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ABSTRACT

The Health Physics Department of the Lawrence Radiation Laboratory, University of California, Berkeley, California, is engaged in a continuing study of fallout and natural background radiation in the San Francisco Bay area. Portable scintillometers are used to gather data. The gamma-ray response of the scintillometers is compared with the response of an integrating ion chamber over an energy range of approximately 1.5 MeV starting at 0.12 MeV.

The results verify the theoretical assumption that the scintillometer response is proportional to the number of γ-ray photons, whereas the ion-chamber response is a measure of the dose, i.e., proportional to the energy of the γ rays as well as to the quantity of the incident gammas. Additional results also demonstrate the validity of using a radium source for calibration of the instruments used for natural background measurements.

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I. INTRODUCTION

The Health Physics Department of the Lawrence Radiation Laboratory, University of California, Berkeley, California, is engaged in a continuing study of fallout and natural background radiation in the San Francisco Bay area.[1] One of the instruments used to gather data for this survey is a portable scintillometer. It is desirable to know the response of this instrument as a function of the incident γ-ray energy. To determine the energy dependence of the response, it was decided to compare the response of the scintillometer with that of an ion chamber. The object of this report is to present the method of solution of this problem and the results obtained.

II. EQUIPMENT

The scintillometer consists of a transistorized portable counting-rate meter designed and built at LRL.[2] This is connected to a scintillation probe consisting of a NaI(Tl) crystal 3 in. long by 3 in. in diameter viewed by a Du Mont 6363 phototube, which provides the output to drive the counting-rate meter. The phototube and crystal are enclosed in a stainless steel case. Three of these units were tested. For purposes of comparison an LRL-built integrating ion chamber was used initially, then a Cary Model 35 vibrating-reed electrometer was used as an integrating ion chamber. The ion chambers themselves are of the air-equivalent type and consist of polyethylene or polystyrene containers with a conducting inner coating of "Aquadag."

A. Calibration

The scintillometers were calibrated by using NBS-calibrated radium sources of 1.35 mg, 0.100 mg, and 0.0100 mg. Preliminary adjustments of high voltage, gain, and discriminator were made with a noncalibrated refined uranium source. The uranium source was chosen for the steep slope of its γ spectrum which facilitated the attainment of desired counting rates through the electronic-circuit adjustments previously mentioned. See Fig. 1. For example, a small change in the high voltage applied to the phototube resulted in a comparatively large change in the uranium counting rate relative to the counting rate from the standard radium source, for which the γ spectrum slope is much less steep. See Fig. 2. The scintillometer system was adjusted to near-maximum sensitivity for the radium source. Discriminator settings were approx 0.100 MeV.

The LRL-built integrating ion chamber was used as a standard for comparing and calibrating the Cary Model 35 vibrating-reed electrometer for use as an integrating ion chamber. The LRL ion chamber was checked first with the NBS radium sources and then used as a checking instrument when the Cary Model 35 was calibrated. From this point on, the Cary Model 35 was used as a standard for comparison with the scintillometers. Its calibration was checked daily for consistency by using the calibrated radium sources.

Each of the instruments used was also checked for inverse-square deviation, and no objectionable amount of deviation was detected.

III. GAMMA-RAY SOURCES

The energy range under consideration is from approx 0.1 MeV to approx 1.50 MeV. Ideally the source should be a monoenergetic γ emitter that does not produce either annihilation radiation through positron emission or strong β emissions. Because of the stainless steel case, which is 1/16 in. thick, surrounding the crystal and photomultiplier, β's of an energy below 2.5 MeV are effectively excluded from the detector, although bremsstrahlung from some of the more energetic β's can be detected.

The ion chamber is, for all practical purposes, also independent of the β radiation of the selected sources. The polyethylene walls are slightly more than 0.10 cm thick. The highest-energy β emitted in quantity is from Cs^{137} and has an energy of 0.51 MeV. From the equations, $I/I_0 = e^{-\mu x}$ and $\mu = 16\,E_{max}^{-1.6}$,[3] where E_{max} is the maximum energy of the β, μ is the absorption coefficient, x is the absorber thickness, e is the base of the natural logarithms, I_0 is the incident radiation flux, and I is the flux after absorption, it can be calculated that the flux after absorption is less than 1% of the initial

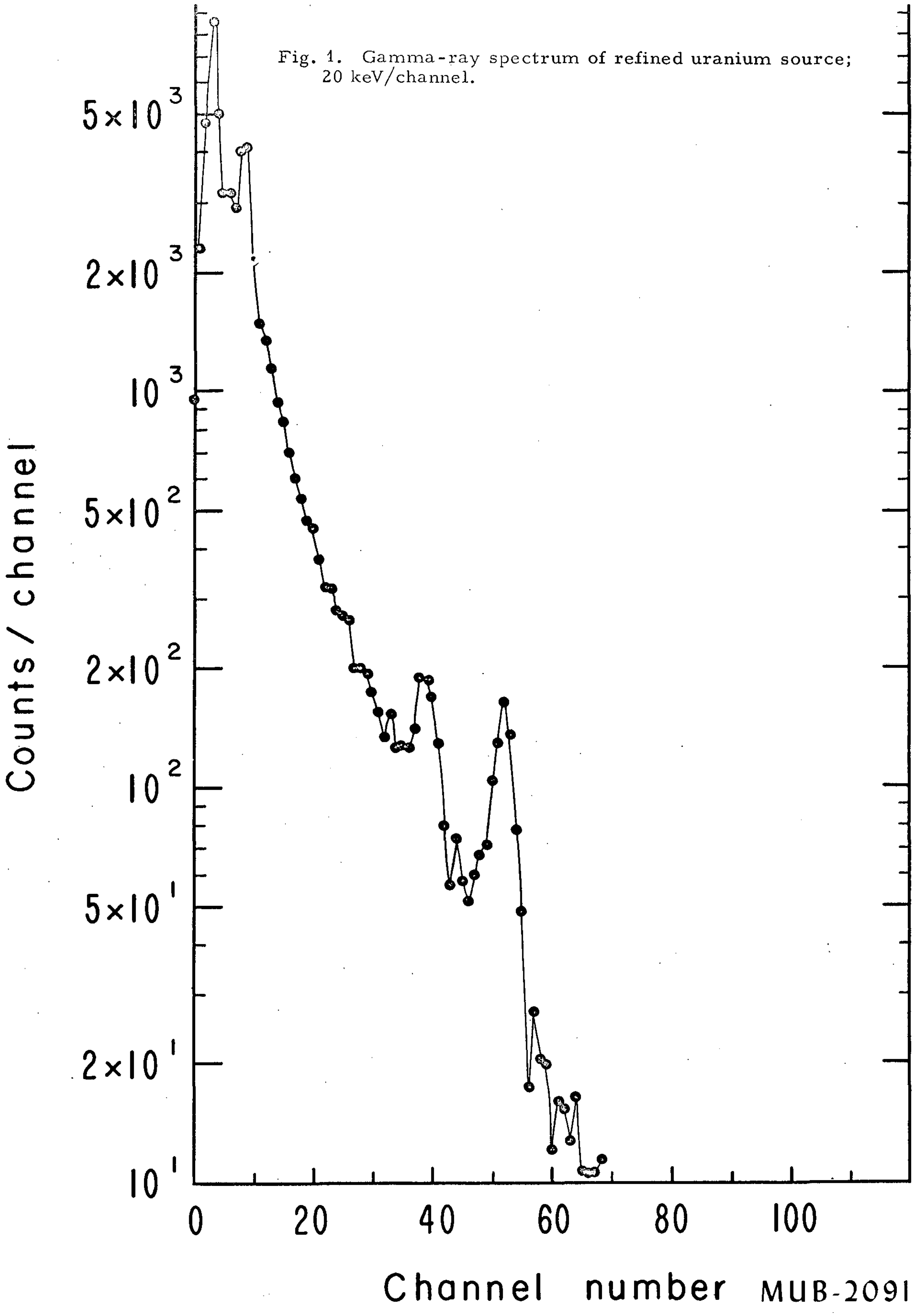

Fig. 1. Gamma-ray spectrum of refined uranium source; 20 keV/channel.

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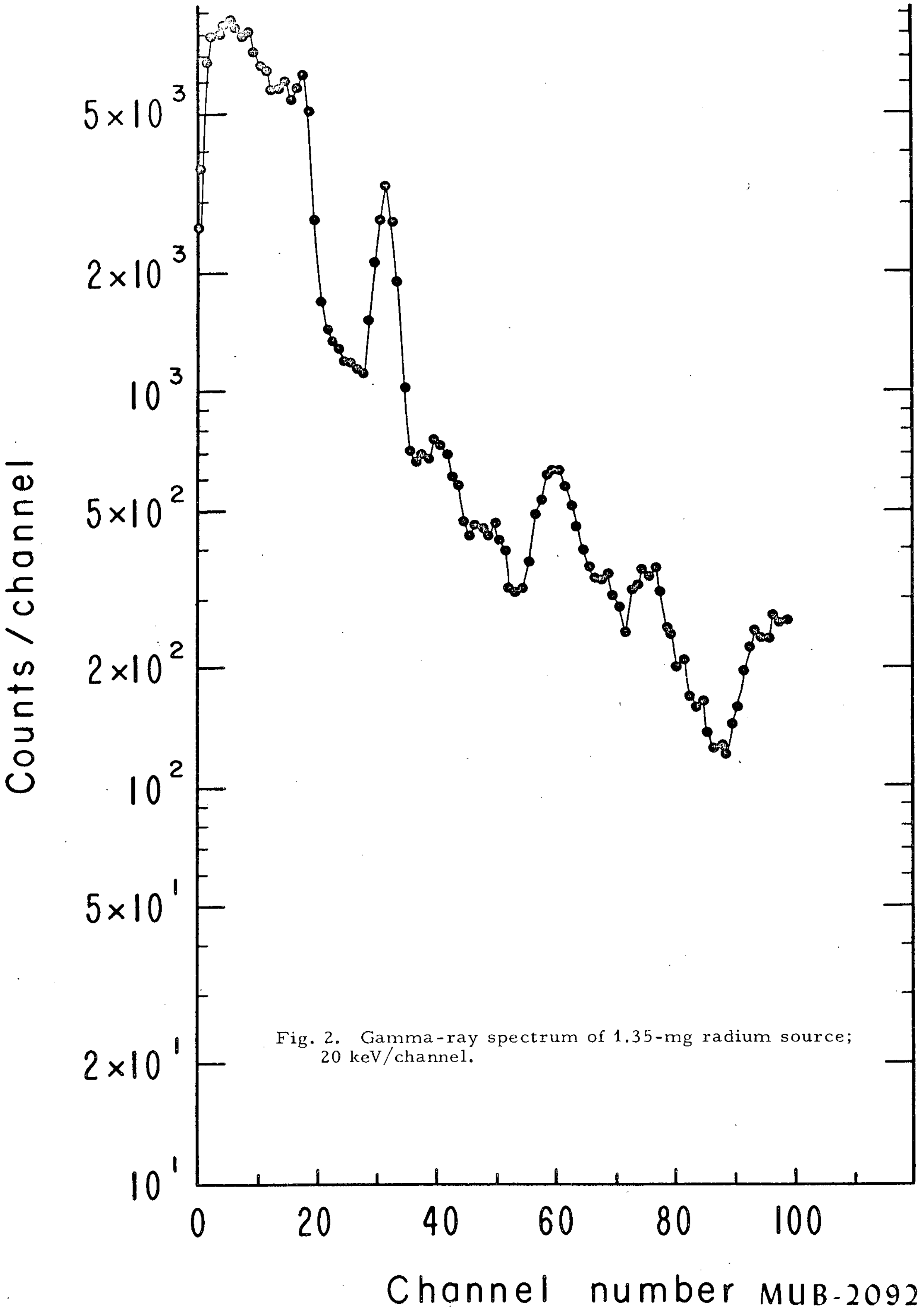

Fig. 2. Gamma-ray spectrum of 1.35-mg radium source; 20 keV/channel.

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flux ($I/I_0 < 1\%$) for the maximum-energy β through 0.10 cm of polyethylene. Air absorption causes a further reduction in the number of β's entering the chamber.

Table I lists the sources selected and some characteristics of these sources. Each of these sources except Co^{60} is, for the purposes of this experiment, a monoenergetic γ emitter. The γ's from Co^{60} are coincidence γ's, and the average of their energies is used throughout the rest of the procedure. Three of the sources, Hg^{203}, Cs^{137}, and Co^{60}, also give off β's, but these are well below the 2.5-MeV shielding limit of the stainless steel case of the scintillometers and, as previously mentioned, are not sufficiently energetic to appreciably affect the ion chamber. The other three sources undergo electron capture (E.C.), which results in a stable isotope after the γ emission. The half-lives are of a reasonable duration. Because of the difficulty of obtaining monoenergetic γ emitters with a reasonably long half-life with energies greater than that of Co^{60}, it was decided to limit the maximum energy in this investigation to that of Co^{60}.

To check the radiochemical purity of the sources, one of the portable crystals was used in connection with a 400-channel pulse-height analyzer (Victoreen Model ST 400 UC). From the spectra obtained, high radiochemical purity was verified.

Table I. Characteristics of γ-ray sources.

Source	γ energy (MeV)	Half-life	Decay scheme
Co^{57}	0.12	270 days	$Co^{57} \xrightarrow{E.C.} Fe^{57} + \gamma$
Hg^{203}	0.28	45 days	$Hg^{203} \longrightarrow Tl^{203} + e^- + \gamma$
Sr^{85}	0.51	64 days	$Sr^{85} \xrightarrow{E.C.} Rb^{85} + \gamma$
Cs^{137}	0.66	33 yr	$Cs^{137} \longrightarrow Ba^{137} + e^- + \gamma$
Mn^{54}	0.84	310 days	$Mn^{54} \xrightarrow{E.C.} Cr^{54} + \gamma$
Co^{60}	1.17 and 1.33	5.2 yr	$Co^{60} \longrightarrow Ni^{60} + e^- + 2\gamma$

IV. PROCEDURE

In order to approximate field conditions under which the portable scintillometers are often used, all calibration procedures were performed outside and sufficiently far away from buildings to minimize backscattering. Both the sources and detectors were located 1 m above ground level. The sources were all in liquid form, contained in small sealed bottles such that the source in equilibrium with its vapor did not exceed 10 cm^3 in volume. The strength of each source is approx 1 mCi. Both the scintillometers and ion chamber were placed at 60 cm from the various sources, and the counting-rate meter readings were noted and recorded. A stop watch was used to accurately time the integrating ion chamber to full-scale reading. At 60 cm the source approximates a point source. However, because the Cs^{137} and the Co^{60} have activities in excess of 1 mCi, counting rates in excess of 50, 000 counts/sec were obtained at 60 cm with these two sources. This exceeds the maximum range of the counting-rate meters. Therefore, the procedure was repeated at 80 cm, 1.00 m, 1.50 m, and 2.00 m with all six sources in order to collect ample data and reduce, somewhat, any statistical errors.

V. ANALYSIS OF DATA

Following the exposure to the six sources at the various distances, all readings were converted into mR/h in terms of the previous radium calibration after they were corrected for background. The background indicated by the scintillometers was approx 5 μR/h (200 counts/sec), whereas the ion chamber indicated 18 μR/h. These two values can be partially reconciled by adding to the crystal background 4 μR/h from cosmic rays that the crystal does not indicate. Even with this correction the ion chamber is too high by a factor of 2 when compared with the crystal detector. This may be caused by the β response of the ion chamber to the natural background, or by some inherent drift or leakage in the ion-chamber circuitry.

This was followed by a calculation of the "efficiency" of the scintillometers, which is defined as

$$\text{eff.} = \frac{\text{scintillometer (mR/h)}}{\text{ion chamber (mR/h)}} .$$

It is assumed at this point that the response of the ion chamber is independent of the energy of the incident radiation for the particular range of energies under investigation.[4] Even if this is not the case, the definition of efficiency agrees with the purpose of this experiment, i.e., to obtain a comparison between the scintillometer response and the ion-chamber response.

The efficiency, averaged over the various distances, was then plotted as a function of γ energy. See Fig. 3. All three portable scintillometers have similar efficiency curves. The graph shows that the efficiency for the lowest-energy γ ray exceeds the efficiency for the highest-energy γ ray by a factor of approx 4.5. This may be partially explained by a second curve also shown on Fig. 3. This is a plot of the relative number of photons/cm^{2}sec equivalent to 1 R/h as a function of energy.[5] The two curves parallel each other closely except at the low-energy end, where the stainless steel case of the crystal shows its effect most strongly.

It was then decided to try to adjust the response of the portable system by the addition of a suitable filter.

VI. FILTERING PROCEDURE

The initial filter used was 1/16 in. of lead covering the stainless steel cylinder completely to a distance of 6 in. beyond the crystal and covering the crystal face at the end of the can opposite the handle. The assembly was again exposed to the six sources at the various distances. The resulting efficiency curve is best shown in Fig. 4.

From this graph it is apparent that this thickness of lead is for all experimental purposes filtering out the 0.12-MeV γ ray. It was then decided to drill some holes in the lead shield covering the face of the crystal that faces the sources. Approximately 15% of the lead was removed by drilling 60 holes of 1/4-in. diam. Again the detector was exposed to the sources at the various distances. The efficiency results are shown in Fig. 5.

The response is considerably smoothed, as illustrated in Fig. 5, which indicates that the ratio of maximum efficiency to minimum efficiency is reduced to a value near 2, in contrast to a factor of 4.25 shown in Fig. 3; nevertheless it appeared that a further smoothing could be obtained with thicker shielding containing the same number of holes as did the previous shielding. Essentially, less than 10% of the 0.12-MeV γ rays penetrate the

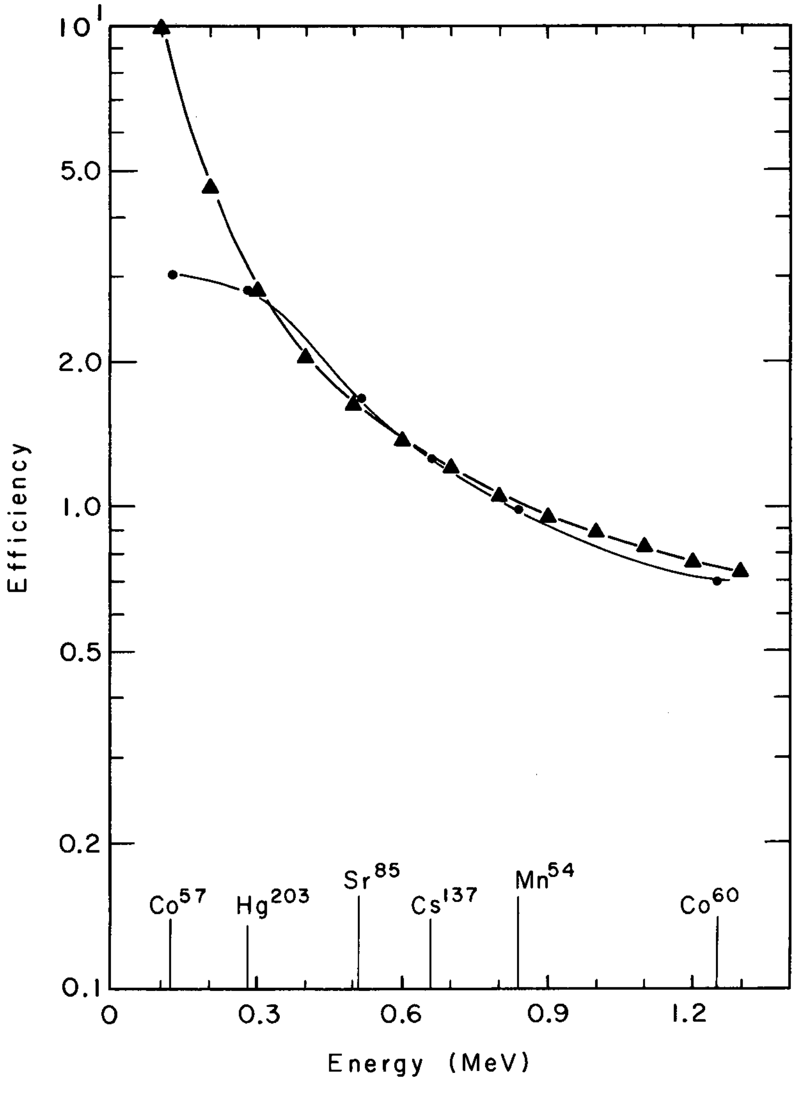

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Fig. 3. o — Sodium iodide crystal efficiency as a function of incident gamma energy. Δ — Relative number of photons/cm^2 sec equivalent to 1 R/h.

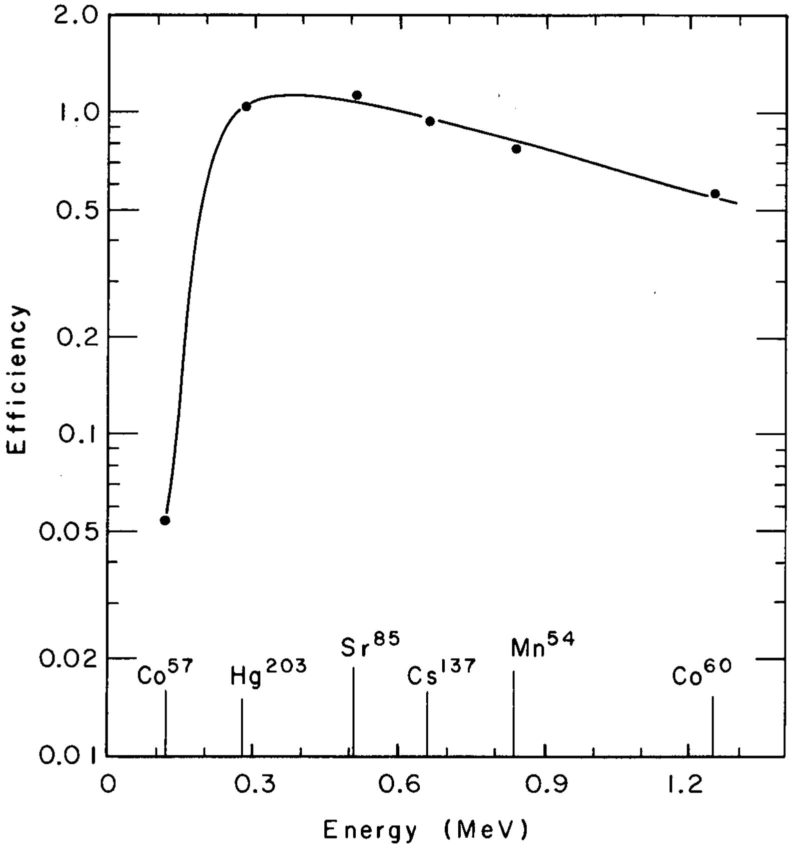

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Fig. 4. Sodium iodide crystal efficiency; 1/16-in. lead filter.

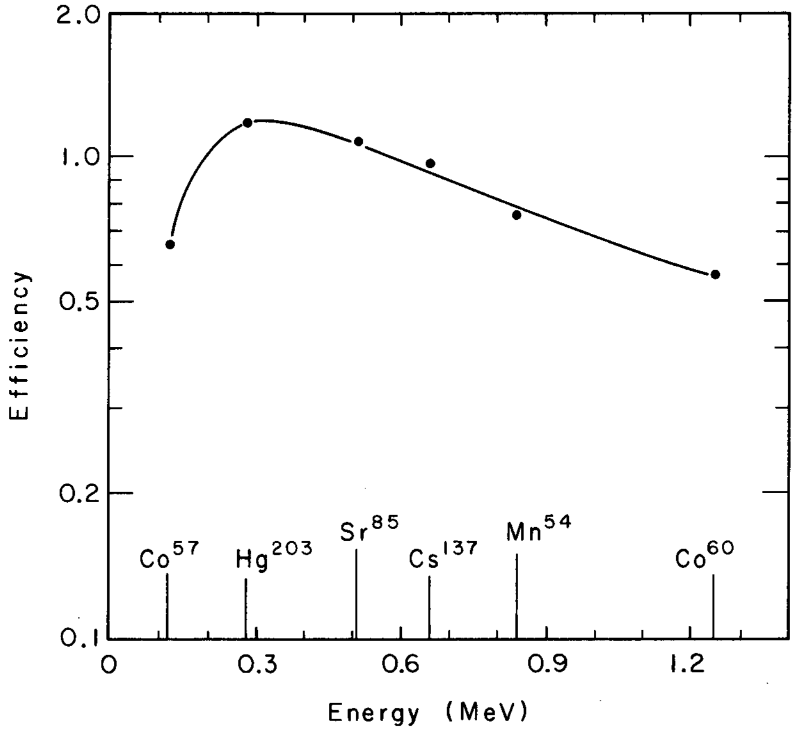

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Fig. 5. Sodium iodide crystal efficiency; 1/16-in. lead filter with 15% of the lead removed from the face of the filter.

thinner shield unless it contains holes. Therefore, if the number of holes remained constant the response to the 0.12-MeV γ (or lower energies) would be nearly independent of the thickness of the lead in excess of 1/16 in., while at the same time the response to the other γ rays would be dependent on shield thickness. The thickness of the shield was therefore increased to 1/8 in. of lead, with the same number and size of holes drilled in the shield on the end facing the source. The detectors were again exposed to the sources at the various distances. The results are shown in Fig. 6. The ratio of maximum efficiency to minimum efficiency is now approx 1.75. This response is considered smooth enough for present purposes.

Again, by following the above procedure, the cylindrical portion of the 1/8-in. lead shield was also perforated with 1/4-in. holes in a uniform manner so as to remove approx 15% of the lead. The response to the standard radium sources and the six other sources with and without the shield was then checked. The response to the natural background was also measured with and without the shield. This was done in order to determine if the reduction in response caused by the shield was in the same proportion for both the standard radium source and the natural background. The results, averaged over the various distances and expressed in terms of a "reduction factor" defined as

$$\frac{\text{mR/h without lead filter}}{\text{mR/h with lead filter}},$$

are shown in Fig. 7. The reduction factor for the radium sources is found to be approx 1.6, which places the effective energy of the radium near 0.55 MeV. Natural background, on the other hand, was reduced by a factor of approx 2.5 and gave an indicated effective energy of about 0.38 MeV. These reduction factors differ by less than a factor of 2, which leads to the conclusion that the radium sources are reasonably suitable for calibration of instruments that will be used for the measurement of natural background radiation.

With holes punched in the entire filter, a slight increase in the overall efficiency is obtained without appreciable change in the ratio of maximum efficiency to minimum efficiency. Figure 8 shows this response, and the response from Fig. 6 is repeated; together, these show the effect of air scattering and its dependence on the energy of the incident radiation.

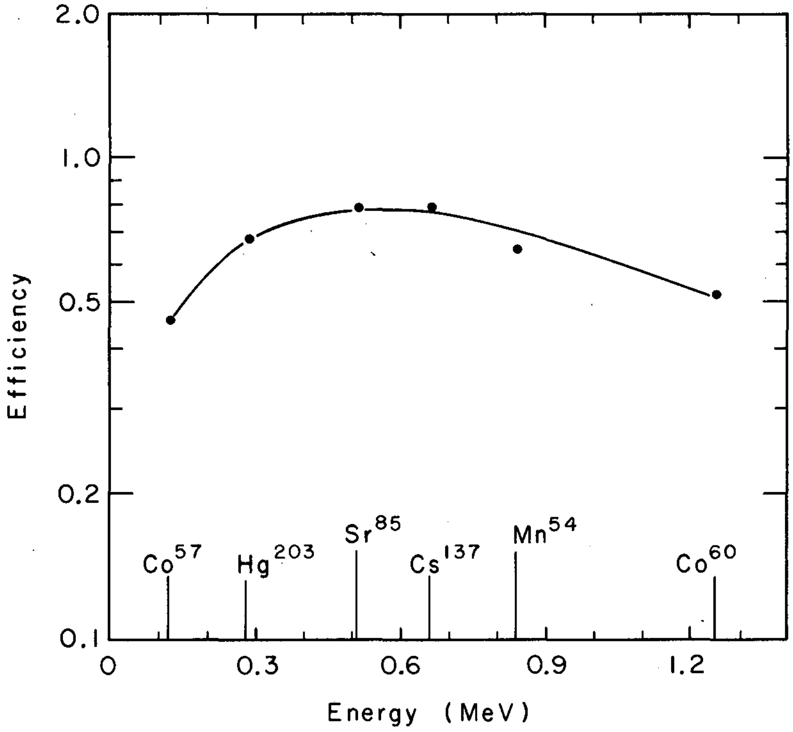

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Fig. 6. Sodium iodide crystal efficiency; 1/8-in. lead filter with 15% of the lead removed from the face of the filter.

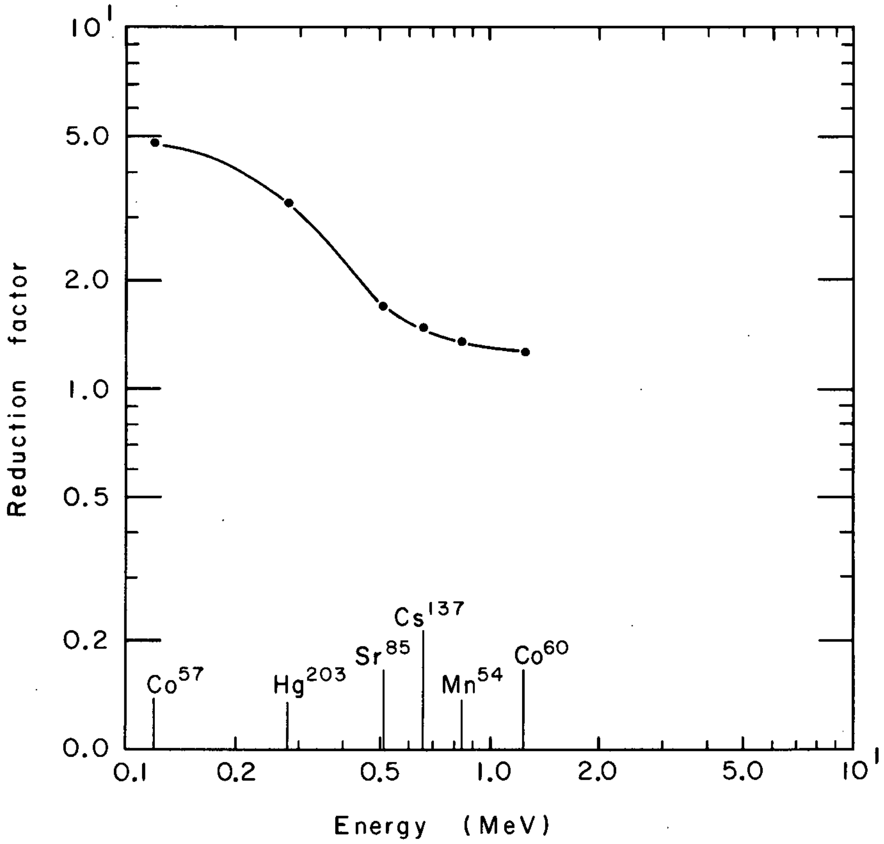

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Fig. 7. Filter reduction factor as a function of energy; 1/8-in. lead filter with 15% of the lead removed from the entire filter.

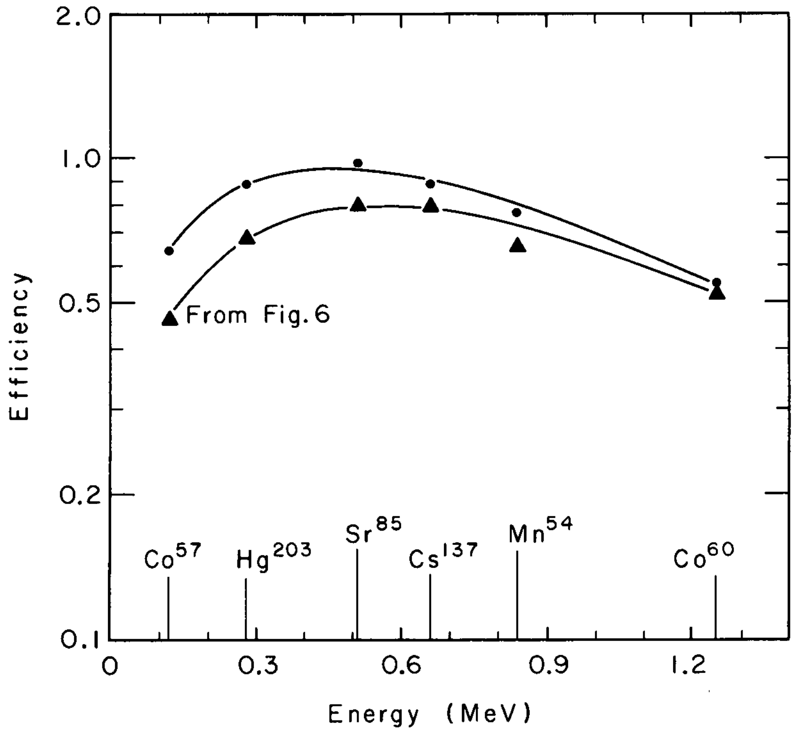

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Fig. 8. o — Sodium iodide crystal efficiency. 1/8-in. lead filter with 15% of the lead removed from the entire filter. △ — Graph from Fig. 6 repeated.

A. Summary of Filtering Effects

In conducting field surveys the amount of low-energy gammas (up to 0.2 MeV) present may be determined by the addition of a 1/16-in. lead filter containing no holes. If these low energies are a prime contributor to the total count rate, a sharp decrease should be observed immediately on the counting-rate meter. Once the presence of relatively large quantities of these low-energy gammas is ascertained, the response of the system may be smoothed by the addition of the 1/8-in. lead filter containing uniformly spaced holes (which have removed approx 15% of the lead).

VII. BACKGROUND SIMULATION

To determine further if the detector response to the natural background was similar to the response to the radium source used in calibration, it was decided that the radium-source spectrum could be made to resemble the background spectrum more closely by shielding the radium source with varying thicknesses of lead. This has the effect of lowering the intensity of the direct lower-energy components and causes the crystal to be exposed to more scattered radiation than would result from an unshielded source. This approximates the field conditions for which natural background radiation or radiation from fallout is spread over an extended plane, and much of the radiation responsible for the scintillometer response is well scattered. The efficiency was again determined both with and without the perforated 1/8-in. lead shield on the crystal; the lead surrounding the source was 1/8, 1/4, 3/8, and 1-1/4 in. thick. The results are shown in Fig. 9. This shows that the efficiencies of the shielded source and the unshielded source differ at most by 25%; the maximum decrease is for 1.25 in. lead. At this thickness of lead the source radiation should resemble that of the natural background. The size of variations in the efficiency is small enough to verify that a radium source is a suitable standard for scintillometer calibration, provided the scintillometer is to be used for measuring natural background. If the instrument is to be used for the measurement of a selective and rather narrow range of γ energies, then the appropriate correction in response can be made by referring to Fig. 3. The corrected response equals the counting-rate meter reading multiplied by the reciprocal of the efficiency for the energy under consideration.

VIII. SOURCES OF ERROR

The use of counting-rate meters for scintillometer measurements causes some degree of uncertainty; however, this uncertainty is not considered to exceed 10%. Fluctuations in the background are quite small compared with the counting rates from the various sources. Variations in the high voltage and gain could cause readings of either too high or too low a value, but frequent checks with the radium and uranium calibration sources were made during the course of the data-gathering periods to detect and correct, if necessary, the gain and high-voltage adjustments. Ample warm-up time was always

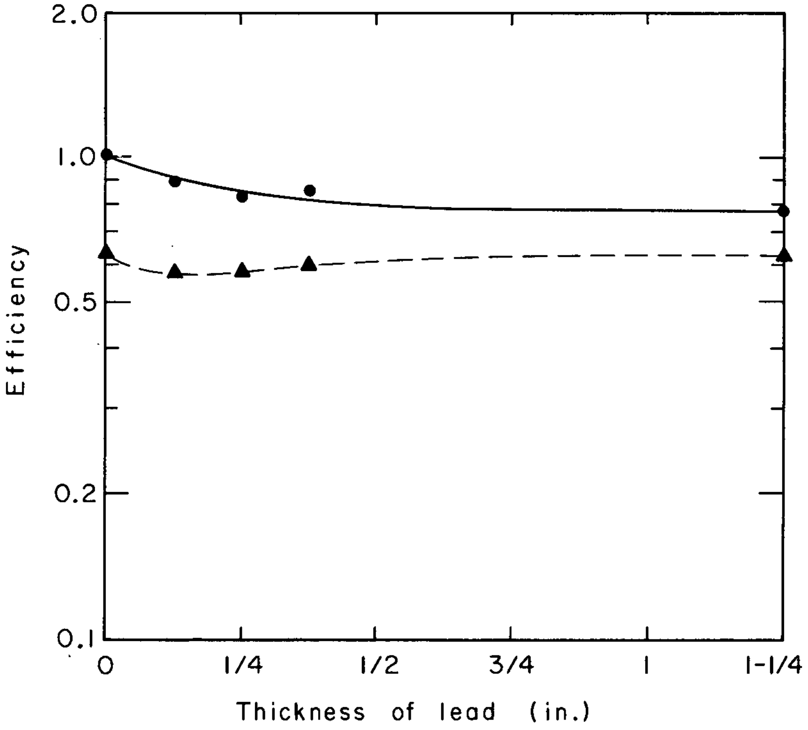

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Fig. 9. Sodium iodide crystal efficiency as a function of source shield thickness: —— no lead filter on detector; - - - with perforated 1/8-in. lead filter on detector.

allowed for both the scintillometer and the ion-chamber instruments even though this should not be necessary in transistorized instruments. Checks for either up-scale or down-scale drift were also performed in a special low-background counting facility at the Health Physics Department.[6]

IX. POSSIBLE FUTURE INVESTIGATION

During the course of the foregoing experiments it was noted that the high-voltage supply to the phototube exhibited sufficient instability to influence the counting rate unless the high voltage was periodically checked and adjusted to the proper value. A member of the Health Physics Department has redesigned and built a new high-voltage supply that may be described as follows: It is a dc-to-dc converter that uses a blocking oscillator technique to develop the required voltages. The output voltage is regulated by using Zener diodes both in the doubler circuit and in the load circuit for coarse voltage adjustments. The new circuit incorporates two important improvements:

(a) The much higher efficiency of the circuit. The oscillator now has a much lower duty cycle than previous models.

(b) The use of Zener diodes. Now the entire converter is quite insensitive to changes in input voltage of the order of ±15%.

This supply was tried in scintillometer No. 2 and found to be without detectable variation. See Fig. 10 for a high-voltage circuit diagram and additional information.

It was also noted that the gain of the amplifier circuit would drift. At present an improved amplifier has been designed and built but has not been tested yet in one of the scintillometers.

It is also possible that part of the circuitry is temperature-dependent to a degree that could cause erroneous readings, particularly under field conditions in which the box containing the electronic components is exposed to full sunlight for extended periods of time. To test this dependence the instrument could be placed in an oven and the response as a function of temperature investigated.

Another possibility for further investigation is the examination of the NaI(Tl) crystal response without the stainless steel case. This might be done in a more precise manner by using a scaler in place of the counting-rate meter. The effect of the discriminator in cutting out a portion of the lower-energy pulses could introduce some incertainty into the present measurements.

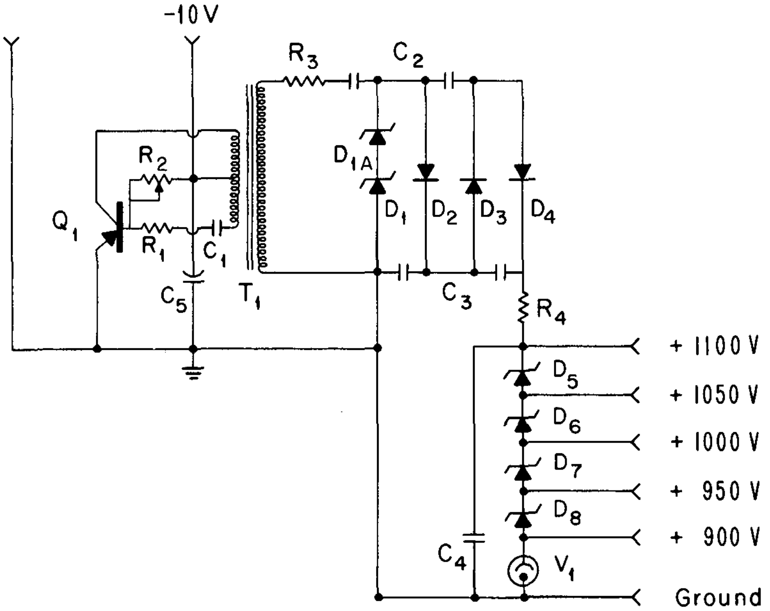

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Fig. 10. Regulated high-voltage power supply for portable scintillation counter. Components: C_1 (1 μF, 15 V); C_2, C_3 (dual 0.005 μF, 600 V); C_4 (0.005 μF, 600 V); C_5 (20 μF, 10 V); D_1 and D_{1A} (1N459A silicon diode, rated 200 piv, selected for a total Zener breakdown voltage of both diodes in series of 580 to 600 V); D_2, D_3, D_4 (1N3255 silicon diode, rated 600 piv); D_5, D_6, D_7, D_8 (1N978B Zener diode, 51 V, 400 mW); Q_1, 2N1305; R_1, 1500Ω, 1/4 W; R_2 (100,000 Ω variable);[a] R_3 (10,000 Ω, 1/4 W); R_4 (1 MΩ, 1/2 W); T_1 (Microtran M-8073); V_1 (Victoreen 5841, 900 V corona regulator).

[a] Adjust R_2 for minimum battery drain to provide adequate regulation with load connected. Set at 47,000 Ω for photomultiplier tube with 240-MΩ voltage divider; battery drain is then about 5 mA.

Perhaps the most basic need for future investigation is examination of the energy dependence of the ion-chamber response. There are good reasons for assuming that its response is independent of incident energy. Any variations in this response can easily be applied to the scintillometers in the form of a correction factor.

X. SUMMARY

In general, when the scintillometer is used to measure radiation fields, especial attention should be given to the energy of the radiation. If the radiation is predominantly scattered low-energy γ rays, then the crystal indicates a field that is too high by as much as a factor of 4. This may be corrected by

(a) selecting the proper filter, and

(b) referring to the efficiency curve and making the appropriate numerical adjustment in relation to the γ-ray energy.

In particular, when the instrument is used in surveys for natural background and fallout, one should determine if there are any predominant low-energy γ rays present by placing the 1/16-in. lead shield over the detector. If the detector response is caused by γ rays of energies near 0.1 MeV, the counting rate should thereupon be reduced by a factor of something like 50. Compare Figs. 3 and 4. However, if the γ energies exceed 0.25 MeV, then the reduction will be of the order of a factor of 3 or less. If a wide range of gamma energies is present, as in natural background, no shield need be employed, as indicated by comparing the response to the shielded radium source with the response to natural background.

ACKNOWLEDGMENTS

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