THE PERFORMANCE OF LARGE-VOLUME PLASTIC SCINTILLATORS WITH REFERENCE TO WHOLE BODY COUNTING

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Introduction

At the 1957 Evanston Conference, a report was given of the performance of large-volume liquid and plastic organic scintillators (1). The units tested were 20 in. long, 10 in. wide and 6½ in. thick (with semi-cylindrical ends) and scintillations were viewed by two 5 in. diameter photomultipliers mounted on one 20 in. x 10 in. face of the scintillator.

From the point of view of spectral resolution, it was found that the NE101 plastic scintillator supplied by Nuclear Enterprises (G.B.) Ltd., Edinburgh, gave a performance which was very slightly superior to the best liquid scintillator containing 3.7 g. PPO and 0.1 g POPOP per litre of oxygen-free toluene. A lead-loaded liquid scintillator was also examined, but because of excessive light attenuation by the lead compounds, the light collection efficiency at the photocathodes was very low, and gamma-ray spectra revealed neither Compton nor photo peaks.

Bearing in mind the application of these detectors to measurement of radioactivity in human beings, it was concluded that the plastic scintillators possessed the following advantages:

1. Spectral resolution slightly better than that obtained with the best liquid scintillator.

2. Freedom from fire hazards.

3. Freedom from toxicity hazards.

4. Greater ease of working. Container design and fabrication become simpler with the elimination of the problem of liquid seals.

The greater expense of the plastic scintillator constitutes an extremely small fraction of the total cost of an apparatus comprising extensive shielding and elaborate electronics.

Multiple-unit design (as opposed to a single large 2π or 4π detector) was favoured because of its greater flexibility and its adaptability for development work. Furthermore, in measuring high levels of radioactivity, overloading of amplifiers and analysers can be avoided by switching-off all units except one, and even that one can, if necessary, be positioned remotely from the source.

The present report describes and illustrates a number of factors relevant to the design of large plastic scintillators used for gamma-ray detection.

Factors Affecting Spectral Resolution

Table 1 illustrates the difference in spectral resolution which can arise from selected and unselected photomultipliers of the same nominal diameter.

Table 1.

RESOLUTION OF 15IN. DIAMETER X 9IN. THICK CYLINDRICAL

NE102 PLASTIC SCINTILLATOR TO K-40 GAMMA-RADIATION

Photomultipliers	Peak/Trough ratio	Half-Resolution * %
4 x EMI 9530 A (5 in. dia.)	1.75	22.5
4 x Du Mont 6364 (5 in. dia.)	1.57	25.5

* "Half-Resolution" is defined as the "half-width" of the peak on the high-energy side divided by the amplitude of the peak. See reference (1) and Fig. 3.

The EMI tubes were selected for a photocathode sensitivity of not less than 55 μ amp per lumen, the Du Mont tubes were unselected. Uniformity of photocathode response is, however, very important as will be shown later.

A series of tests was conducted using a single EMI Type 9545 photomultiplier of 12 in. nominal diameter on 15 in. diameter plastic scintillators. Some of these results are summarised in Table 2.

Table 2

RESOLUTION WITH SINGLE 12" DIA. EMI TYPE 9545 PHOTOMULTIPLIER

ON 15" DIA. CYLINDRICAL PLASTIC SCINTILLATORS

Scintillator		Radiation Source	Peak/Trough	Half-Resolution % *
Type	Thickness			
NE102	9"	K^{40} at side	1.43	32
NE101	9"	" " "		35
		K^{40} against face opposite P/M		22
NE 101	6" bevelled	K^{40} opposite P/M	1.50	22
		Cs^{137} " "	1.17	31
NE101	3" bevelled	K^{40} " "	1.21	13
		Cs^{137} " "	1.08	30

* The absolute values quoted for K^{40} in this series are too low due to non-linearity in the pulse-amplifier.

Attention should be drawn to the following points:-

1. NE101 and NE102 scintillators gave a roughly comparable performance.

2. The shape of the spectrum obtained with the 9 in. thick scintillator was markedly dependent upon the position of the source.

3. Although the half-resolution improved when the scintillator thickness was reduced, the peak-trough ratio fell to a very low value for the 3 in. thick scintillator.

These observations incicated that the pulse-height observed for a given event depends upon the position of that event in the scintillator, and to investigate this aspect further, a collimated beam of Co^{60} gamma-rays was fired through the scintillator. The results are illustrated in Fig. 1.

When the beam is fired parallel and close to the photocathode of the large tube, the solid angle subtended by the photcathode to scintillation events is large, and the average light attenuation is low. This results in a large average pulse-height, but due to the lowered photocathode sensitivity towards the periphery, scintillation events occurring directly beneath peripheral areas of the photocathode will give a lower pulse-height than the same events occurring directly beneath the central regions of the photocathode, As the beam is moved away from the photocathode, the solid angle is decreased and light attenuation is increased. These two factors account for the reduction of the average pulse-height but because of the more uniform illumination of the photocathode surface, the same scintillation event occurring at different points along the beam will give rise to a smaller spread in pulse-height. The peak is therefore sharpened.

Fig. 1 also shows the variation in the pulse-height of the peak when the single 12 in. diameter photomultiplier is replaced by four 5 in. diameter tubes. We find now that the average solid-angle subtended by the combined photocathodes for scintillation events occurring near to the top surface is very much reduced. Consequently, the variation in light collection efficiency as the beam is moved away from the photocathode surfaces is also reduced. Indeed we observe optimum light-collection for events that take place

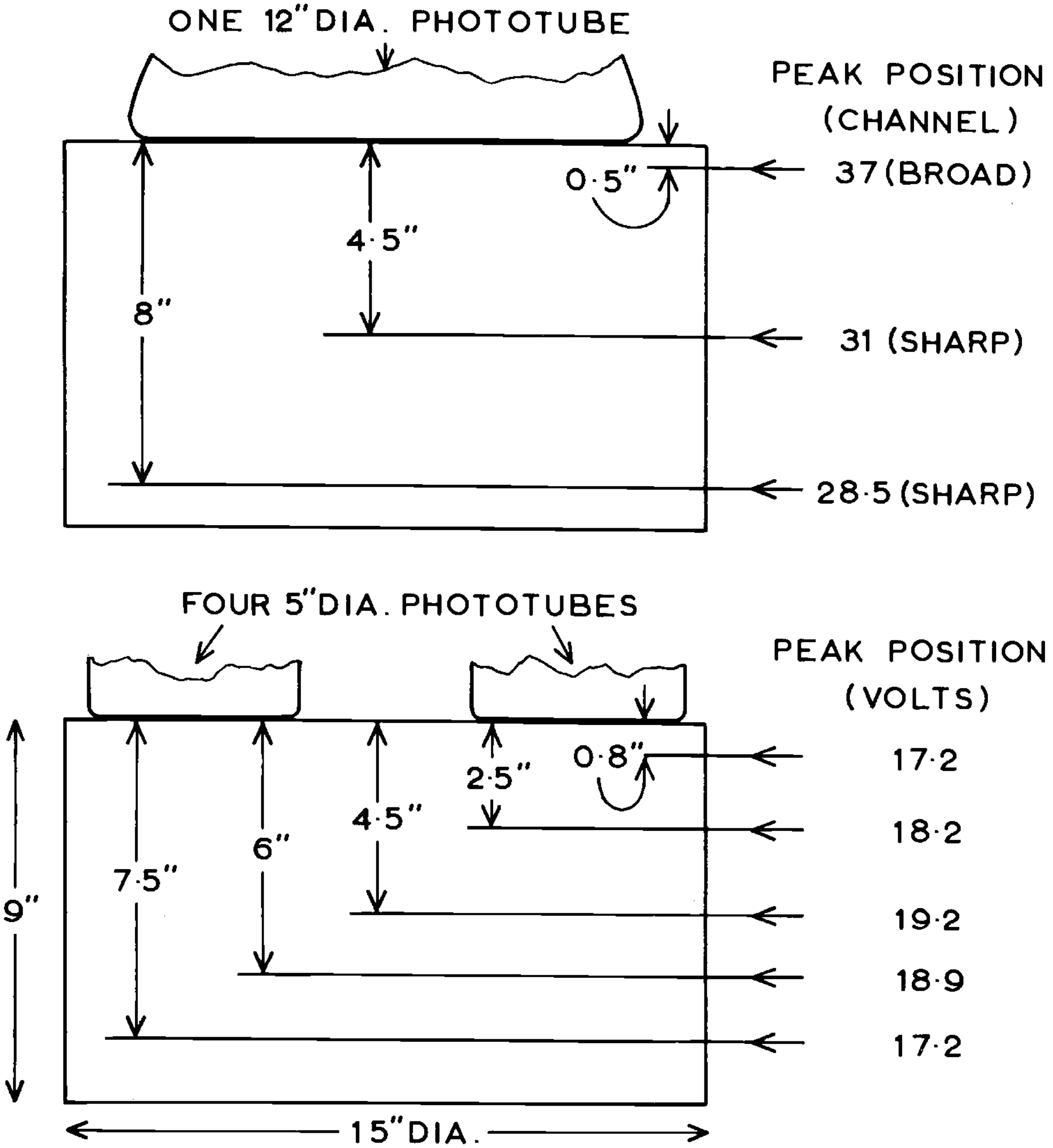

Fig. 1. Variation in peak amplitude with position (indicated by arrows) of collimated beam of Co-60 gamma rays 15 in. dia. x 9 in. thick NE102 plastic scintillator viewed by (i) a single 12 in. dia. photomultiplier, and (ii) four, 5 in. dia. photomultipliers. The beam was fired through the central axis of the scintillator and parallel to the surface of the photocathodes.

approximately half-way down the axis of the scintillator; there is an approximately symmetrical fall-off on either side of this point.

The non-uniformity of the photocathode response of the 12 in. photomultiplier is illustrated more directly in Fig. 2. When the collimated beam is fired along the central axis of the 3 in. thick scintillator, the ratio of large- to small-pulse events is much greater than when the beam is fired near to the edge of the scintillator.

In view of these non-uniformity factors with the single large photomultiplier, it might be expected that their effect would be diminished by the use of light guides, despite the fact that light losses would thereby be introduced. Table 3 shows that this expectation is realised.

There is a progressive improvement in spectral resolution as we proceed from no light-guide, through 3 in. to the 6 in. light-guide. Under the last condition, the single 12 in. tube (with an effective photo-cathode area of 82 in.^{2} and a photocathode sensitivity of about 30 μA/L) out-performs three 5 in. diameter tubes (with a combined effective photocathode area of 42 in.^{2} and average photocathode sensitivities of about 50 μA/L).

None of the results obtained with 15 in. diameter cylindrical blocks rival the best obtained with the original 20 in. x 10 in. x 6½ in. NE101 block. However the results reported originally with this scintillator were too optimistic due to some non-linearity in the pulse-amplifier, kicksorter combination and the half-resolution reported (1) as 14.5% should in fact have been about 17.5%

Several photomultiplier types have now been tested on this scintillator and the results are shown in Table 4.

The best results obtained so far have been given by Twentieth Century 7 in. diameter photomultipliers, without light guides. In this case, the use of a 3 in. thick truncated-cone light guide worsens the performance, indicating that any gain in uniformity of illumination is more than offset by light losses. Spectra obtained with this combination are shown in Fig. 3.

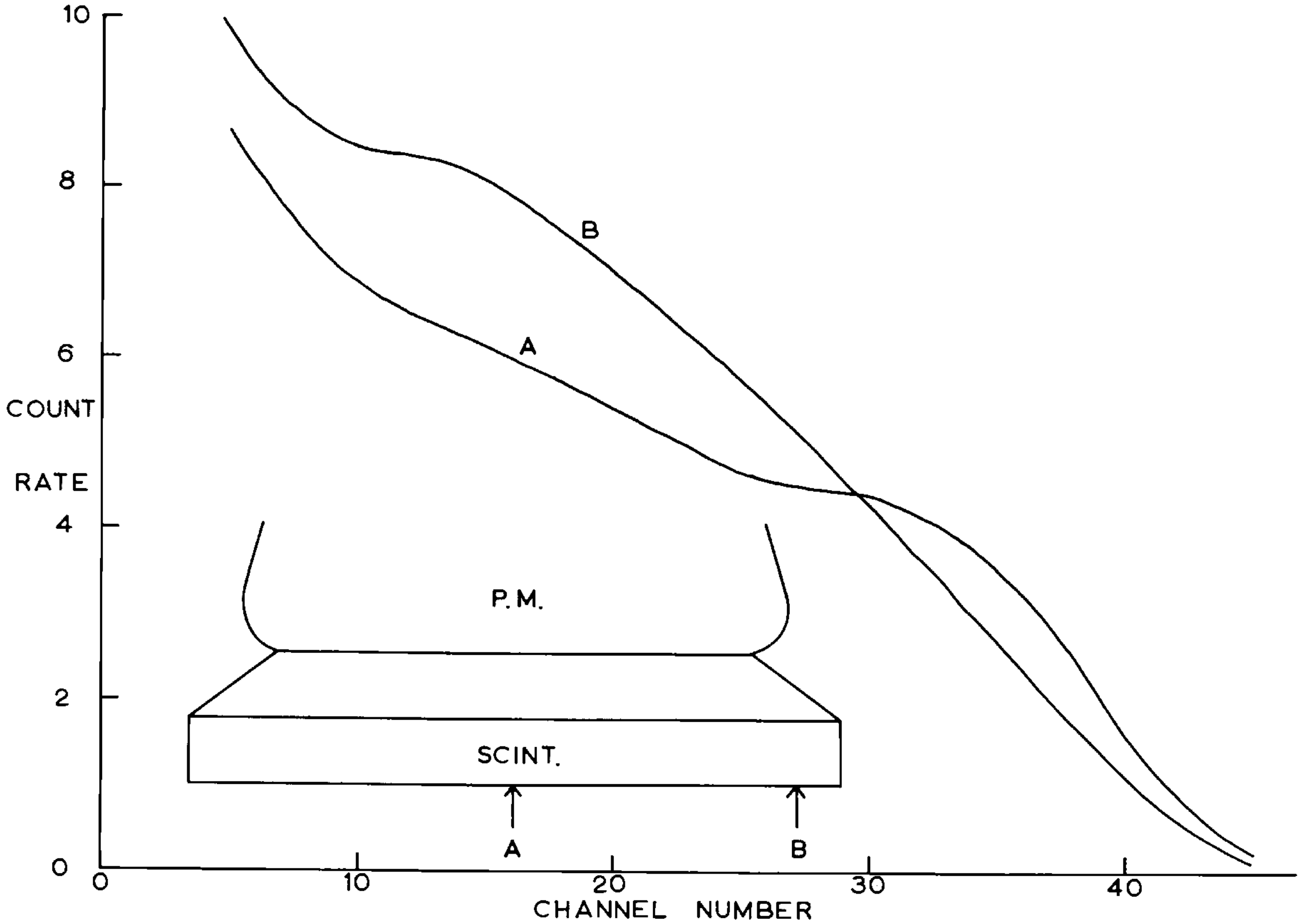

Fig. 2. Spectra from collimated beam of Co^{60} gamma rays fired (a) along the central axis of the scintillator, and (b) parallel to the central axis, but 1 in. from the edge. 15 in. dia. x 3 in. thick NE101 plastic scintillator, 12 in. dia. EMI type 9545 photomultiplier.

Table 3.

EFFECT OF LIGHT GUIDES ON PERFORMANCE OF CYLINDRICAL NE101

PLASTIC SCINTILLATOR 15" DIA. X 6" THICK

Light Guide	Photomultiplier(s)	Gamma-ray Source	Peak/ Trough	Half - Resolution %
None	One EMI 12" dia. Type 9545	K^{40} Cs^{137}	1.3	31 34
3" Truncated Cone	"	K^{40} Cs^{137}	- 1.15	27 30
6" Truncated Cone	"	K^{40} Cs^{137}	1.5 1.3	21 30
" "	One EMI 5" dia. Type 6009	K^{40} Cs^{137}	1.02 1.04	29 39
" "	Three 5" dia.	K^{40} Cs^{137}	1.35 1.13	25.6 34.7

Table 4

RESOLUTION OF 20" x 10" x 6½" THICK, OVAL NE101 PLASTIC SCINTILLATOR

Photomultipliers and Light Guides	Gamma-Ray Source	Peak/Trough	Half-Resolution %
2 x EMI 6009A 5" dia.	K^{40} Cs^{137}	1.75 1.24	18.5 31.2
2 x EMI 9530A 5" dia.	K^{40} Cs^{137} Th (2.62 Mev)	1.91 1.46 -	17.4 26 13.4
2 x EMI 10" dia. exptl. with app. 3" Light Guides	K^{40} Cs^{137} Th (2.62 Mev)	1.80 1.40 1.79	17.3 32.3 16.9
2 x Twentieth Century 7" dia. 3" Light Guides	K^{40} Cs^{137} Th (2.62 Mev)	1.90 1.36 1.93	15.6 28.1 11.8
2 x Twentieth Century 7" dia. no Light Guides	K^{40} Cs^{137} Th (2.62 Mev)	2.13 1.56 2.12	13.1 28.2 10.4

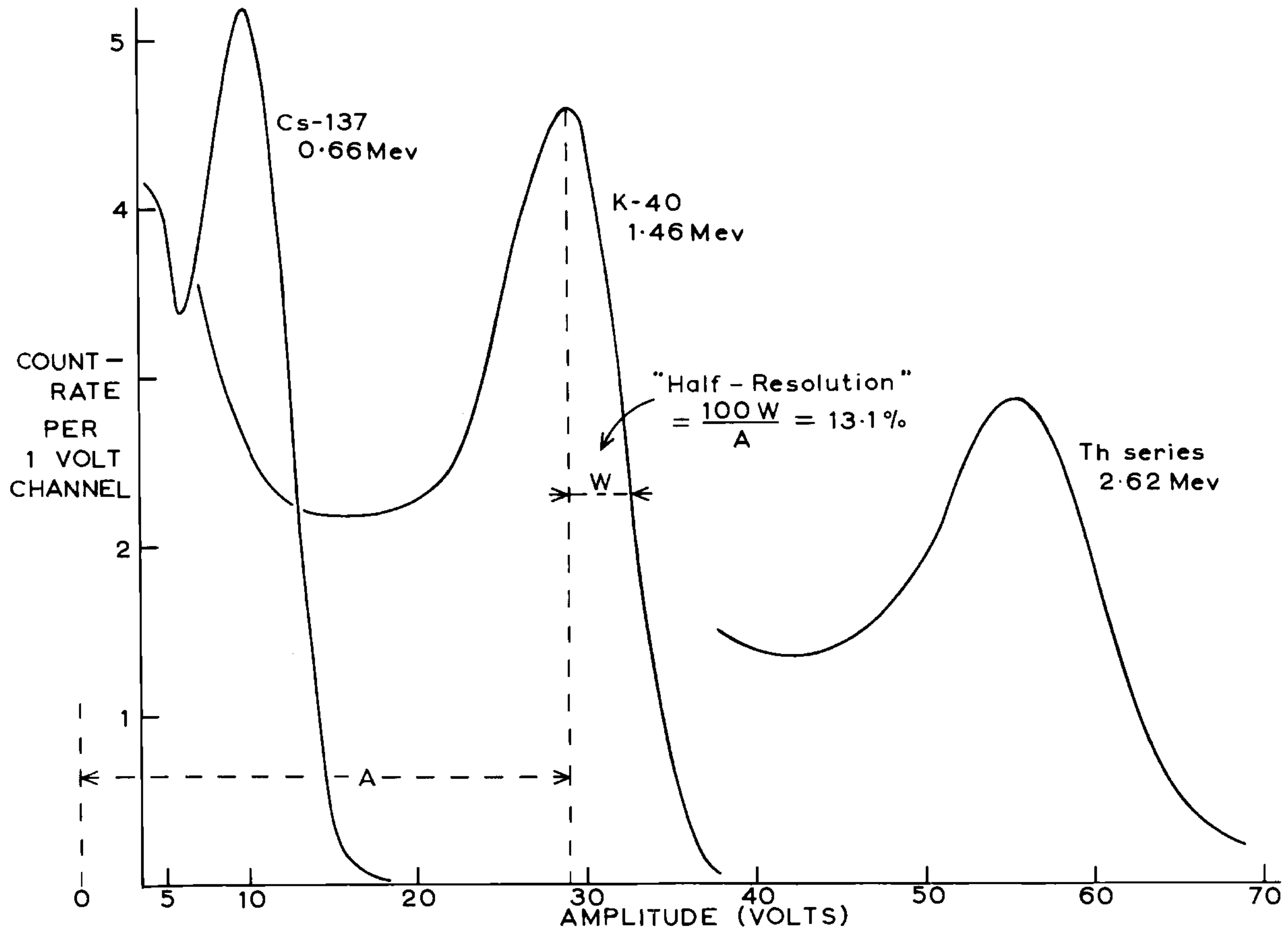

Fig. 3. Gamma ray spectra obtained with NE101, 20 in. x 10 in. x 6-1/2 in. plastic scintillator, viewed by two Twentieth Century 7 in. dia. photomultipliers.

Conclusions Regarding Spectral Resolution.

Apart from obvious factors such as photocathode sensitivity and the ratio of photocathode area to the surface area of the scintillator, the resolution of large volume units depends on geometrical factors arising from two distinct causes, (a) macroscopic non-uniformities in the photocathode response and (b) light-transmission losses within the scintillator itself. (Since in all these experiments either heavily smoked magnesium oxide or packed magnesium carbonate reflectors were used, light was lost mainly through internal absorption in the scintillator.)

When the sensitivity of the peripheral area of the photocathode is appreciably lower than that of the central area, light guides improve the performance, but when such differential sensitivity is less marked, light guides produce deterioration because any gain in the uniformity of illumination of the photocathode is more than offset by light losses. From our experience with existing photomultipliers it seems likely that light guides will be advantageous only when the photocathode diameter is somewhat greater than 7 inches.

Because of light transmission losses, thick scintillators of a given cross-section give a poorer half-resolution than thin scintillators of the same cross-section. Thin scintillators suffer, however, from a double disadvantage. Firstly, fewer gamma-rays will be detected and secondly, the peak/trough ratio is poor. Part of the second disadvantage arises from non-uniformities in the photo-cathode response, but another factor is the decrease of multiple Compton interactions between scattered gamma-rays and the scintillator. (If a mono-energetic gamma-ray source was completely surrounded by a very thick spherical shell scintillator, the energy from every gamma-ray would be totally absorbed, and if perfect light-collection could be attained, a nearly monochromatic spectrum - with an infinite peak/trough ratio- would be recorded.)

There is a conflict of requirements therefore, and until perfectly transparent and uniform scintillators, perfect reflectors, and perfectly uniform photocathodes become available, some kind of compromise has to be made. The best compromise unit we have found for our requirements is based on the 20 in. x 10 in. x 6½ in. NE101 scintillator with two 7 in. diameter Twentieth Century photomultipliers and no light guides.

Counting Statistics with A 3-Unit Apparatus.

A three-unit (20 in. x 10 in. x 6½ in.). apparatus will shortly be installed in a new shield. Some preliminary results have been obtained in the original steel room (1). Two units are located at the back of the seated patient; the third, adjustable and pivoted from the floor, is placed opposite the chest (Fig. 4). So far only one unit has been fitted with 7 in. diameter photomultipliers, the other two having 5 in. diameter tubes; the counting statistics obtained with this arrangement are set out in Table 5.

Table 5

WHOLE BODY GAMMA-RAY COUNTING STATISTICS WITH

3-UNIT (20 IN. X 10 IN. X 6½ IN. NE101) PLASTIC

SCINTILLATOR APPARATUS. PRELIMINARY RESULTS.

Radiation Source		Typical Count-Rate Counts/Sec.
150 g Potassium in body	in "K^{40} region" *	20
Background		36
10^{-9}c Cs^{137} in body	in "Cs^{137} region" +	2
Background		70
Contribution in "Cs^{137} region" from 150 g potassium.		15

* From 0.8 to 1.8 Mev (K^{40} Compton edge at 1.24 Mev).

\+ From 0.25 to 0.73 Mev (Cs^{137} Compton edge at 0.48).

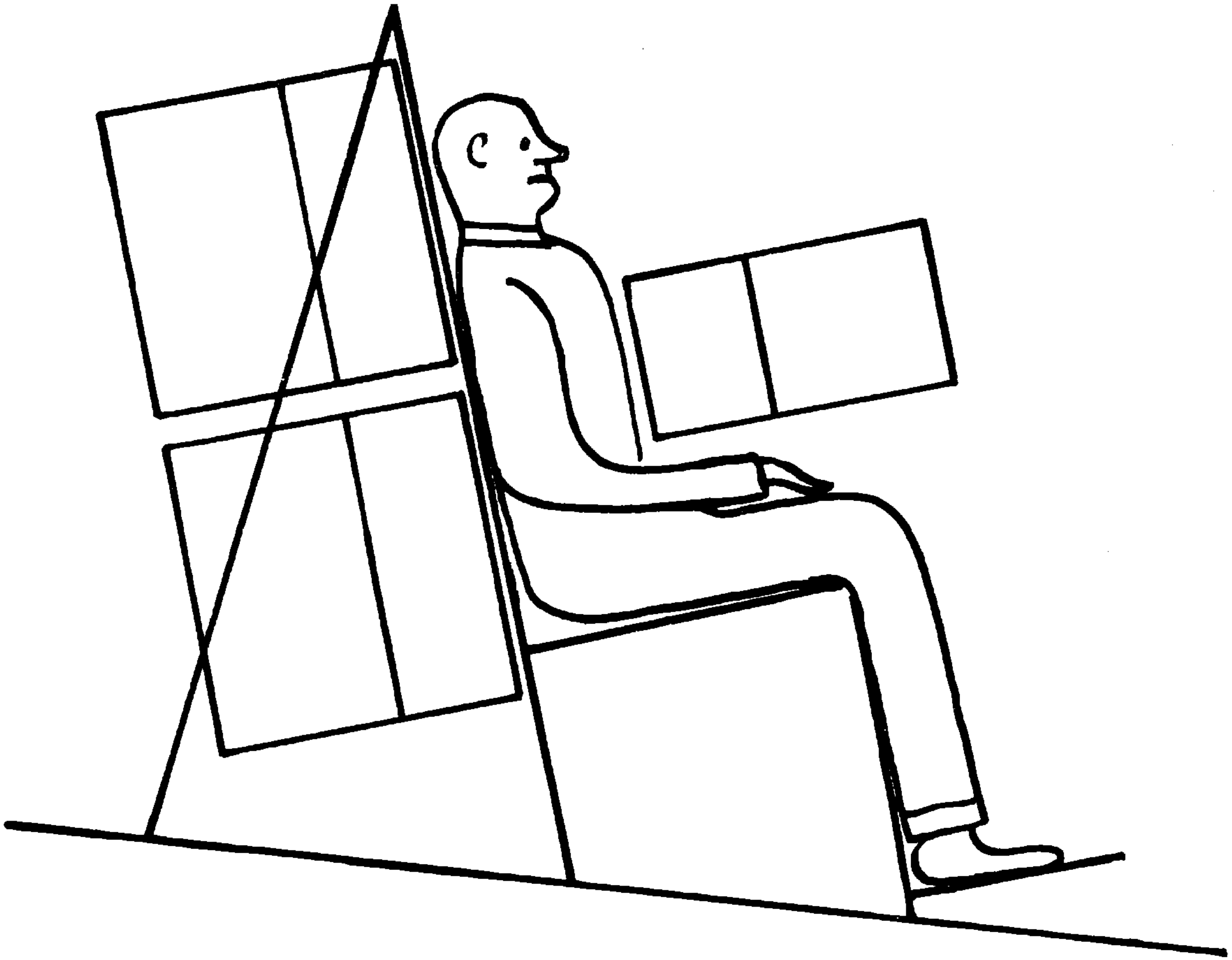

Fig. 4. Arrangement of three 20 x 10 x 6-1/2 in. plastic scintillator units with respect to seated patient.

From the above table it can be deduced that the counting statistics of a natural potassium determination consisting of one 15 min. patient measurement sandwiched between two 15 min. background observations, will give a standard error of just over ± 1%. Alternatively if a fairly stable and frequently determined background can be assumed, the corresponding standard error for a 200 sec. determination of natural body potassium will be ± 3 to 4%. These statistical errors are only slightly inferior to those (± 3% in 2 min.) given by the much larger (nearly 4π) Los Alamos liquid scintillator human counter (2).

For a 15 min. determination of the Cs^{137} content of the body, the counting statistics component of the standard error will be equivalent to approximately $\pm (2 \times 10^{-10})c$; errors of interpretation will however generally be larger than this.

Acknowledgments.

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References

(1) P.R.J. Burch and P.M. Bird, "Liquid Scintillation Counting", p.274, Pergamon Press, New York, London, 1958.

(2) E.C. Anderson and M.A. Van Dilla, I.R.E. Trans. Professional Group on Nuclear Science, Vol. NS-5 No. 3, 194 (1958).