradiation channel is in a radial direction with respect to reactor core, with internal diameter of 20 cm. Inside of this channel are inserted 2 aluminum tubes, for assembly of filters, collimators and other components to extract the neutrons beam.

The total factor reduction for the neutrons flux, caused by the filters and collimators is $2{,}5\times10^{-8}$, resulting in a flux of $\sim1{,}75\times10^{6}$ n/cm^2.s in the irradiation site with a gamma dose of ~20 milisievert/h and ~70 milisievert/h (dose equivalent rate) for neutrons. Also there is a external shielding composed basically of paraffin, boric acid, cadmium, lead and high density concrete together with the reactor biological shielding [22].

Fig. 3 shows the facility assembly and the SSB TMF-01 detector measurement setup. The incident neutrons were estimated previously using the gold foil activation technique and reactor thermal power was 2 MW [23].

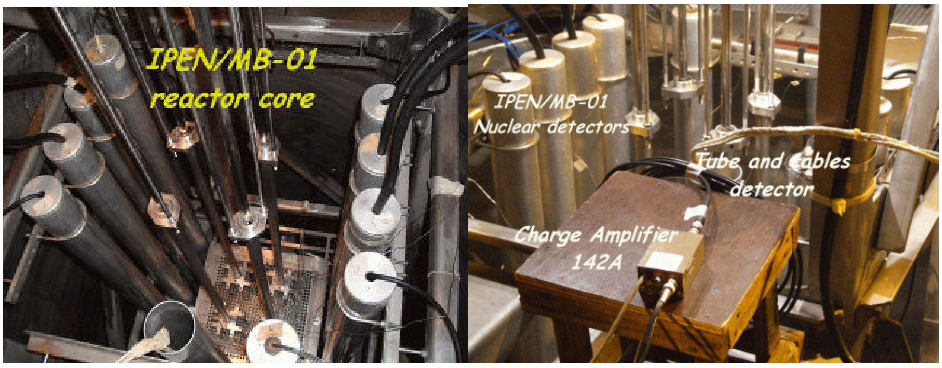
Figure 3: Neutrongraphy assembly (left) and the TMF-01 detector setup (right)



3.1.4 IPEN/MB-01 (UCRI) facility Description

The IPEN/MB-01 is a Brazilian nuclear research reactor designed and constructed by researchers and engineers from the institution with financial support from Brazilian Navy, its first criticality was at November 5th of 1988. This reactor is a nuclear facility that provides simulation of all parameters of a high power nuclear reactor in scale without necessity to build a complex system for heat removing. This kind of reactor is known as Zero Power Reactor or Critical Unit, being in our case designed to operate at a maximum full power of 100 Watts. Fig. 4 shows the reactor core and the detectors measurement setup.

Figure 4: reactor core (left) and detectors measurements setup (right)



This type of reactors represent a basic tool for researchers to study not only theoretical calculus but also through experimental measurements, the performance and characteristics of a power reactor core before its construction and installation, simulating the design parameters.

The nuclear core of the IPEN/MB-01 reactor has a parallelepiped shape with active dimensions of 390x420x546 with an array of 28x26 fuel elements and 48 guide tubes for control and safety of reaction chain and reactor shutdown (SCRAM) allowing different core configurations with the assembly that support the core with 900 holes 15 mm spaced in a array of 30x30. This kind of arrangement allows the experiment for fast neutron detection using two types of semiconductors.

Measurements were carried out in the IPEN/MB-01 zero power-type reactor, operated at 1, 2, 4 and 10 Watts. The incident neutrons were estimated previously using the gold foil activation technique, resulting in an average thermal neutron flux of 5.04×10^{8} $n.cm^{-2}.s^{-1}$ [24].

3.2 Methods

A nuclear reactor as a neutron source generates gamma radiation, which can interfere in their neutron flux measurement. Then, it is necessary that the detecting system be capable to discriminate the gamma interference.

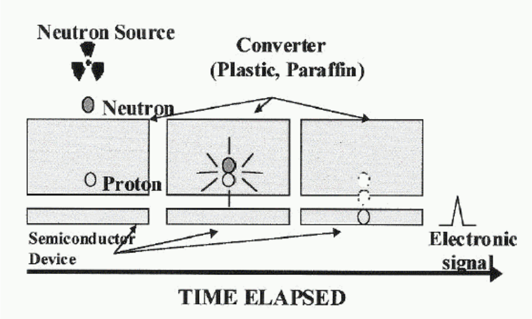
Several techniques have been proposed, among them two are commonly used: (i) pulse-height analysis applying threshold electronic discriminator and (ii) pulse-shape discrimination. The choice between these alternatives depends fundamentally on the pulse height generated from the gamma photon and the neutron particle. If they are similar and overlapping each other, then the pulse shape discrimination can be used, otherwise the technique of electronic discrimination would be preferable.

In this type of reactors, the neutrons generated in the primary process have energies around 20 MeV, which are classified as fast neutrons. Other devices, such as the particle accelerators and AmBe sources, also produce fast neutrons. However, in detector designs the most used nuclear converters, such as ^{10}B and ^{7}Li, are not efficient in that energy level. This limitation can be overcome by using a moderator material to reduce the neutron energy level [19]. Also due to the absence of charge, in order to neutron detection is necessary to use a material converter.

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 high 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. 5 [25].
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.
In this work, neutron detector using silicon semiconductor, surface barrier type (TMF-01 developed at IPEN), using polyethylene as (n, p) recoil protons generation converters were developed and as a comparison in performance we also used a PIN Photodiode type S3509-02 from Hamamatsu. In such design the optimum thickness of the converters is an important parameter to be established. The optimum thickness was determined experimentally and theoretically[19].

Figure 5: Semiconductor associated with a (n, p) converter to detect a source of neutrons



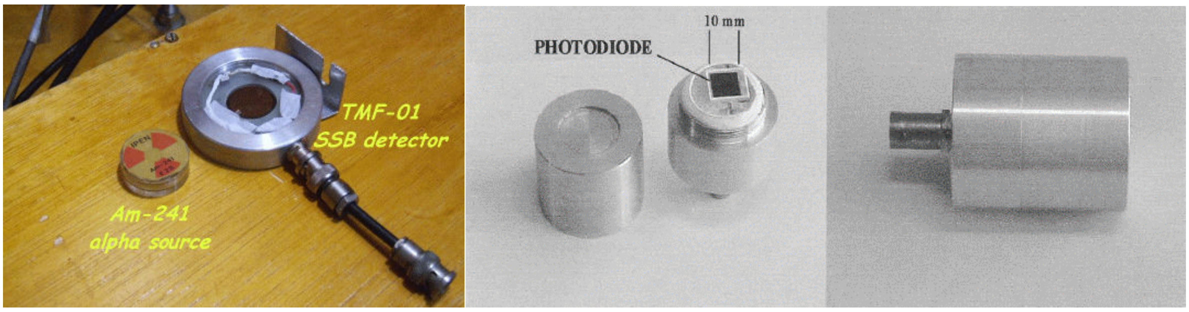
3.2.1 The TMF-1 Silicon Surface Barrier Detector

The Silicon Surface Barrier detectors were made from wafers (Topsil), with resistivity of 50 kΩ.cm, 2.54 cm in diameter - total area 5 cm^2 and 1mm in thickness, according to Takami et al. [26]. Approximately, 3.14 cm^2 sensitive surface was covered with 80 $\mu g.cm^{-2}$ Au and the rear face with 40 $\mu g.cm^{-2}$ Al in order to form the ohmic electrode, using the vacuum deposition technique.
Such assembly presents depletion layer depth of 420 µm at 40V bias voltage and specific capacitance of 70 $pF.mm^{-2}$ [26-27], Fig. 6 (right) shows the SSB detector.

3.2.2 The Hamamatsu PIN Photodiode

The other sensor was the PIN silicon photodiode Hamamatsu S3590–02 windowless type, sensitive area of 10x10mm covered with foils of polyethylene, thickness of 0,12 mm (experimental data) in front of detector. The stray capacitance of the S3509-02 detector was about 70 pF and its dark current was less than 1.5 nA at a bias voltage of 40 volts. The polyethylene converter was used as a recoil proton generator, Fig. 6 (left) shows the Hamamatsu detector.

Figure 6: TMF-1 (left) and S3509-02 (center and right) with the aluminum enclosure to avoid interference and light.



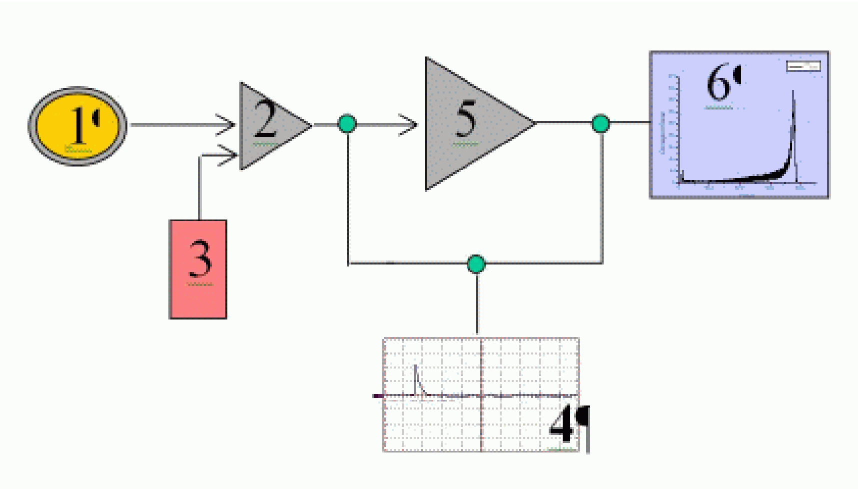
3.2.3 The Converter

The use of a converter implies in losses and benefits due to the effect of the self-absorption of the produced particle inside the converter material itself [28]. A very slim thickness of the converter is not efficient, because it inserts a little layer of atoms for interaction with the incident neutrons. On the other hand, with thicker films, the interaction probability increases and, consequently, a larger amount of charged particles is produced. However, since these particles (alpha or protons) have little range in the materials [29], they can be absorbed or it disappears in the converter itself.
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 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 [30].

3.2.4 Set up instrumentation

In order to develop the experiments an instrumentation configuration was implemented as shown in Fig. 7. The set up instrumentation used to detect fast neutrons from the AmBe source and the IPEN/MB-01 reactor and epithermal neutrons from the facility described above in the IEA-R1 reactor was as follow: each sensor was connected to a charge sensitive preamplifier (ORTEC 142A) with a High Voltage module (ORTEC HV 459), the output of this preamplifier was sent via a RG 75 cable to an amplifier with gain (x100) and shape (6 µseconds) adjustment (ORTEC 572), the output of this amplifier was connected to a Spectrum Master 919 processing module linked with a PC computer with Maestro Signal Analyzer software (ORTEC) in order to get the acquisition of neutron spectrum.

Figure 7: Set up of measurements for all the experiments: 1) detector, 2) charge sensitive amplifier, 3) power supply (HV), 4) Oscilloscope, 5) amplifier and 6) Computer with Maestro software.

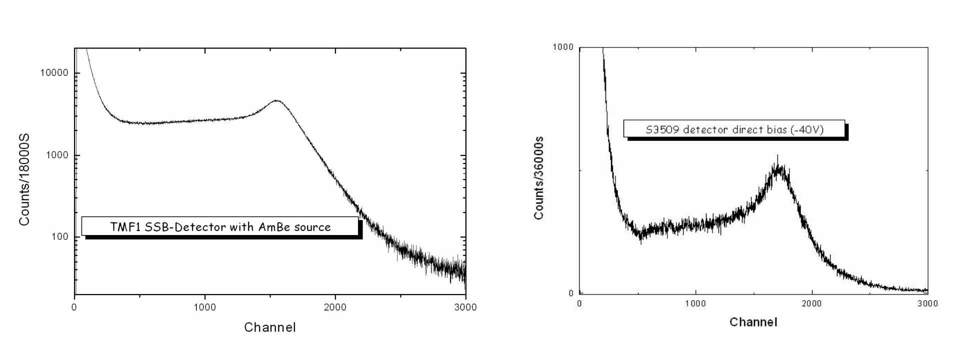


4. Results

4.1 VDG Lab Experiments results.

Measurements were carried out in the Laboratory using an Am-Be neutron source in order to get the AmBe fast neutron spectrum for the TMF-01 and the S3509-02 detectors with the instrumentation setup shown in Fig. 7.
The results are shown in Fig. 8 for the optimized thickness (0.12 cm experimental).
For direct fast neutrons detection from the Am-Be source, a 0.12 mm thick polyethylene converter was placed in front of the photodiode.

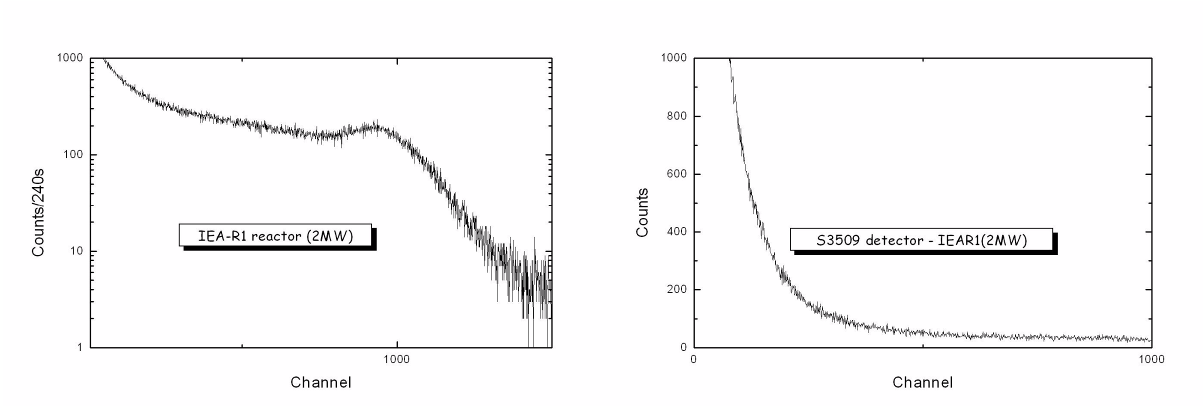
Figure 8: Spectrum for SSB TMF-1 (left) and for S3509-2 (right) detectors (Am-Be neutron source).



4.2 Neutrongraphy facility results

In this facility the following spectrum were obtained with the reactor IEA-R1 operating at nominal thermal power of 2 MW as shown in Fig. 9.

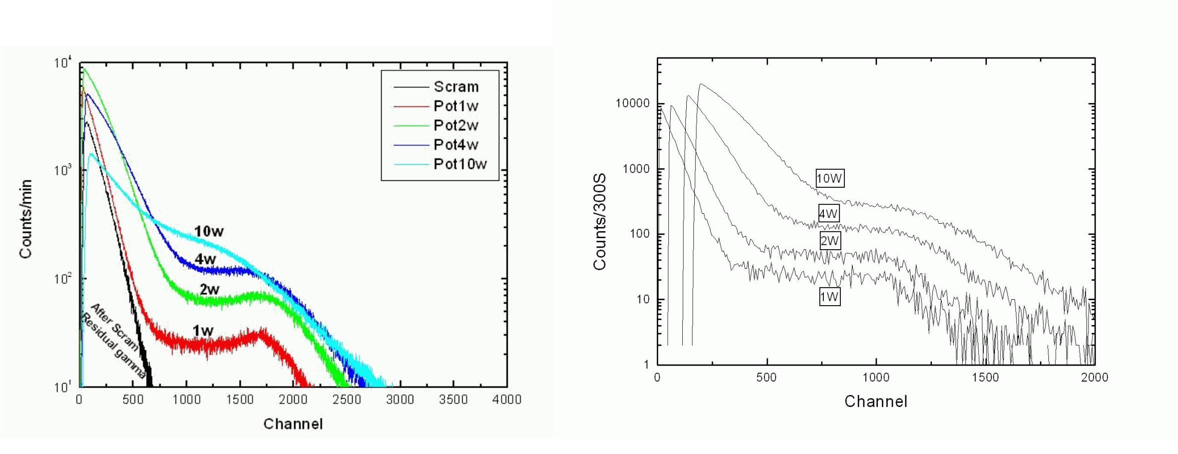
Figure 9: Spectrum for SSB TMF-1 (left) and for S3509-2 (right) detectors for 2 MW power reactor.



4.3 IPEN/MB-01 facility results

In the IPEN/MB-01 reactor the spectra of the recoil protons were obtained. Both detectors, TMF-01 and S3509-02, were placed around the reactor core, then the reactor IPEN-MB01 operates at nominal thermal power of 1, 2, 4 and 10 Watts, as shown in Fig. 10.

Figure 10: Spectrum for SSB TMF-1 (Left) and for S3509-2 (right) for 1, 2, 4 and 10 W power reactor



4.4 BNCT Facility results

Due to the fact the IPEN BNCT facility was under maintenance (since November 2007) it wasn't possible to check the measurements acquired before this routine job.

5. Conclusions

The response as neutron detector of a silicon surface barrier TMF1 and a silicon photodiode type S3590-02 from Hamamatsu together with a multi-channel analyzer Maestro configuration (ORTEC instrumentation) were investigated in an AmBe field (CENF Laboratory) and in the neutron environment of the IEA-R1 and IPEN/MB-01 reactors at the IPEN/CNEN facility.

The results showed that the SSB detector has a better response than the S3509 detector. The SSB detector also can be used as a power monitor-controller for the IPEN/MB-01 reactor.

In the future the detectors will be a) modeled to predict, in a better way, the response and to estimate the efficiency, b) compared with LiF TLD600 or TLD700 for calculations of neutron fluence rate spectrum of energy deposited, c) calibrated using the Test Pulse Technique, d) studied for saturation effect of the proton pulse height in order to estimate the effective thickness of the detector depletion layer, e) studied for analytical corrections and a design of a new detector for better resolution and applicability in microdosimetry and f) compared (data) with ISO 8529-2 recommended neutron energy distribution for the case of AmBe source.

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