Position Sensitive Slow Neutron Detectors Using Fibre Optic Encoding

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1. Introduction

The advantages of using "position sensitive detectors" (PSD's) in neutron scattering measurements have been recognised for a number of years(1). Hitherto, the most successful PSD's have been based on the gas proportional counter principle(2)(3) in which a gas containing ^{3}He or ^{10}B in the form of borontrifluoride is used both to absorb the slow neutrons and to obtain gas multiplication of the resulting ionisation. An outstanding example of the application of these detectors has been to small angle scattering such as the D11 instrument at the Institut Laue-Langevin. The recent interest in intense pulsed neutron sources such as the Spallation Neutron Source (SNS) being constructed at the Rutherford Laboratory or the Intense Pulsed Neutron Source at the Argonne National Laboratory, has created new requirements for PSD's. These arise from the time-of-flight technique used for all measurements and from the fact that the neutron energy spectrum from these new sources is much richer in epithermal neutrons than that from reactor sources. It is anticipated that much of the new science will arise from the use of these higher energy neutrons. The requirements of a detector for use at a high intensity pulsed source are summarised below:

a. *the thickness must be less than about 20 mm for most types of* measurement to avoid uncertainties in the flight path length. Some instruments such as quasi-elastic scattering devices require detectors not more than a few mm thick.

b. dead time of about 100 ns to cope with the high instantaneous count rates with acceptable dead time corrections.

c. adequate detection efficiency over a wide range of neutron energies extending up to epithermal energies, eg an efficiency of about 30% at a neutron energy of 1 eV.

d. positional information with a spatial resolution about 10 mm or more.

It is very difficult to meet these requirements with the gas proportional counter technique. The dead time is limited by the drift velocity of electrons in the gas and cannot be much less than 1 μs in practical detectors. Also the need for adequate efficiency at epithermal neutron energies implies a high pressure gas filling with the attendant need for thick windows.

Detection methods using a solid neutron convertor are more likely to meet the needs of instruments at pulsed neutron sources. The use of gadolinium foils together with conventional multiwire proportional counters to detect directly the charged particle products of the neutron interaction have been proposed(4). The foils must be thin (< 10m micrometres) to allow the escape of a reasonable fraction of the *charged particles,which results in a low detection efficiency for a* single foil at epithermal neutron energies. The rapid fall of the gadolinium absorption cross-section with increasing neutron energy above about 0.2 eV accentuates this problem for epithermal neutron detection. For example a foil of ^{157}Gd of thickness 5 micrometres would have a stopping power for 1 eV neutrons of 0.2%. The method is promising however for beams of cold neutrons. Furthermore, if the cost of multiwire proportional counters could be greatly reduced in the future so that several could be placed in series, at reasonable cost, then the detection efficiency could be increased. At the present time, however, it is considered that the scintillator technique offers the best solutions for pulsed source detectors.

Scintillators

2. Two types of neutron scintillator have been used in the present work, both incorporating ^{6}Li as the neutron convertor. Both are well known and commercially available.

2.1 Lithium Loaded Glass

Silicate glass containing ^{6}Li and using cerium as an activator(5) has the following properties as a slow neutron detector:

a. it is transparent to its own light emission which has a wavelength of 3900 Å at the peak of the emission spectrum(6).

b. about 10^4 photons are emitted per neutron absorbed(7) the light output decaying to half peak intensity in ∿ 20 ns and to one-tenth peak intensity in ∿ 100 ns(8).

c. the absorption efficiency of 2mm thick scintillator is typically 80% for neutrons of energy 0.08 eV (wavelength ∿ 1Å). The efficiency as a function of neutron energy is shown in Fig.1

d. scintillator of thickness 2 mm has appreciable gamma sensitivity(9) but this can be reduced by arranging it in the form of 0.5 mm thick wafers interspaced with 1 mm thick sheets of plain glass. The predominant mode of interaction with gamma rays is via Compton scattering producing a recoil electron. The range of the electron in glass is such that it deposits most of its energy in the non-scintillating parts of the sandwich thus reducing the pulse height and enabling simple pulse height discrimination to be used. The ranges of the charged particles produced from the neutron interaction (an alpha particle of energy 2.1 MeV and a triton of energy 2.7 MeV) are short and contained within the layers of scintillator. This technique will be described more fully elsewhere. In the present work with glass scintillator it has been found possible to use pulse shape discrimination against noise but not gammas.

2.2 Lithium Loaded Zinc Sulphide

Silver activated zinc sulphide is a well-known phosphor and it is combined with ^{6}LiF and a plastic binder to form a slow neutron scintillator which has been used for many years for neutron radiography. It has the following properties:

a. it is translucent with strong absorption and scattering of its own light which has a wavelength of 4500 Å at the peak of the emission spectrum(10). It can only be used in thin sheets (thickness ≳ 0.6 mm) if all neutrons absorbed are to be "seen" by a photomultiplier.

b. about 10^5 photons are emitted per neutron absorbed(7), the light output decaying to half peak intensity in ∿ 150 ns and to one-tenth peak intensity in ∿ 1 μs(11).

c. the absorption efficiency of 0.6 mm thick scintillator is ∿ 20% for neutrons of energy 0.08 eV and ∿ 6% for an energy of 1 eV.

d. the gamma sensitivity is low and, in addition, pulse shape discrimination can be used.

e. the cost is very roughly one-tenth of that of lithium glass scintillator.

3. Principle of Operation

For PSD's using the scintillation technique and requiring many spatial resolution elements, the obvious method of optically coupling a photomultiplier (PM) to each element is impracticable due to the cost and complexity of a system containing many thousands of PM's. The present system uses a fibre optic encoder to couple a large number of resolution elements to a much smaller number of PM's. Each resolution element is a separate piece of scintillator and is connected by 3 fibre optic channels to a unique combination of 3 PM's out of a bank of N. Thus a coincident output signal on 3 particular PM's identifies the resolution element in which a neutron capture event took place. The number of resolution elements, n, which can be encoded by N PM's using a triple coincidence is given by:

$$n = \frac{N!}{3!(N-3)!}$$

and the number of elements connected to each PM, M, is given by:

$$M = \tfrac{1}{2}(N-1)(N-2)$$

Also, any group of 3 PM's is connected to a large fraction of the total number of resolution elements and so a neutron detected in one element "linear" detector in the form of a spiral, an area detector with "r-θ" resolution can be made.

4 Methods of Construction

4.1 Use of Zinc Sulphide Scintillator

The zinc sulphide scintillator is useful for cold neutrons where moderate stopping power is not a disadvantage, in an environment with high γ background and where moderate count rates only are encountered (about 10^4c/s over a whole detector for example). The scintillator must be viewed normally to its surface with an arrangement shown schematically in Fig.2. A prototype detector system has been used successfully in a neutron scattering experiment on the D7 instrument at the Institut Laue Langevin(14). This system used bundles of glass fibre optics in the encoder, but much better results are now achieved using coated plastic fibres. These have better transmission for blue light, are much easier to handle and finish and are of lower cost. The method of making an encoder is illustrated in Fig.3. Spacer bars with 'V' grooves spaced at the pitch corresponding to the resolution required are mounted on a simple winding machine. Three fibres are wound into each groove, the 'V' shape ensuring self alignment. A cover strip is then glued on top to trap the fibres. Twelve strips can be wound simultaneously. The strips are then stacked up as shown and the fibres encoded by hand into the appropriate number of output channels. This whole process can be completed easily in 2 days for a detector module having a few thousand resolution elements. The assembly is then encapsulated in a neutron absorbing material to form a strong monolithic block.

4.2 Use of Glass Scintillator

The light output from the glass scintillator is not high enough for good optical coupling to the fibres in the manner described above. However, its good transmission for its own light output enables good coupling to be made to the edges of the scintillator elements, the light being transmitted to the fibres by total internal reflection. An arrangement using this principle is illustrated in

paralyses many other elements until the detection and decoding process is complete. The number of elements, P, coupled to any group of 3 PM's is given by:

$$P = \tfrac{1}{2}(3N^2 - 15N + 20)$$

We note that the code is free of ambiguities if the decoder accepts 3 and only 3 coincident PM output signals. Thus two neutrons arriving simultaneously on two different resolution elements would produce more than 3 PM outputs and no ambiguity in spatial information would result though the counts would be lost. Table I shows some sets of these quantities by way of illustration.

Table I

No. of PM's	No. of Elements Encoded	No. of elements coupled to each PM	No. of elements coupled to any group of 3 PM's
N	n	M	P
15	455	91	235
20	1140	171	460
30	4060	406	1135
40	9880	741	2110

Still higher economies in PM's could be achieved by using a higher order coincidence, but for the geometries required for neutron work, it would be difficult to pack more than 3 or 4 fibre optic channels behind each resolution element and still achieve enough light collection efficiency for reliable operation. The present system uses triple coincidence and a 3 out of N code as a practical arrangement.

A similar scheme was developed independently by Hoftiezer et al.(12) who used a binary code in a detector for high energy charged particles.

The particular arrangement of the resolution elements can vary widely. For example they can be of any shape and be arranged on any surface such as a cylinder or sphere. Furthermore an area detector having resolution in two dimensions is simply a folded linear one. By arranging a

Fig.4. Fibres wound on spacer strips, as described above, can still be used. The scintillator elements are no longer in one plane but this is not important for most applications. Gamma discrimination can be achieved by arranging the scintillator in a sandwich as described in section 2.1(d). A variation of this principle would be to construct the sandwich without the plain glass, each scintillator layer being coupled with fibre optics as a separate detector element. A gamma event producing light in more than one layer would result in more than 3 simultaneous signals and would therefore be rejected by the decode electronics. An interesting outcome of the capability of collecting light from individual layers of a scintillator sandwich is that there is no limit to the number of layers, so that thick assemblies could be built up (say 10 layers of 1 mm thickness) without increasing the γ sensitivity. Such a device would have an efficiency of over 50% for 10 eV neutrons (see Fig.1).

A detector module of 400 channels with 1 cm resolution and 1 mm thick glass scintillator is being constructed. It is expected that this module will have a count rate capability of over 10^6c/s with pulse pair resolution time of $\sim$ 100 ns.

5. Electronics

Light levels at the outputs of the encoders are low and a photon counting technique is used to identify neutron events in the scintillator(13). A fast system for use with the glass scintillator has been built which uses a time window of 100 ns opened on the detection of any pulse. A further 3 or more pulses counted within the window indicates a neutron event. A high voltage bias curve for a three channel unit is shown in Fig.5. In this measurement 6 plastic fibres 1 mm diameter were coupled to the edge of a 1 mm thick piece of scintillator, 0.6 cm wide and 4 cm long, the fibres being connected to the narrow edge. A good plateau is achieved.

6. Conclusions

The successful operation of the fibre optic encoding principle has been demonstrated in a neutron scattering experiment and recent developments have enabled the method to be extended to the use of lithium glass scintillator with the advantages of high count rate capability and good detection efficiency. Methods of manufacture have been developed which use straightforward technology. The cost of detector modules of a few thousand elements should be between £1 and £3 per channel including electronics depending on geometry required and on which scintillator is used.

REFERENCES

1. B H Meardon and D C Salter, Rutherford Laboratory Report RHEL/R.262, 1972.
2. R Allemand et al., Nuclear Instruments and Methods, 126 (1975) 29-42.
3. M K Kopp and C J Borkowski, Oak Ridge National Laboratory Report, ORNL-TM-5083, December 1975.
4. A P Jeavons et al., CERN Report, CERN 77-01, January 1977.
5. D G Anderson et al., Proceedings of the 5th International Instrumentation and Measurements Conference, Stockholm, pp.616-630.
6. A R Spowart, Nuclear Instruments and Methods, 140 (1977) 19-28.
7. A R Spowart, Nuclear Instruments and Methods, 75 (1969) 35-42.
8. E J Fairley and A R Spowart, Nuclear Instruments and Methods, 150 (1978) 159-163.
9. L A Wright et al., Nuclear Instruments and Methods, 33 (1965) 181-183.
10. J B Birks, The Theory and Practice of Scintillation Counting, Pergammon Press, 1964, p.543.
11. J C Barton and P W Ranby, Journal of Physics E: Scientific Instruments, 10, (1977) 437-438.
12. J H Hoftiezer et al., Nuclear Instruments and Methods, 147 (1977) 465-469.
13. R Bond, D K Ross, C J Carlile and I S Anderson, Annual Conference of the Condensed Matter Division of the European Physical Society, Antwerp 1980. Proceedings to be published in Solid State Communications.
14. P L Davidson, Rutherford Laboratory Report RL-77-106/A.

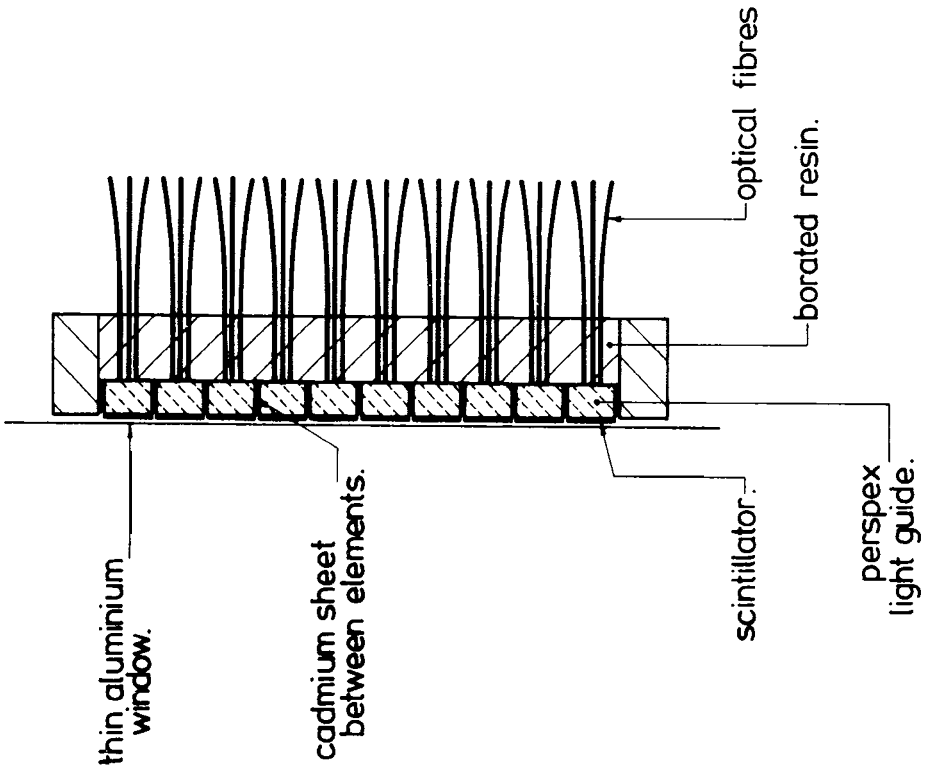


Fig.2 Schematic Cross-Section Of Input End Of Detector.

λ	E	μ	EFFICIENCY FOR VARIOUS THICKNESSES IN MM						
			0.5	1	2	3	5	10	20
Å	eV	cm^{-1}							
0.1	6.190	0.830	.041	.080	.153	.220	.340	.564	.810
0.15	3.640	1.245	.060	.117	.220	.312	.463	.712	.917
0.3	.910	2.49	.117	.220	.392	.526	.712	.917	.993
0.5	.328	4.15	.187	.340	.564	.712	.874	.984	1.000
1	.0819	8.30	.340	.564	.810	.917	.984	.999	1.000
2	.0205	16.60	.564	.810	.964	.993	.999	1.000	1.000
4	.00512	33.20	.810	.964	.999	1.000	1.000	1.000	1.000
6	.00228	49.80	.917	.993	1.000	1.000	1.000	1.000	1.000

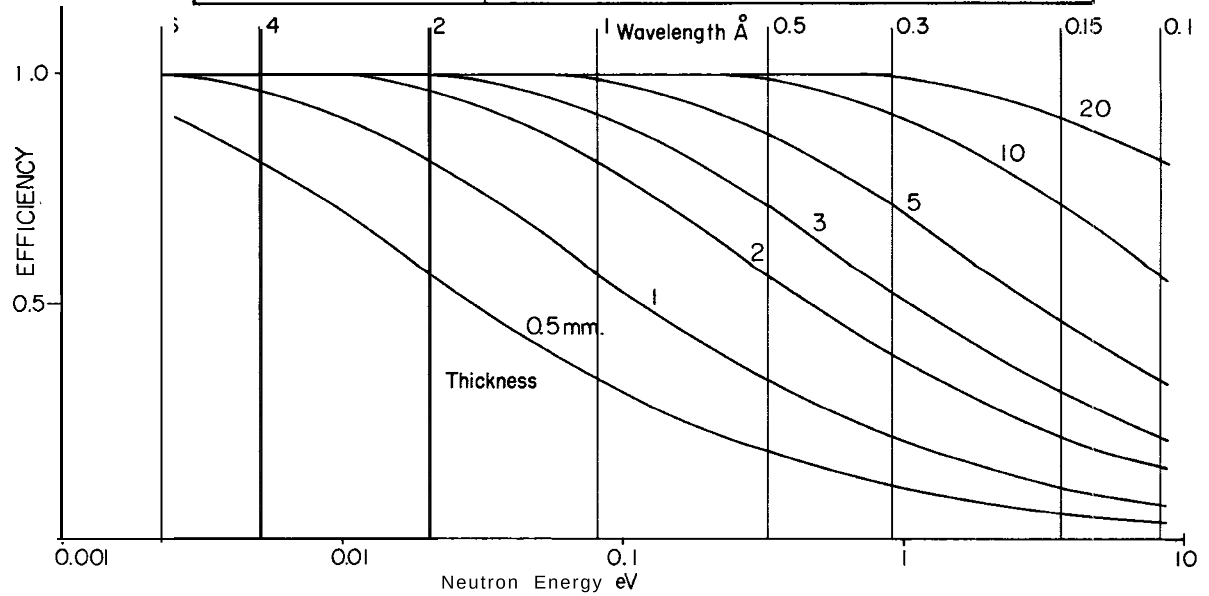


FIG.1 EFFICIENCY OF NE905 (GS20)LITHIUM GLASS SCINTILLATOR VS ENERGY & THICKNESS

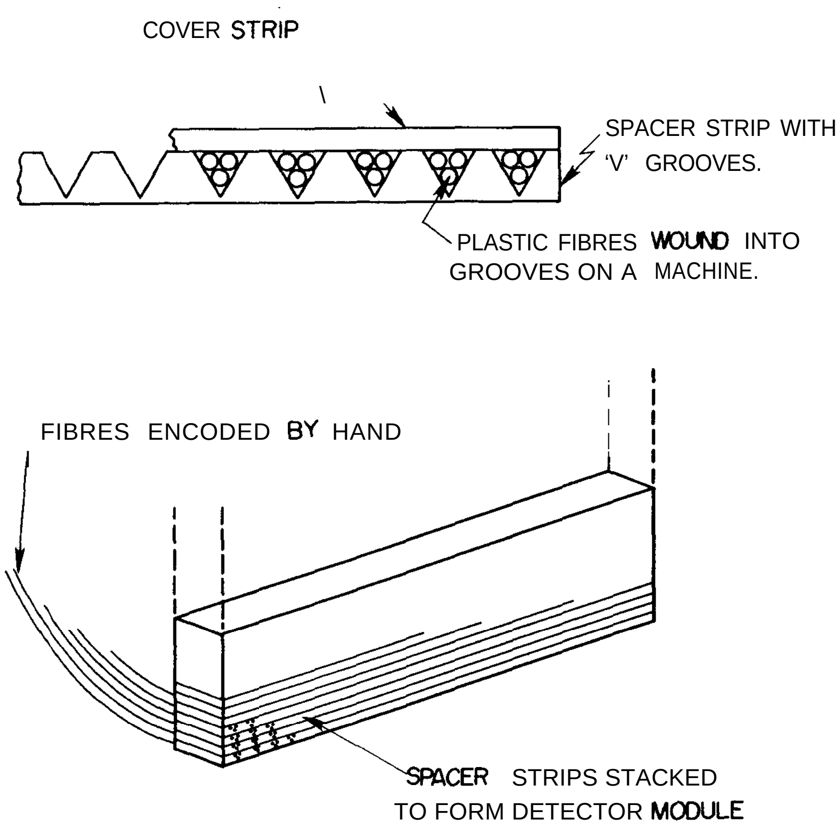
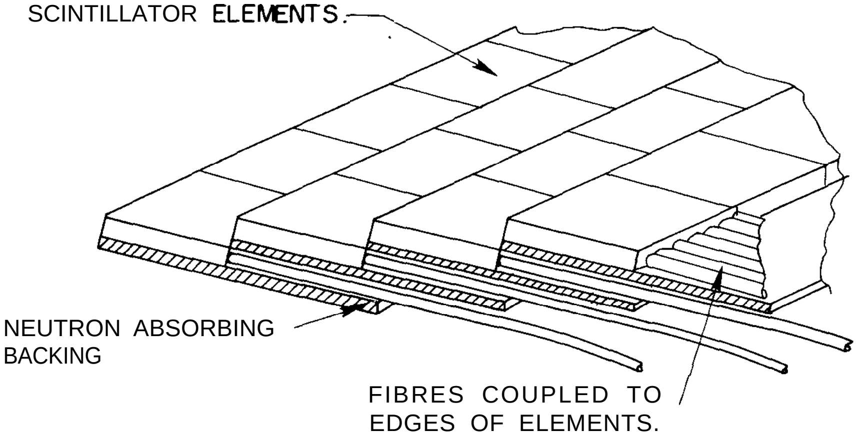
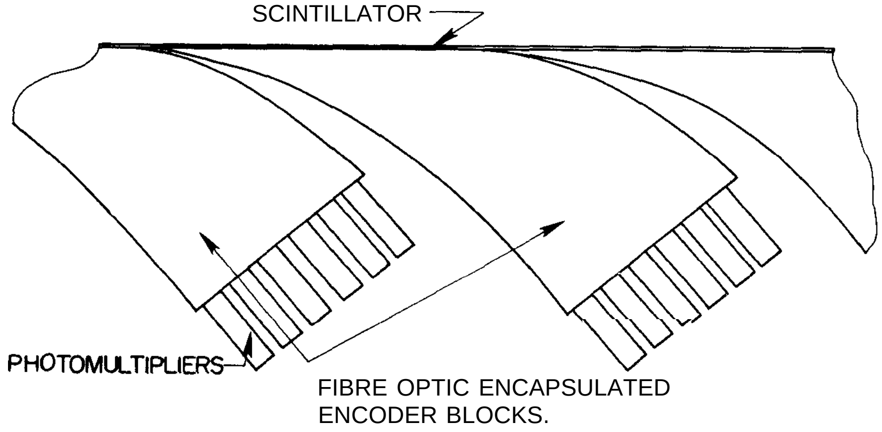


FIG.3. ILLUSTRATING METHOD OF MANUFACTURE OF FIBRE OPTIC ENCODER.





PLAN VIEW SHOWING STACKING OF MODULES TO FORM LARGE DETECTOR AREA.

FIG.4. ILLUSTRATING METHOD OF BUILDING AN ENCODER USING EDGE COUPLING OF PLASTIC FIBRES.

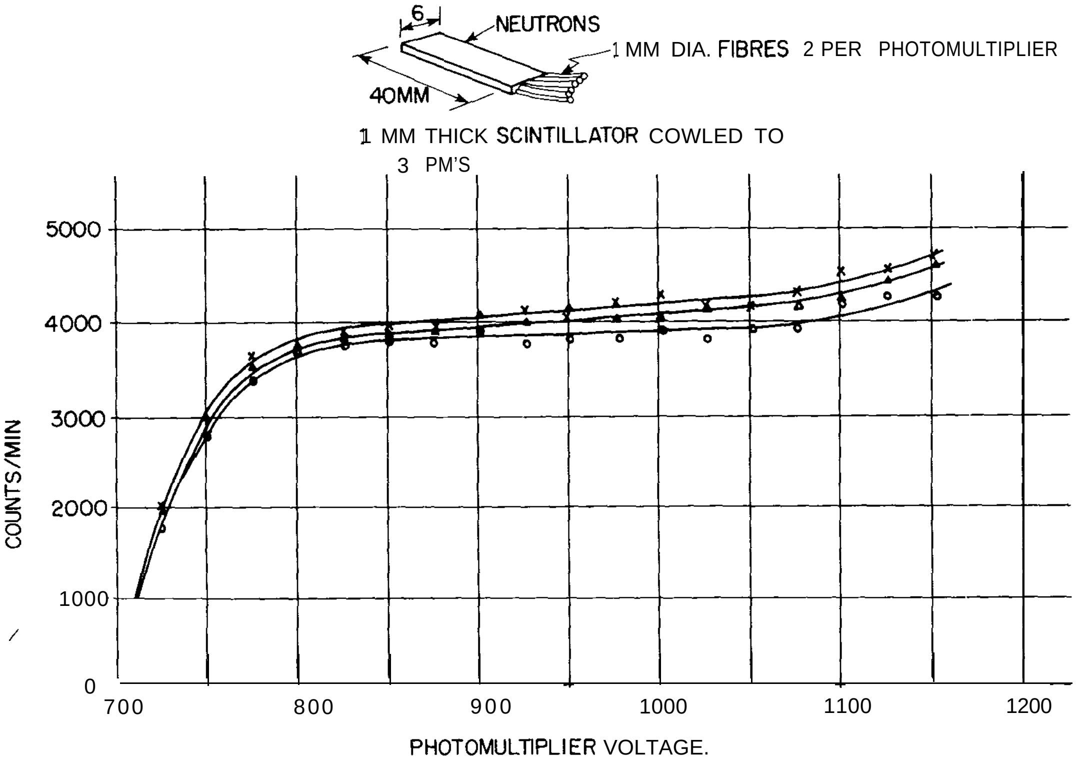


FIG.5. HIGH VOLTAGE CURVES FOR 3 CHANNEL, EDGE COUPLED TEST PIECE