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ELSEVIER

Thermal neutron detection using pyroelectric ceramics together with boron converters

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Abstract

A method for detecting thermal neutrons using pyroelectric ceramics is described. The detector system consists of a commercially available PZT (lead zirconate titanate) ceramic disk, silvered on both faces to provide electrical contact, a pellet of boron converter to induce the temperature variation in the ceramic through the energy released in the $^{10}B(n, \alpha)^{7}Li$ reaction, and an appropriate pulse amplifier system for amplification and stabilization of the signal generated by the detector. Two types of H_3BO_3 converters have been employed: one with natural isotopic abundance and another with 92.41% enrichment in ^{10}B isotope. In our application two different neutron spectra extracted from the BH-3 and BH-8 beam tubes of the IEA-R1 reactor have been used. The signal amplitude obtained with this detector system has shown to be proportional to the ^{10}B enrichment of the boron converters and remarkably linear with the thermal neutron flux within the calibration interval from 1.8×10^6 to 1.0×10^4 n/cm^{2}s.

1. Introduction

A new technique for thermal neutron detection with pyroelectric ceramics (from Edon-Western Corp. USA) has been recently developed in this Laboratory, using uranium converters with 20% enrichment in ^{235}U. Details concerning the method used can be found elsewhere [1,2] and therefore, it will not be described here in any depth. Summarizing, the technique consisted in irradiating in a pulsed thermal neutron beam a uranium pellet attached to a PZT (lead zirconate titanate) polarized ceramic. The modulated power generated in the $^{235}U(n, f)$ reaction, induces a polarization due to a change of temperature in the ceramics [3,4]. This polarization is equivalent to a source of voltage V in series with the ceramic capacitance C. Therefore, the system operates as a voltage source where the signal amplitude is proportional to the power produced by the uranium fission which in turn, is directly proportional to the thermal neutron flux incident on the detector system. However, the output signal is very low (μV) and in order to separate it from the background it was necessary to realize the measurements in a synchronous form, employing a lock-in amplifier. With this type of detector system, it is essential that the neutron beam be pulsed in order do avoid effects due to the thermal time constant of the ceramic [3,4].

The output voltage amplitude (V) produced by the detector system, can be related to the modulation frequency (ω) and thermal neutron flux (ϕ) by the following expression [2]:

$$V(\omega,\phi) = C(P\phi E)/(2\varepsilon\omega), \quad (1)$$

where the symbols are: P the pyroelectric coefficient, ε the dielectric constant of the material, E the energy released in the $^{235}U(n, f)$ or $^{10}B(n, \alpha)$ reaction, and C contains the correction term for neutron absorption in the converter and terms which are dependent on the thermal characteristics of converter and ceramic materials.

Eq. (1) is valid for converters with high enrichment in ^{235}U or ^{10}B. Otherwise, $V(\omega, \phi)$ should vary as $\omega^{-1.5}$ (see Ref. [2]).

The main goal of the present work was to develop another detector system, similar to the one described above, incorporating the following improvements:

–use of locally available PZT ceramics,

–boron converters with natural isotopic abundance as well as with 92.41% enrichment in ^{10}B,

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–operation mode in the pulsed form without the necessity of employing the phase modulation technique with a lock-in amplifier,

–output pulse amplifier much simpler and cheaper than the lock-in amplifier,

–readout system for the amplified pulse through a common digital voltmeter,

–possibility of working as a portable device.

2. Experimental methods

A block diagram of the experimental apparatus used for thermal neutron detection is shown in Fig. 1.

The irradiations have been carried out at two beam tubes of the IEA-R1, 2 MW pool type research reactor. In the first beam tube (BH-8), the neutron spectrum is a Maxwellian-type, distorted in relation to the thermal neutron spectrum near the reactor core, due to a 20 cm bismuth filter placed inside the neutron collimation system [1,5]. The neutron spectrum extracted from the second channel (BH-3) is practically cold, very narrow (FWHM $\approx$ 0.002 eV and average energy around 0.004 eV) and is a typical neutron spectrum obtained with a (40 cm) metallic beryllium filter [6]. The thermal neutron flux densities at the irradiation positions have been measured by the activation technique with gold foils [7] and the results obtained were 1.8×10^6 and 5.8×10^4 n/cm^{2}s respectively for the BH-8 and BH-3 beam tubes.

As is shown in Fig. 1, the thermal neutron beam was modulated by means of a mechanical chopper, built with 1 mm thickness cadmium foil, before impinging on the converter. The chopper rotation frequency was controlled by a DC power supply (0 to 9 V) and was monitored with a photodiode system through a reference signal (square wave) sent to the sample-and-hold device.

The boron converters have been built in the form of pellets, with an approximate mass of 115 mg (0.5 mm thickness and 13 mm diameter) using samples of H_3BO_3 with natural isotopic abundance and enriched to 92.41% in ^{10}B. All the boron pellets were compacted at a pressure around 5000 psi. This material is well suited to be used as converter because, as in the case of the ^{235}U(n, f) reaction, the cross section for the ^{10}B(n, α) reaction is very large ($\approx$3800 b) and the 2.792 MeV energy released per reaction is deposited locally by the reaction products [8].

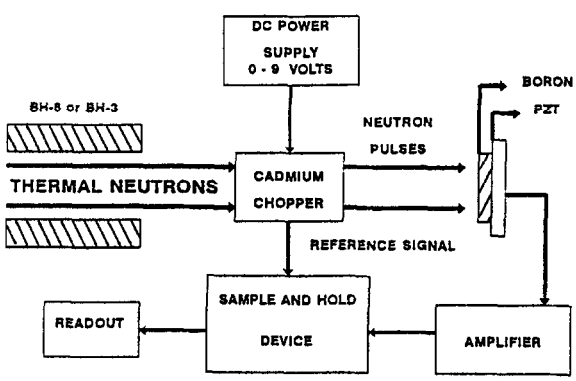

Fig. 1. Block diagram of the neutron detector system.

The pyroelectric ceramics were produced by Thorton Inpec. Electronica S/A and are commercially available in the form of disks with 1 mm thickness, 20 mm diameter and silvered on both faces to provide electrical contacts. According to a recent work [9] on physical characterization for this ceramic, an average density of 7.48 g/cm^3 has been measured and an approximate composition of $Pb(Zr_{0.52}, Ti_{0.48})O_3$ was suggested, for the pyroelectrical material.

The pyroelectric detector is an extremely sensitive microphone [3] and to insulate it against mechanical vibrations and acoustic noise from its environment, the ceramic-converter assembly has been installed inside a cylindrical aluminum chamber, mounted on a basis of special plastic cushion [1].

After modulation by the chopper, the thermal neutron beam impinges on the boron converter and the heat produced in the ^{10}B(n, α) reaction causes the electric polarization of the ceramic. A good thermal coupling between ceramic and boron pellet has been obtained employing an Apiezon-L type grease. The output signal generated by the pyroelectric detector passes through an amplifier (Fig. 2), similar to the one used by Carvalho [10], which provides a tension gain of 435 and a very high ($\approx$1.5 TΩ) impedance load. The amplified signal then goes to a sample-and-hold device (Fig. 3) which has the function of detecting the signal peak and to maintain it stable in order to allow its readout through a digital voltmeter.

3. Results and discussion

Calibration curves for the signal amplitude versus thermal neutron flux, have been obtained for the detector system, using in both irradiation tubes foils (200 μm thickness) of Makrofol E to attenuate the neutron beam [1]. These studies were realized using converters of natural boron as well as enriched to 92.41% in ^{10}B, at a modulation frequency around 3 Hz. The experimental data obtained in BH-3 and BH-8 irradiation channels have been plotted together, after normalization in relation to the attenuation thickness and the results are presented in Fig. 4.

The background contribution has been determined in this experiment, by interrupting the thermal neutron beam with a cadmium foil (1 mm thickness)

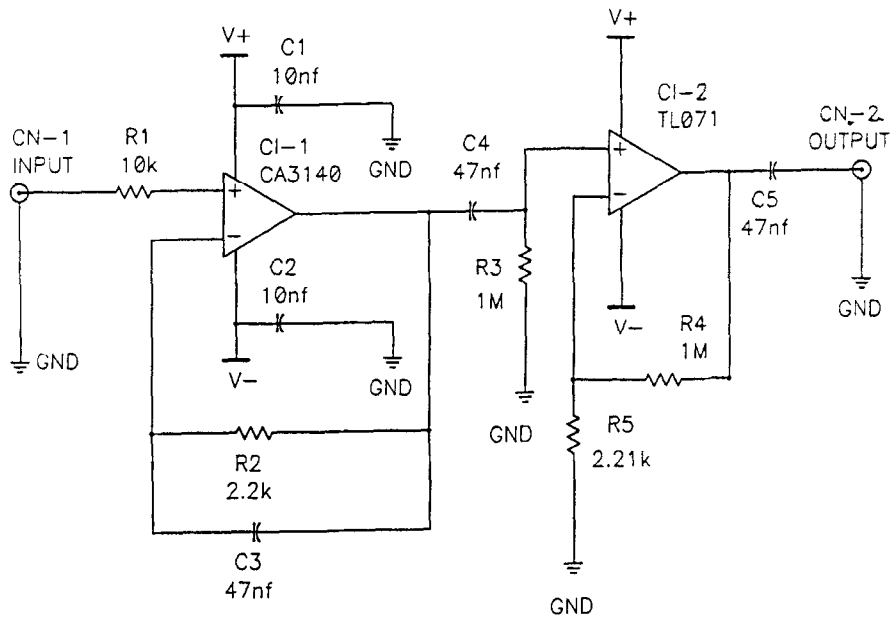

Fig. 2. Electronic circuit of the amplifier system.

stopper and adopting the same experimental procedures as in the calibration study. Under this condition, it is expected that only epithermal and fast neutrons as well as gamma radiation should contribute to the signal generation in the detector system. It was observed that the background contribution was practically constant for all Makrofol E thickness interval and also, approximately equal for both types of boron converters. The values obtained for the background signal amplitudes were 135±5 mV and 20±1 mV respectively for BH-8 and BH-3 irradiation channels. With the reactor in the shut-down position, the signal amplitude generated by the pyroelectric detector was 6.0±0.9 mV.

The use of two neutron irradiation channels has permitted an evaluation of the detector system response in a range of neutron flux intensities much higher than should be possible with only one beam tube, because of the occurrence of neutron multiscattering in the attenuation process. Due to this effect, the response of the detector system obtained in the BH-8 irradiation channel, was practically invariant, after approximately 14 mm thickness of Makrofol E. However, by using the BH-3 beam tube facility, it was possible to extend the measurements up to an equivalent thickness of Makrofol E around 22 mm, which allowed the detector system calibration within an interval of neutron flux from 1.8×10^{6} to 1.0×10^{4} n/cm^{2}s.

The measurements with the two neutron beams

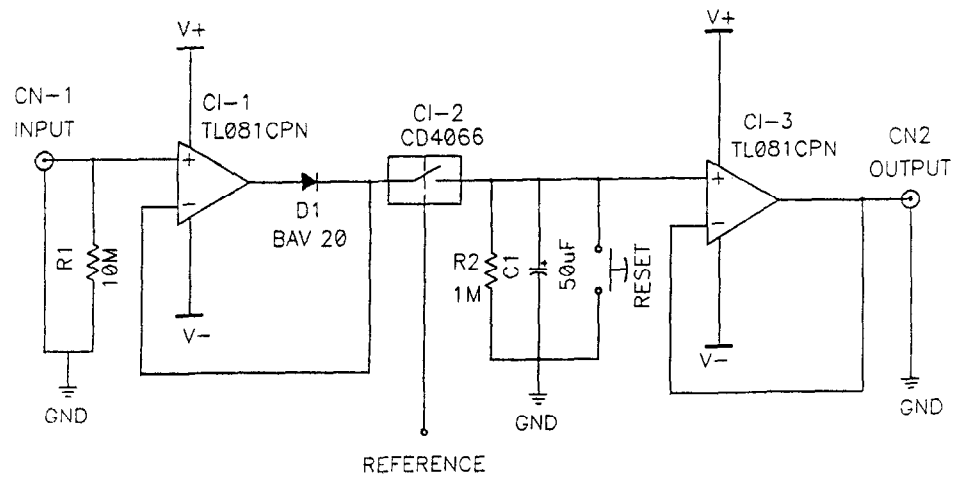

Fig. 3. Electronic circuit of the sample and hold device.

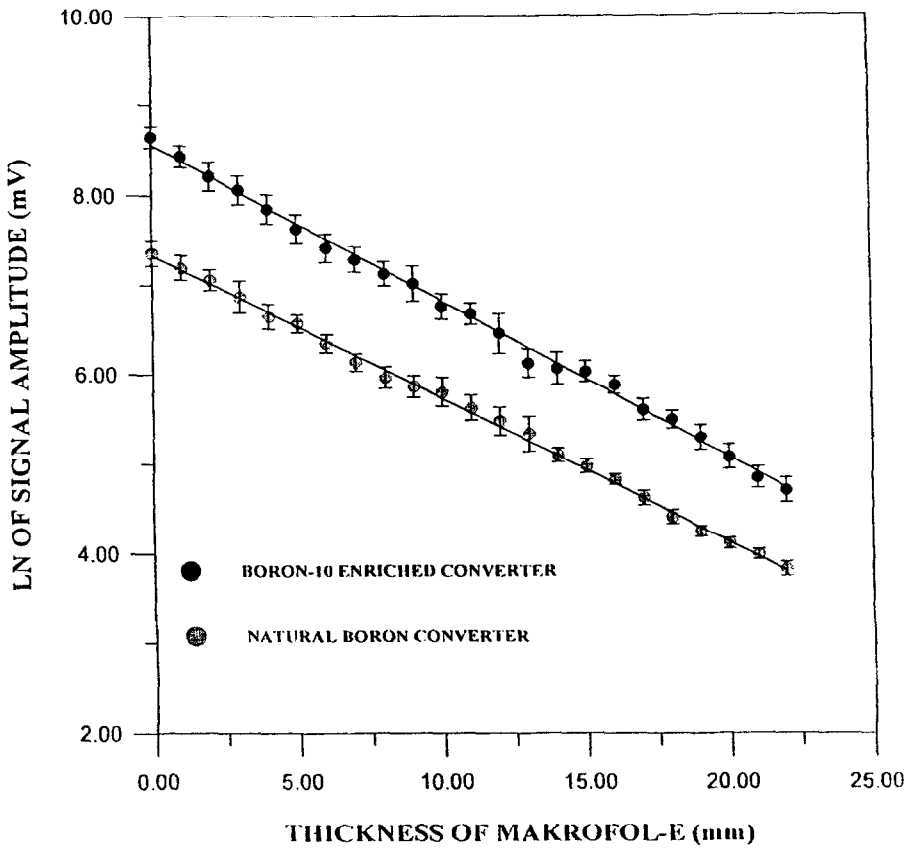

Fig. 4. Logarithm of the signal amplitude as a function of Makrofol E thickness, for the pyroelectric detector system.

further allowed to verify the behaviour of the detector response in two different neutron fields. As can be seen in Fig. 4, there is a good agreement between the linear trend of the experimental data points obtained with both neutron spectra.

The solid lines in Fig. 4 represent the least-squares fitting of the experimental data points and are expressed by the following equations:

$$\ln(V) = 7.339(\pm 0.025) - 0.160(\pm 0.001)X \qquad (2)$$

and

$$\ln(V) = 8.566(\pm 0.027) - 0.174(\pm 0.002)X$$

respectively for converters of natural boron and enriched to 92.41% in ^{10}B. In (2) V represents the signal amplitude generated by the detector in mV and X is the Makrofol E layer thickness in mm.

As can be seen in Fig. 4, the experimental results obtained through the neutron beam attenuation with Makrofol E foils, follow the exponential transmission law [11] expressed by:

$$\phi = \phi_0 \exp(-\beta X), \qquad (3)$$

where ϕ is the neutron flux after attenuation by a X thickness of material with an average macroscopic cross section β and ϕ_0 represents the incident neutron flux.

One can also verify through Fig. 4 and Eq. (2) that the fitted curves are approximately (within 8%) parallel to each other and thus, indicating that the detector system response is proportional to the converter enrichment in ^{10}B, at least within the range of neutron flux intensities from 1.8×10^6 to 1.0×10^4 n/cm^{2}s. This result shows that the present technique, in principle, could be employed for measurements of ^{10}B enrichment in boron samples, similar to the previous case for uranium converters [2].

A study of the detector response behaviour, as a function of the modulation frequency, has been performed, in a same neutron flux extracted from the BH-8 beam tube, and using both boron converters. As can be seen in Fig. 5, the pyroelectric signal amplitude (V) varies linearly with the inverse of the modulation frequency (ω) in excellent agreement with (1). The solid lines in this figure are the results of the least squares fitting of experimental data points and are expressed by the following equations:

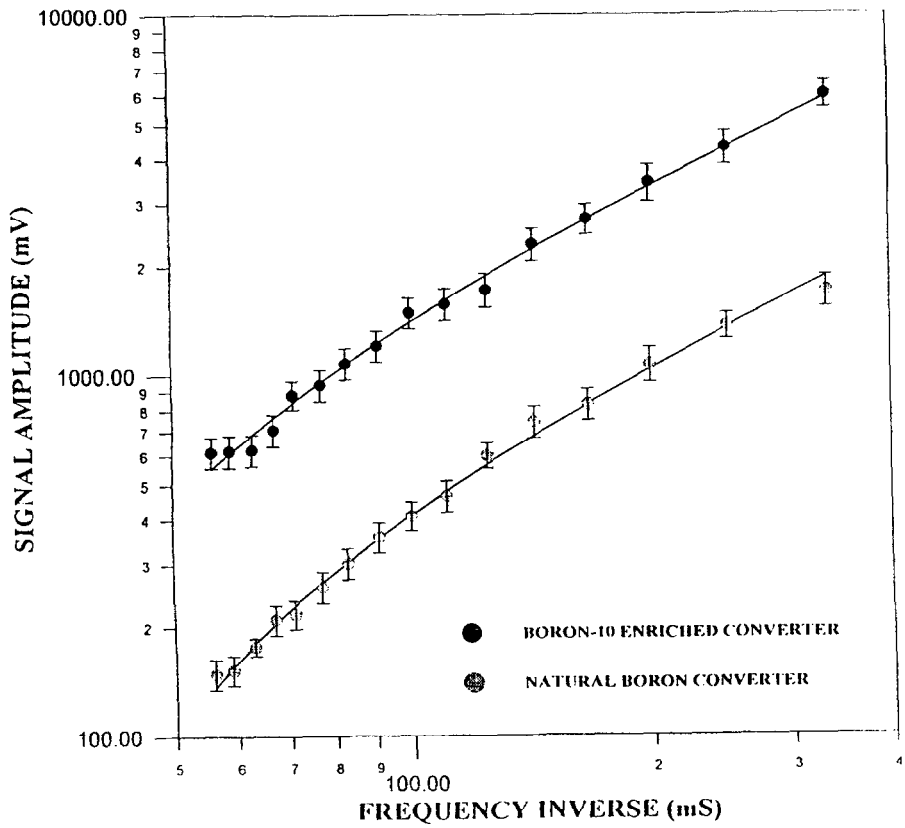

Fig. 5. Signal amplitude plotted as a function of the chopper modulation frequency for the pyroelectric detector system.

$$V(\mathrm{mV}) = -214.2(\pm 9.7) + 6.25(\pm 0.13)\omega^{-1}, \quad (4)$$

and

$$V(\mathrm{mV}) = -528(\pm 37) + 19.27(\pm 0.48)\omega^{-1}$$

respectively for converters of natural boron and enriched to 92.41% in ^{10}B. These fitted curves are also approximately (within 7%) parallel to each other demonstrating, once again, that the detector response is proportional to the ^{10}B enrichment of the converters.

4. Conclusions

The development of a new detector system for thermal neutron detection is presented. The technique has shown to be well suited for monitoring of thermal neutron fluxes above 10^3 n/cm^{2}s. It offers several advantages, such as:

–simple construction and low costs,
–possibility of operating as a portable device,
–does not require external bias field,
–stable output signal even for long time periods of observation,
–low sensitivity to gamma radiation,
–allows a fast alteration of signal amplitude by varying the modulation frequency of the chopper,
–responds linearly to the ^{10}B enrichment of the boron converters.

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