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AN ATTEMPT TO MAKE A FLAT-RESPONSE NEUTRON DETECTOR

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ABSTRACT

A valuable instrument for health physicists would be a neutron detector with a uniform response to neutrons with energies ranging from thermal to fast. The author has produced a simple variable-thickness moderator and has tried it with a BF_3 -filled proportional counter. He has found that there is a good possibility of making a flat-response neutron detector in the range from thermal energies to about 10 MeV and that the average neutron energy can be determined by measuring the maximum detector sensitivity to field of neutrons of unknown energies.

INTRODUCTION

The BF_3 -filled proportional counter (hereafter called a BF_3 counter) is widely employed for measurement of neutron flux. Thermal neutrons are measured by a bare BF_3 counter, and fast neutrons are measured by this same counter after they are moderated by paraffin, polyethylene, or other hydrogen-containing materials.

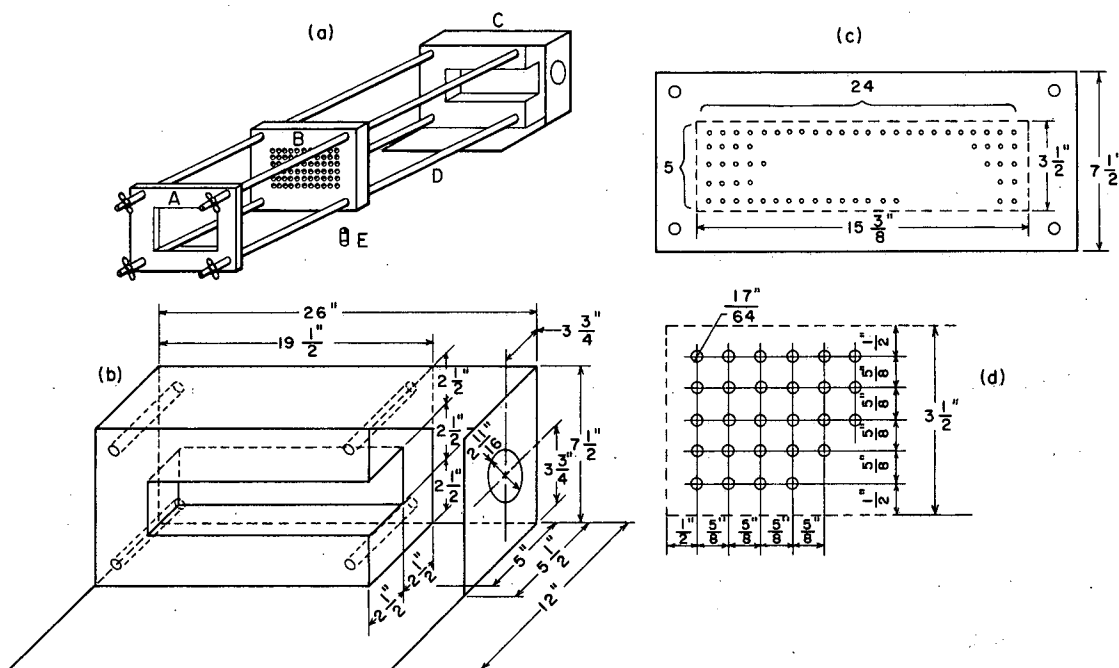
For radiation measurements, the energy dependence of the detector is one of the most significant elements, and much has been done to develop flat-response counters, and many reports have been published on these efforts.¹

For example, a BF_3 counter surrounded by 5 to 7.5 cm of paraffin is independent of the incident-neutron energy within about 30% from 20 keV to 14 MeV.² Further, a recent experiment shows that the response of a BF_3 counter surrounded by 6.5 cm of paraffin is independent of the incident neutron energy from 5 keV to 2 MeV.³

To get a flat energy response in the lower energy range, the author has produced and tested a simple variable-thickness moderator. Construction and operation of the device are described in this report.

APPARATUS

The detector is shown in Fig. 1. Four different thicknesses of moderator, shown in Table I, are combined in various ways. The thickness of the moderator therefore can be varied from 0 to 8.5 in., and the total number of holes in the moderator is changeable by plugging with polyethylene plugs. The moderator base is made of 2.5-in.-thick polyethylene, based on the results of reference 2, and is not covered with cadmium.



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Fig. 1. (a) Variable-thickness moderator, including (A) a 1/16-in. aluminum frame, (B) a polyethylene moderator, and (C) a 1/16-in. aluminum frame with a polyethylene moderator base. The assembly is held together by (D) four bolts with wing nuts. A polyethylene plug is shown at (E). (b) moderator base and (c) polyethylene moderator. (d) Hole distribution in moderator.

Table I. Moderators.

Thickness (in.)	Number used	No. of holes	Plug	
			Diam(in.)	Length(in.)
1/2	3	120	1/4	1/2
1	2	120	1/4	1
2	2	120	1/4	2
1/2	2	0	-	-

A block diagram of the electronic circuit employed is shown in Fig. 2.

The monitor shown in Fig. 2 is a BF_3 counter with a 2-in.-thick cylindrical paraffin moderator covered with cadmium. It is used for observation of the neutron background during measurements. Throughout the course of the experiment, the high voltage fed to the BF_3 counters was kept a constant value of 2300 V, the gain of linear amplifiers was kept at approximately 60 db, and the discriminator bias voltages were set at 10V.

NEUTRON SOURCES

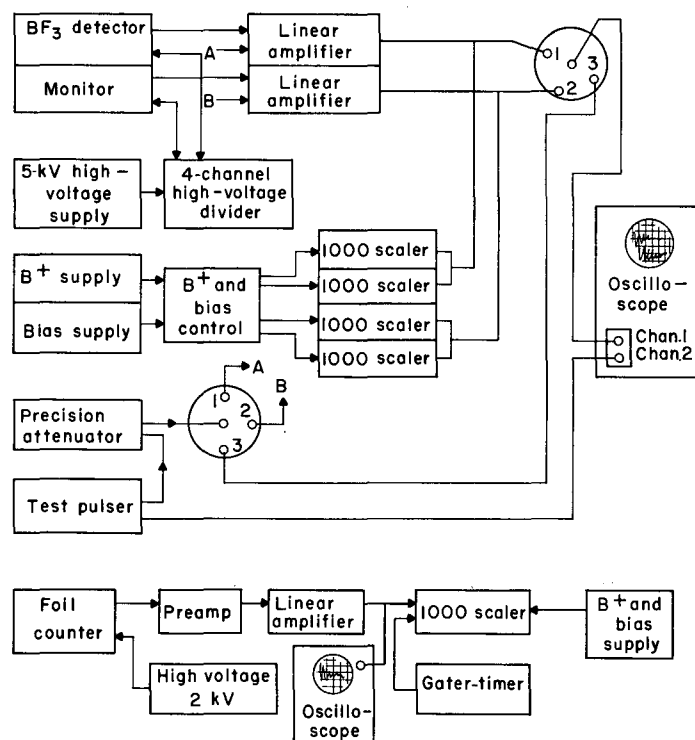
Neutron sources used are listed in Table II. One of these neutron sources was calibrated at the National Bureau of Standards (N. B. S.), one at Mound Laboratory, and the Sb-Be source at the Lawrence Radiation Laboratory; therefore they can be considered reliable for the extent of the experiment. In order to get the thermal-neutron flux, the polonium mock-fission (M. F.) source (No. 623) was placed at the center of the 10-cm-thick paraffin moderator (the external diameter is 24 cm).

NEUTRON FLUX DENSITY

The fast-neutron flux density was determined from the source strength and the distance between the source and the detector.

The thermal-neutron flux density was determined as follows:

1. The sensitivity of the BF_3 counter used (Anton 375E) was calculated as being 10.36 counts/sec per unit flux density by using the manufacturer's specifications.^{4,5} Since the thermal-neutron counting rate measured by this counter was 541 counts/min (difference between the counting rate measured by the bare BF_3 counter and the counting rate measured by the BF_3 counter



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Fig. 2. Block diagram of electronic counting system.

Table II. Neutron sources.

Source	Half life	Effective energy (MeV)	Strength (n/sec)	Calibrated by
Pu-Be (No. 584)	2100 y	4.2	$1.56 \times 10^6 \pm 3\%$	Nat. Bur. Standards
Po-M. F. ^a (No. 623)	138.4d	1.5	$7.55 \times 10^6 \pm 5\%$ (11-30-1962)	Mound Laboratory
Sb-Be	60 d	0.025	$1.58 \times 10^7 \pm 4\%$ (1-14-63)	Livermore L. R. L.

^aM. F. indicates mock fission.

covered with cadmium) on October 2, 1963, the thermal-neutron flux density at the position of the BF_3 counter was determined to be $0.870 \text{ n/cm}^2\text{-sec}$.

2. Indium foils were located at 12 and 25 cm from the Po-M. F. source moderated by a 10-cm-thick cylindrical paraffin moderator. They were activated for a total of 312 min. The activated indium foils were counted in a methane-flow proportional counter. A foil activated to saturation gave about 8 counts per min/g for a thermal-neutron flux of $1 \text{ n/cm}^2\text{-sec}$. The foil counter used at this laboratory has a background counting rate of about 9 counts/min.

The thermal-neutron flux densities at the above-mentioned points were $0.96 \text{ n/cm}^2\text{-sec}$ and $1.05 \text{ n/cm}^2\text{-sec}$, respectively. So, the average thermal flux density at the detector is determined as $1.01 \text{ n/cm}^2\text{-sec}$. This value agrees reasonably well with the calculated value, $0.870 \text{ n/cm}^2\text{-sec}$.

SENSITIVITY MEASUREMENTS

The BF_3 detector including moderator was mounted outdoors on a light aluminum framework so as to minimize the reflection of neutrons by obstacles. Normally it was 180 cm above the ground, with the axis perpendicular to the neutron source.

Each fast-neutron source was suspended by a stand and located at a point that was 2 meters from the long axis of the BF_3 counter and 180 cm above the ground.

The thermal-neutron source was mounted on the framework and was located 1.5 meters from the long axis of the BF_3 counter. Many measurements were made for each neutron source by varying the combination of moderators.

The sensitivity of the BF_3 counter to neutron flux was determined by dividing the counts per unit time by the calculated neutron flux density at the detector. Some typical curves of counter sensitivity vs moderator thickness are given in Fig. 3 and 4. Figure 3 shows detector characteristics that correspond to the case where the variable-thickness polyethylene moderator is placed in front of the BF_3 counter, without the moderator base, and Fig. 4 corresponds to placing the variable-thickness moderator in front of the moderator base containing the bare BF_3 counter.

CONSIDERATION OF DATA

1. Effect of the Moderator Base

Comparing Fig. 3 with Fig. 4, we see that use of the moderator base raises the detector's sensitivity to a fast-neutron flux by a factor of 5 to 7 and its sensitivity to a thermal-neutron flux by a factor of 2.24.

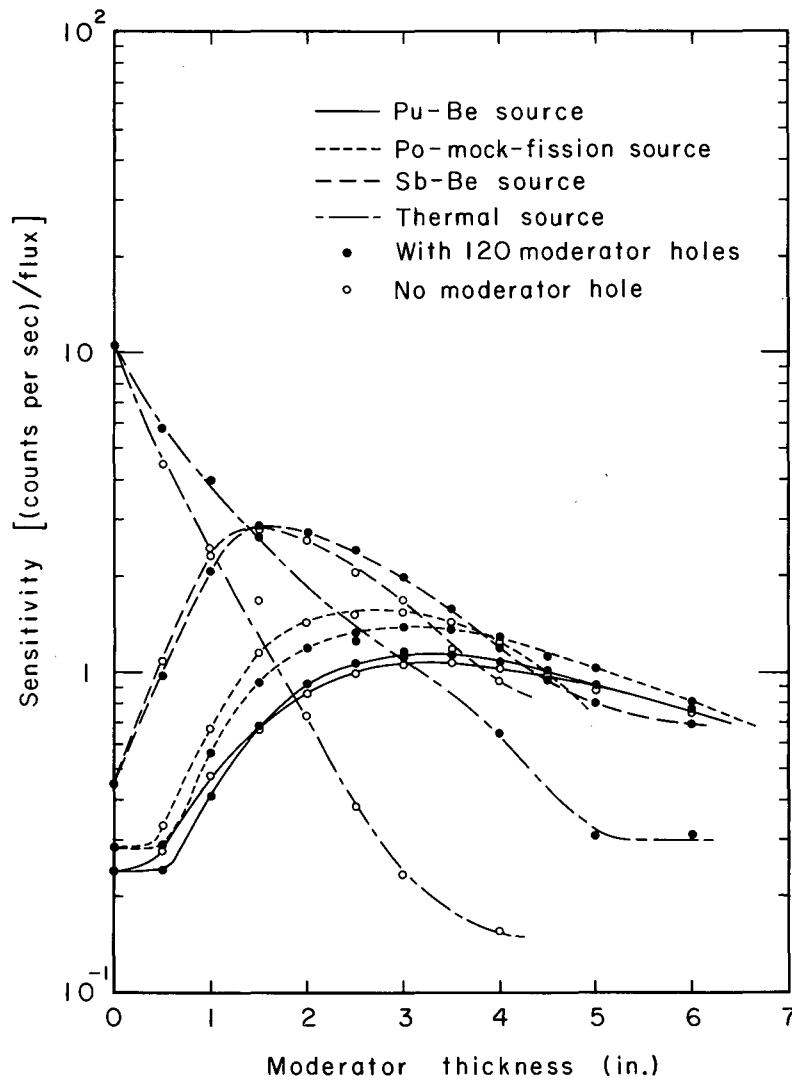
2. Energy Dependence of the Detector's Sensitivity

The relation between the detector's sensitivity and the incident-neutron energy (Figs. 5 and 6) is derived from Fig. 3 and 4 respectively.

3. Effect of Moderator Holes and Thickness

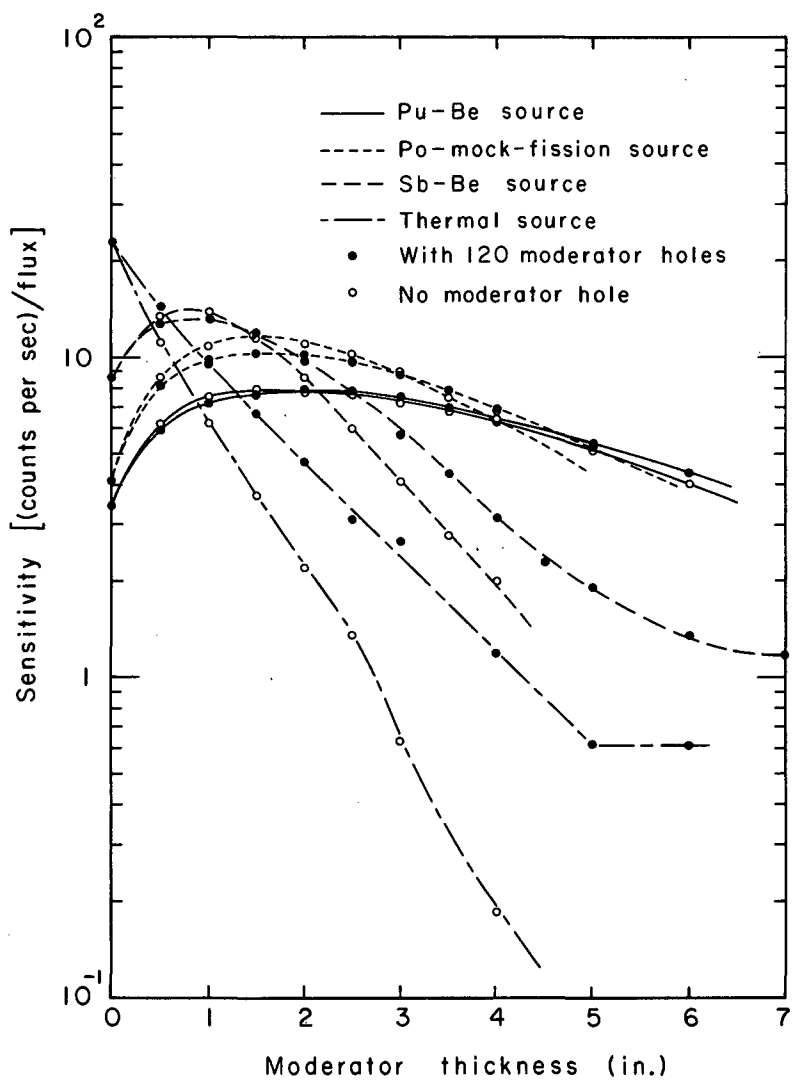
There is little effect of moderator holes on the detector's sensitivity in the higher neutron-energy range, but a remarkable effect in the lower neutron-energy range. It is natural that the moderator holes raise the detector's sensitivity in the lower neutron-energy region because these low-energy neutrons can easily reach the BF_3 counter by passing through the moderator holes with relatively few collisions.

The Pu-Be neutron-detector's sensitivity curves are fairly flat for moderator thicknesses from 1 to 4 in., but curves of the detector's sensitivity to thermal neutrons rapidly fall with increasing moderator thickness.



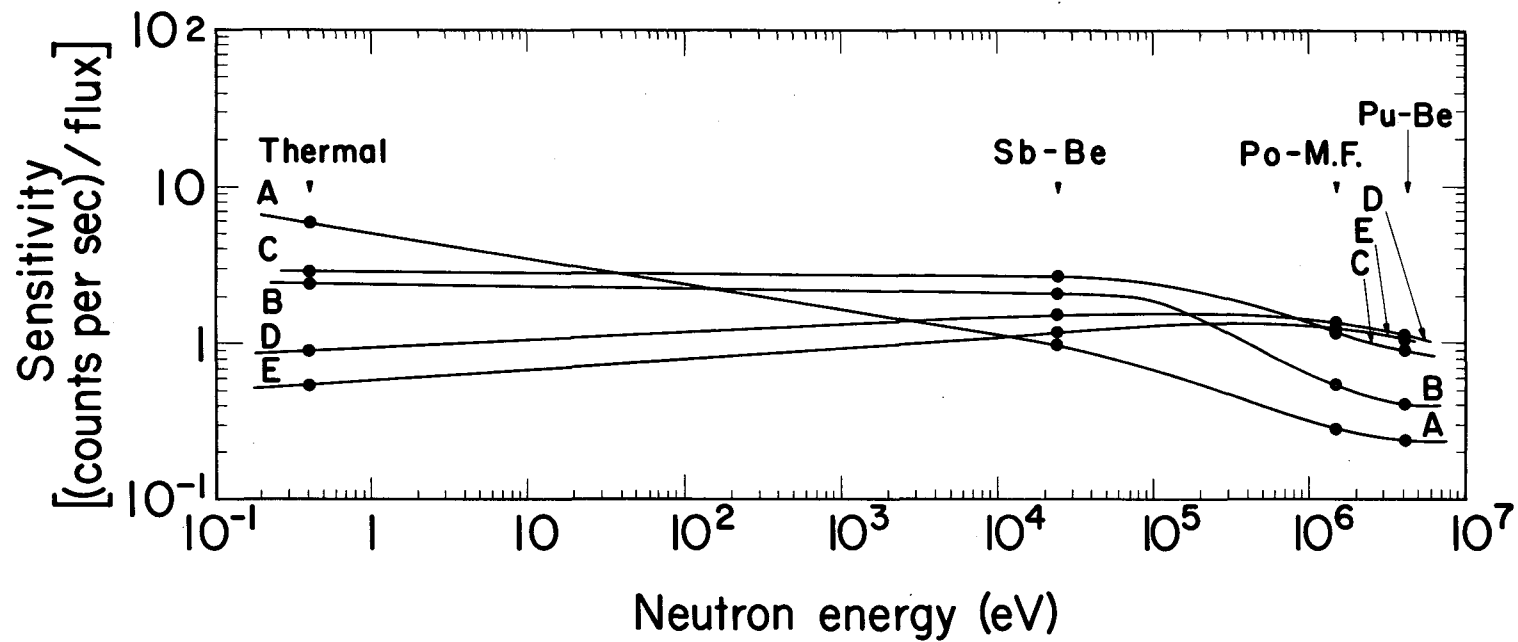
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Fig. 3. Curves of detector sensitivity vs moderator thickness, without moderator base.



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Fig. 4. Curves of detector sensitivity vs moderator thickness, with moderator base.



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Fig. 5. Energy dependence of detector sensitivity, with 120-hole moderator and without moderator base. Moderator thicknesses are (A) 1/2 in., (B) 1 in., (C) 2 in., (D) 3-1/2 in., and (E) 4 in.

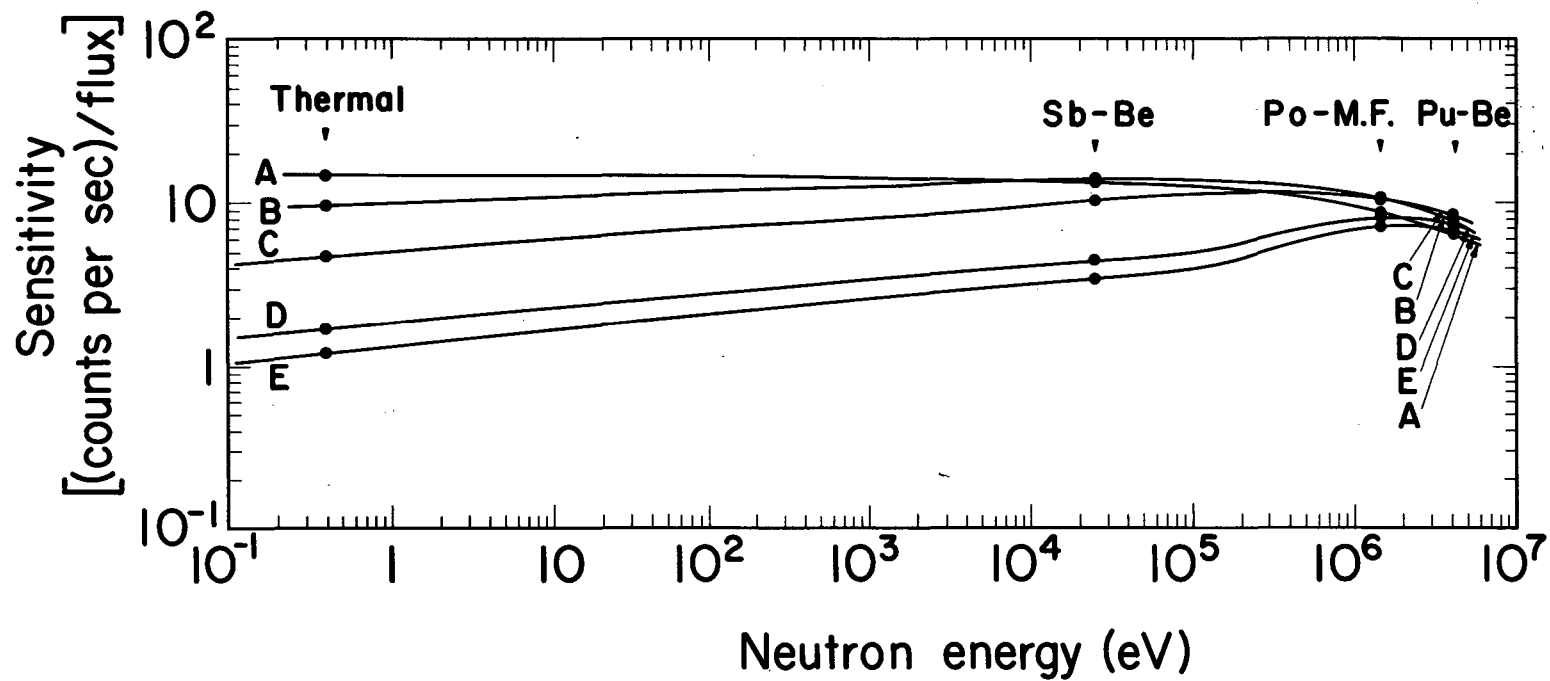


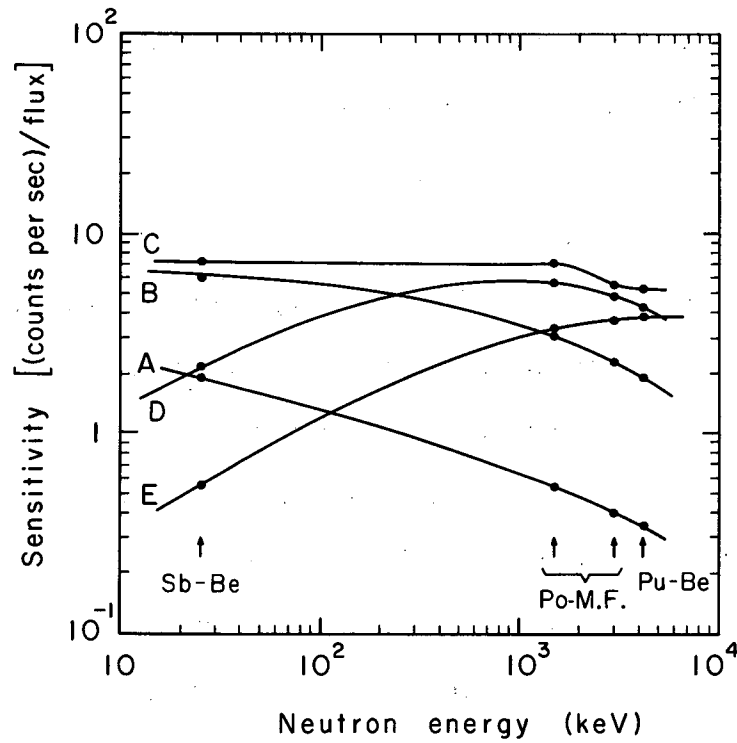
Fig. 6. Energy dependence of detector sensitivity with 120-hole moderator and moderator base. Moderator thicknesses are the same as in Fig. 5.

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For perforated moderators, these curves cross at the 1.3-in. moderator-thickness point (see Fig. 4). Since the detector's sensitivity to thermal neutrons is variable, depending upon the total number of holes in the moderator and the area of individual holes, we can make the detector's energy dependence practically flat in the energy range from thermal energies to about 10 MeV. The total area of 120 holes in the moderator is only 4.5% of the moderator area at present, and so the sensitivity of the detector to thermal neutrons is insufficient for moderator thicknesses of 1.3 in. or more. To further flatten the response of the detector, we must increase the area of the holes either by larger diameter holes or a greater number of holes or a combination of both. From the standpoint of moderator thickness, it is clear from Fig. 4 that thicknesses less than 2 in. do not suit our purpose, because increasing the area of the holes not only raises the response to thermal neutrons but also, depending upon the moderator thickness chosen and hole area, raises or lowers the response of the detector to neutrons from the Sb-Be source.

4. Comparison between the Cylindrical Cadmium-Covered Moderator and the Experimental Flat-Response Moderator

Figure 7 shows the relation between the detector's sensitivity and incident-neutron energy for the aforementioned BF_3 counter equipped with a cylindrical paraffin moderator covered with cadmium. If we compare Fig. 7 with Figs. 5 and 6, it is clear that the experimental moderator described here is considerably less sensitive to variations in incident-neutron energy than the cylindrical moderator used for comparison.



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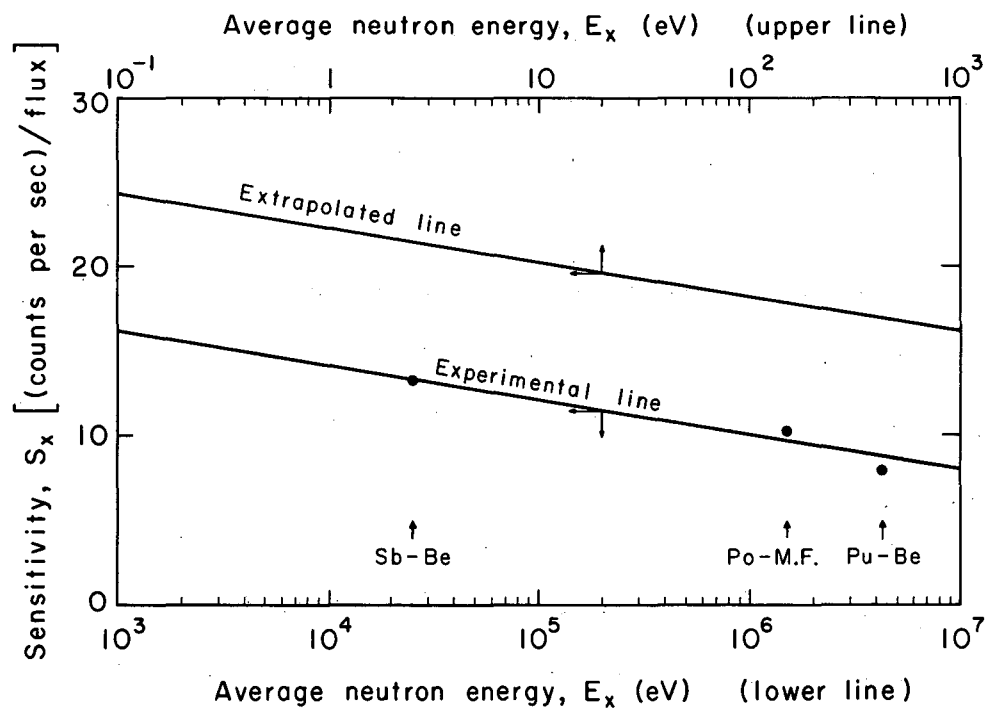
Fig. 7. Energy dependence of detector sensitivity for a cylindrical paraffin moderator covered with cadmium. Moderator thicknesses are (A) 1/2 in., (B) 1 in., (C) 2 in., (D) 3-1/2 in., and (E) 5 in.

5. Determination of the Average Neutron Energy

The relation between the incident-neutron energy and the maximum sensitivity measured by the BF_3 counter surrounded by the moderator base and the moderator with holes is shown in Fig. 8. Extrapolating the lower line in Fig. 8 linearly to thermal energies, we obtain 23.2 counts per unit flux as the detector's sensitivity at 0.4 eV.* On the other hand, the BF_3 counter's sensitivity to thermal neutrons calculated from the counter specifications is 10.36 counts per unit flux. As described before, the moderator base raises the detector's sensitivity to thermal neutrons by a factor 2.24. So we get 23.2 counts per unit flux for the maximum sensitivity to the thermal flux. This value is in excellent agreement with the extrapolated sensitivity at 0.4 eV.

We also experimentally measured the BF_3 counter's sensitivity to thermal neutrons, using a Pu-Be source in a 2-ft cubical cavity within a 4-ft concrete cube, with walls 1 ft thick. The sensitivity of the BF_3 counter was determined to be 9.5 counts per unit flux by dividing the measured counting rate of the BF_3 counter by the calculated thermal-neutron flux density.⁶ As previously noted, the moderator base increases the sensitivity of the BF_3 counter by a factor of 2.24, and accordingly we get 21.3 counts per unit flux for the maximum sensitivity of the BF_3 counter with the moderator base. This value is about 8.2% less than each of the previously noted values. From these facts, we can determine roughly the average neutron energy for an unknown neutron flux less than a few MeV by first measuring the neutron flux density with the flat-response thickness of moderator, then varying the the thickness to determine the maximum detector sensitivity, and consulting the curves in Fig. 8.

*We assume thermal neutrons to be those with energies of 0.4 eV or less, because the energies were determined by a cadmium difference method.



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Fig. 8. Relation between the incident-neutron energy and the maximum detector sensitivity.

The empirical equation for the relation between the maximum detector sensitivity and the average neutron energy is

$$\log \left(\frac{E_x}{0.4} \right) = \frac{S_{0.4} - S_x}{K},$$

where E_x is the average neutron energy in eV, S_x is the maximum detector sensitivity at E_x in counts per unit flux, and K is a constant related to apparatus. Substituting 23.2 counts per unit flux for $S_{0.4}$ and 0.9 for K , we get

$$E_x = 0.4 \exp[(23.2 - S_x)/0.9].$$

A method has been proposed by Moyer et al. that uses both a BF_3 counter and a polyethylene-lined proton-recoil proportional counter to obtain the average neutron energy.² Polyethylene-lined proton recoil proportional counters are very sensitive to gamma radiation and therefore are not suitable detectors of a low-energy neutron field accompanied by high gamma radiation. By comparison, BF_3 counters are useful tools to measure neutron fluxes even when accompanied by gamma radiation, because the gamma pulses are easily discriminated against by an increase in the detector bias voltages. This is true up to a few roentgens per hour of gamma radiation.

CONCLUSION

There is good reason to believe that a flat-response neutron detector in the range from thermal energies to about 10 MeV can be constructed. Through a careful choice of the percent of the total moderator material removed by perforation holes, the detector's sensitivity to low-energy neutrons can be much improved with negligible depression in the detector's sensitivity to fast neutrons. Using the experimental data accumulated for thermal and fast neutrons, we would say that an area of moderator holes from 10 to 20%

and moderator thicknesses from 2.5 to 4 in. would make the response nearly flat over the energy interval desired. Within these limits, more detailed work must be carried on with neutrons of other intermediate energies as well as those already used.

The average neutron energy less than a few MeV of an unknown-energy neutron field can be determined from the relation between the maximum sensitivity and the average neutron energy. Owing to the difficulty of getting low-energy neutron sources, there is little quantitative data available, and there still remains the necessity for more work with the size, shape, and distribution of moderator holes.

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Finally, I should like to express my appreciation to those individuals at both the Lawrence Radiation Laboratory and the Japan Atomic Energy Research Institute for making possible this exchange visit.

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