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Report

A FAST NEUTRON COUNTER FOR DOSIMETRY

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June, 1960

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ABSTRACT

This report contains a more complete description than that given in AERE EL/R 2149 of a simply constructed fast neutron counter.

The counter takes the form of a series of polythene-lined cells with a common anode wire and filled with a mixture of methane and argon. The dimensions of a three-cell counter are 2 inch diameter by 5.5 inch length. Its sensitivity can be adjusted so that at any energy in the range 0.1 - 15.0 MeV the counting rate is 0.9 ± 0.18c $\sec^{-1}$ per maximum permissible level (m.p.l.) of fast neutron flux; the m.p.l.'s are those recommended by the International Commission on Radiological Protection. At this sensitivity 219 m.p.l. of Radium gamma radiation or 99 m.p.l. of slow neutrons also produce a counting rate of 0.9c $\sec^{-1}$, and the minimum pulse size at the counter anode with an applied potential of 1400 volt corresponds to the collection of $5.5 \pm 2.5 \times 10^{6}$ ion pairs.

By increasing the length of the counters sensitivities of up to 3.6c $\sec^{-1}$ $(\text{m.p.l.})^{-1}$ can be obtained.

Procedures for the setting-up of the counter sensitivities are outlined. A sensitivity of 0.7c $\sec^{-1}$ $(\text{m.p.l.})^{-1}$ for a three cell counter is recommended when the counter is used with electronic equipment whose discriminator bias level is not very stable.

The counters are non-directional.

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1. Introduction

A detector which is to be used for fast neutron dosimetry may be based on one of several criteria of neutron dose, but the most important is the recommendations of the International Commission on Radiological Protection (I.C.R.P.) for the maximum permissible levels (m.p.l.) of neutron flux as a function of energy(1) for a dose rate to the human body of less than 7.5 m.rem/hr. These are shown in Table I, and formed the basis of the detectors described in this report, which replaces A.E.R.E. EL/R 2149(2).

TABLE I

Maximum permissible levels of neutron flux intensity recommended by the International Commission on Radiological Protection

Neutron Energy	Neutron flux intensity, n/cm^2/sec
0.025 ev	2000
10 ev	2000
10 kev	1000
0.1 Mev	200
0.5 Mev	80
1.0 Mev	60
2.0 Mev	40
3.0 - 10 Mev	30

In addition to satisfying a criterion of dose, the detector should be relatively insensitive to other types of radiation, in particular gamma radiation and slow neutrons. The arbitrary condition has been adopted that at least one hundred m.p.l. of gamma radiation or thermal neutron flux should be required to produce a response equal to 1 m.p.l. of fast neutrons. Further, if the detector is to find widespread application, it should be non-directional in response, rugged and easily produced in quantity; any associated electronic equipment should be of a simple or standard pattern.

2. Counter design and construction

The design is based on a theoretical analysis outlined in the Appendix I. Each counter, Fig. 1, consists of a number of polythene-lines cells placed in line, with a common anode wire made from 0.001 inch diameter tungsten wire. The cells are formed from polythene discs and cylinders, Fig. 2, which act as proton radiators

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in a fast neutron flux, and at any orientation to a neutron beam present approximately the same area of radiator. This ensures that the response is independent of the direction of the beam.

The radiators are made from natural grade B polythene in accordance with B.S.S. 1973 (I.C.I. grade 7) and are completely vacuum-coated with aluminium to produce an electrically conducting surface; a resistance of the order of 10 ohms is measured between the envelope of the counter and the inside surface of the radiators.

Care has been taken in the design to avoid drifts in the operating characteristics due to electrostatic charging of the insulators, by placing these outside the collecting volume of the counter.

The vacuum envelope is a stainless steel container with welded ends, through which an electrical connection to the anode is made by a standard metal/glass seal.

The gas filling is 17.3 cm Hg pressure of methane and 1.7 cm Hg pressure of argon. The gases are allowed to mix for about 16 hours before the counters are finally sealed off during which time the gas pressure decreases by about one percent due to absorption by the polythene.

With the above gas filling the neutron sensitivity of each cell varies with neutron energy in such a way that in the energy range 0.1 - 14 Mev the counting rate is proportional to the dose-rate. The counting rate of a single cell is 0.3 counts/sec for one m.p.l., and thus a typical three-cell counter will have a sensitivity of 0.9 counts/sec/m.p.l. Counters containing two, three, six and twelve cells have been constructed, having similar characteristics and a neutron sensitivity which is proportional to the number of cells.

To maintain the quality of the counters it is necessary to adhere to a strict processing schedule and they are pumped at a temperature of 60°C for about 10 days at a pressure of 10^{-5} - 10^{-6} mm Hg, until the outgassing rate over a period of 16 hours is less than 10^{-5} litre-microns/sec.

3. Fast neutron sensitivity

Integral bias curves obtained with a typical three-cell counter irradiated by mono-energetic neutrons are shown in Fig. 3. The curves were taken with the neutron beam parallel to the counter axis; with the beam perpendicular to this axis similar but somewhat steeper curves were obtained.

Mono-energetic neutrons were produced by using suitable targets in the proton beam from a Van de Graaff generator or the deuteron beam from a Cockcroft-Walton set. It was not possible to produce neutron fluxes of accurately known intensity with energies between 3 and 14 MeV.

A potential of 1400 volt was applied to the counter and the output was fed to a standard pulse amplifier with differentiating and integrating time constants of about 1.0 microsec. It will be noted that the response is very sensitive to changes in the overall gain of the system, particularly at high neutron energies; at 14 MeV a 5% change in the amplifier gain or a 0.5% change in the potential applied to the counter will change the counting rate by 7%.

Using the curves of Fig. 3 the response of the counter can be determined as a function of neutron energy at any discriminator bias level, and for a small range of this bias it approximates to that required by the I.C.R.P. recommendations. For the three-cell counter the best approximation corresponds to a sensitivity of 0.9 counts/sec/m.p.l.

It was found that at this bias level each counter gave the same counting rate, within close limits, when a Ra-Be source of known neutron emission was placed in a fixed position with respect to the counter. This is used as a convenient method of finding the operating point of any three cell counter; the exact procedure is discussed more fully in Appendix II. The average response of three counters selected at random and set up in this way is plotted in Fig. 4 and compared with that required by the I.C.R.P. recommendations.

The experimental points fit the required response more closely than is preducted by the simple theory; the reasons for this are discussed in the Appendix. The maximum deviation from the required response between neutron energies of 0.1 - 14 MeV is 20%.

4. Gamma sensitivity

When the counters are irradiated at a dose-rate R due to a radium source the counting rate C is related to the discriminator bias level V_B by an expression of the form:-

$$C = pRe^{-\delta V_B} \qquad \ldots\ldots \; 1$$

where p and δ are constants. The value of δ is such that the gamma sensitivity varies rapidly with small changes in bias level. Thus a 1% change in bias voltage results in a 20% change in gamma sensitivity although the sensitivity to 14 MeV neutrons is altered by only 2.5%. Equation 1 is found to hold for dose-rates from 2×10^{-4} r/hr to 2.7 r/hour.

There is a slight variation in gamma sensitivity between different counters but at the operating bias for a three-cell counter, when the neutron sensitivity is 0.9 counts/sec m.p.l., the counting rate due to a gamma-radiation dose rate of 2.6 r/hour (360 m.p.l.) will not exceed 1.5 counts/sec.

It is found that the ratio of gamma/neutron sensitivities of counters is increased markedly if the full pumping and outgassing procedure has not been completed. It is possible that gaseous impurities from the polythene cause an increase in the recombination coefficient of the filling gas, which has a greater effect on the more densely ionised proton tracks than on electron tracks. The ratio is not affected, however, by traces of air or mercury vapour in the filling gas.

5. Slow neutron sensitivity

The measured counting rate from three-cell counters when irradiated in a slow neutron flux equivalent to 100 m.p.l. is about 1 count/sec. This value and the shape of the bias curve are consistent with the $^{14}N(n,p)^{14}C$ reaction taking place in the 0.3% nitrogen impurity present in the argon used in the gas filling. By surrounding the counters in a cadmium shield the thermal neutron response may be eliminated.

6. Pulse characteristics

In the range 1300-1500 volts, the relation between the mean pulse size S and the applied voltage is of the form

$$S = Ae^{0.008V} \qquad \ldots\ldots \; 2$$

This equation is typical of a proportional counter in which gas multiplication takes place only in the electron avalanche and no secondary processes occur. For a batch of 40 counters set up using a Ra-Be source as described earlier, the pulse size at the counter anodes at the operating bias was equivalent to the collection of between 0.47×10^{-12} and 1.23×10^{-12} coulombs for an applied potential of 1400 volts. The variation is presumed to be due to differences in gas filling pressure, gas purity and slight constructional differences.

The mean gas gain at 1400 volts is of the order of one thousand.

7. Conclusions

A proton-recoil proportional counter is described in which the counting rate is directly proportional to the estimated biological dose due to fast neutrons in the energy range 0.1 - 14 Mev. The fast neutron sensitivity varies from 0.6 counts/sec/mpl to 3.6 counts/sec/mpl depending on the physical size of the counter.

Over 150 counters have been constructed in a size giving a sensitivity of 0.9 counts/sec/mpl, and are in general use.

Acknowledgements

Our thanks are due to Mr. A. B. Clare of A.E.R.E., Harwell, for several helpful discussions, and also to members of the Nuclear Physics and Reactor Divisions for the use of experimental facilities in connection with the neutron measurements. Counters were manufactured for us by the "Solus" Electronic Tubes Ltd. and by 20th Century Electronics Ltd.

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APPENDIX I

Theory of counter response

The following derivation of the response of a fast neutron proton recoil counter is a simplified account since the presence of complicated wall and end effects together with the variation in gas multiplication along the anode wire would make a rigorous derivation extremely difficult.

The problem of proton recoils from thick and thin radiators and from hydrogenous gases when bombarded with energetic neutrons has been treated many times(3-7) and it is not proposed to repeat these calculations in detail. Protons are assumed to obey a range-energy relation of the type $R = kE_p^n$ in hydrogenous materials, where n and k are constants. For polythene, when R is measured in cm and the proton energy E_p in Mev, k_1 and n_1 both have the value 1.79 in the energy range 0.2 - 10 Mev, and in the range 0.1 - 0.2 Mev k_1 is 3.10. For methane, when R is measured in mgm/cm^2, k_2 and n_2 are 1.56 and 1.80 respectively. When these values are substituted in the range-energy relation the values of R are within 10% of those given by Hirschfelder and Magee(9). Adopting the notation of Hurst(3), the number of protons, N_S, which emerge with energies in the range B_1 to B_2 from a thick slab of hydrogenous material is given by the expression

$$N_S = N(E).A.Q.6(E).K_1 \left[B_1^{n_1} \left\{ \frac{4n_1}{6n_1 + 9} \left(\frac{B_1}{E}\right)^{3/2} - \frac{2}{3} \right\} - B_2^{n_1} \left\{ \frac{4n_1}{6n_1 + 9} \left(\frac{B_2}{E}\right)^{3/2} - \frac{2}{3} \right\} \right] \qquad \ldots\ldots 3$$

where N(E) = number of neutrons of energy E incident on the slab per unit area per unit time, at right angles to the surface of the slab.

A = area of slab

Q = number of hydrogen atoms per unit volume of slab.

6(E) = neutron-proton scattering cross-section for neutrons of energy E.

A thick slab is one for which the thickness is greater than, or equal to, the range of the most energetic recoil proton.

The number of proton recoils, N_G, in a hydrogenous gas with energies in the range B_1 to B_3 is given by

$$N_G = N(E).A.t.Q.6(E)\left(\frac{B_3}{E} - \frac{B_1}{E}\right) \qquad \ldots\ldots 4$$

where t = depth of gas volume.

In a recoil counter the lower energy limit B_1 in equations 3 and 4 is determined only by the discriminator bias level, but as high energy protons are lightly ionising the upper limits B_2 and B_3 are governed by the path length in the counter as well as by the bias setting. B_2 and B_3 may be evaluated as follows:

If the path length in the counter gas of a proton from the slab is λ mgm/cm^2 and it leaves the counter volume with a residual energy E_R then

$$R - \lambda = k_2 \, E_p^{n_2} - \lambda = k_2 E_R^{n_2} \qquad \ldots\ldots \; 5$$

The mean energy expended by a proton in the counter is

$$E_p - E_R = E_p - \left(E_p^{n_2} - \frac{\lambda}{k_2}\right)^{1/n_2} \qquad \ldots\ldots \; 6$$

For energetic protons the energy $(E_p - E_R)$ expended in the counter may be less than B_1, due to their low total specific ionisation. Thus the upper energy limit B_1 for detection is that value of E_p for which $E_p - E_R = B_1$. The value of λ will dpend depend on the direction of the proton recoil, and an arbitary figure of 1.3 times the cell depth has been used in the calculations; the maximum possible path length in a cell is 1.6 times the depth.

Proton recoils from the gas will have shorter path lengths in the counter than those from the walls. The energy $E(x)$ deposited by recoils from an element dx of the counter at a distance $(\lambda - x)$ from the wall will be

$$E(x) = E_p - \left(E_p^{n_2} - \frac{x}{k_2}\right)^{1/n_2} \qquad \ldots\ldots \; 7$$

and the mean energy deposited in the counter by recoils from the gas may be roughly evaluated as

$$\bar{E} = \int_0^\lambda E(x)dx / \int_0^\lambda dx.$$

$$= E_p - \frac{k_2 n_2}{\lambda(n_2 + 1)} \left\{ E_p^{(2n+1)} - \left(E_p^{n_2} - \frac{\lambda}{k_2}\right)^{\frac{n_2 + 1}{n_2}} \right\} \qquad \ldots\ldots \; 8$$

The cut-off level for the gas, B_3, has been taken to be that value of E_p for which $\bar{E} = B_1$. The calculated values of B_2 and B_3 for $\lambda = 4$ cm and a gas pressure of 19 cm Hg of methane are plotted in Fig. 5; and the combined response of slab and gas for 19 cm Hg total pressure (4.75 cm Hg of argon + 14.25 cm Hg of argon + 14.25 cm Hg of methane) is plotted in Fig. 6 for different values of B_1, the gas mixture was assumed to have the same values of n_2 and k_2 as pure methane. It is apparent from this diagram that by a suitable choice of bias level B_1 the sensitivity of the combination as a function of neutron energy can be made to match approximately that required by the I.R.C.P. recommendations.

At low energies (0.1 - 0.5 MeV) the response will be less than that calculated because of attenuation of the neutron beams by the polythene walls, while at energies above 10 MeV the response will not fall off as rapidly as the calculation indicates, because the contribution to the response due to recoiling carbon nuclei will become appreciable. The effect of carbon recoils is difficult to calculate because the elastic scattering is not isotropic and non-elastic collisions take place in competition with the elastic scattering, and also because the range energy relation for carbon is unknown. However it seems likely that the total contribution of carbon recoils may be as high as 10-15% at 15 MeV.

It might therefore be expected that a closer fit to the I.C.R.P. response curve will be obtained than the simple calculation indicates, and this is borne out by the results in Fig. 4.

For end-on irradiation of the counters the high-energy response will be further increased, since some protons will travel through more than one cell and will have a longer path length than assumed. However at lower energies the response will be further depressed. It is probably advisable to use six-cell and twelve-cell counters sideways on to the neutron beam.

APPENDIX II

Operation and procedures for setting-up and testing

When used with mains-operated equipment, a counter is typically connected to a cathode-follower pre-amplifier, the output of which is coupled to a high gain amplifier with integrating and differentiating time constants of about 1 microsec. A potential of 1400 volts stable to ± 0.1% is applied to the counter anode. The output from the amplifier is fed to a scaler or ratemeter, and the amplifier gain and the discriminator bias level are adjusted to the correct values by using a radium-beryllium source as described below.

Because of the sharp dependance of the gamma sensitivity of the counters on the bias level, an increase in the gamma sensitivity may be observed when a counter is used with electronic equipment in which the effective bias level is unstable. This is most likely to occur with portable battery-operated equipment. It is then advisable to increase the operating bias by 25% to reduce the neutron sensitivity of a three cell counter from 0.9 c/sec/m.p.l. to 0.7 c/sec/m.p.l., Fig. 7, this very greatly decreases the gamma sensitivity and increases the reliability of the setting up procedure.

Whether the counters are used with mains or battery operated equipment, the operating bias level and the gamma sensitivity of the equipment should be checked from time to time.

(1) Setting up the operating bias level using a Ra-Be source

A Ra-Be source of convenient strength for setting-up equipment contains 5 mC of Radium and has a neutron emission of about 7.5 x 10^4 neutrons per second. The source is placed with its centre 5 cm from the side of the counter and in a plane, which intersects the axis of the counter at right-angles, passing through the centre of the counting volume, as shown in Fig. 8. The amplifier gain and the discriminator bias controls of the equipment are then adjusted to give the correct counting rate. The value of this counting rate depends on the neutron emission of the source used; the values for different counters in the table II below are for source giving 10^5 neutrons/second as measured by the Radio Chemical Centre, Amersham. For sources with other neutron emissions the counting rate is proportional to the neutron emission.

TABLE II

Counting rates obtained from fast neutron counters at the correct operating bias levels with a Ra-Be source giving 10^5 neutrons/second

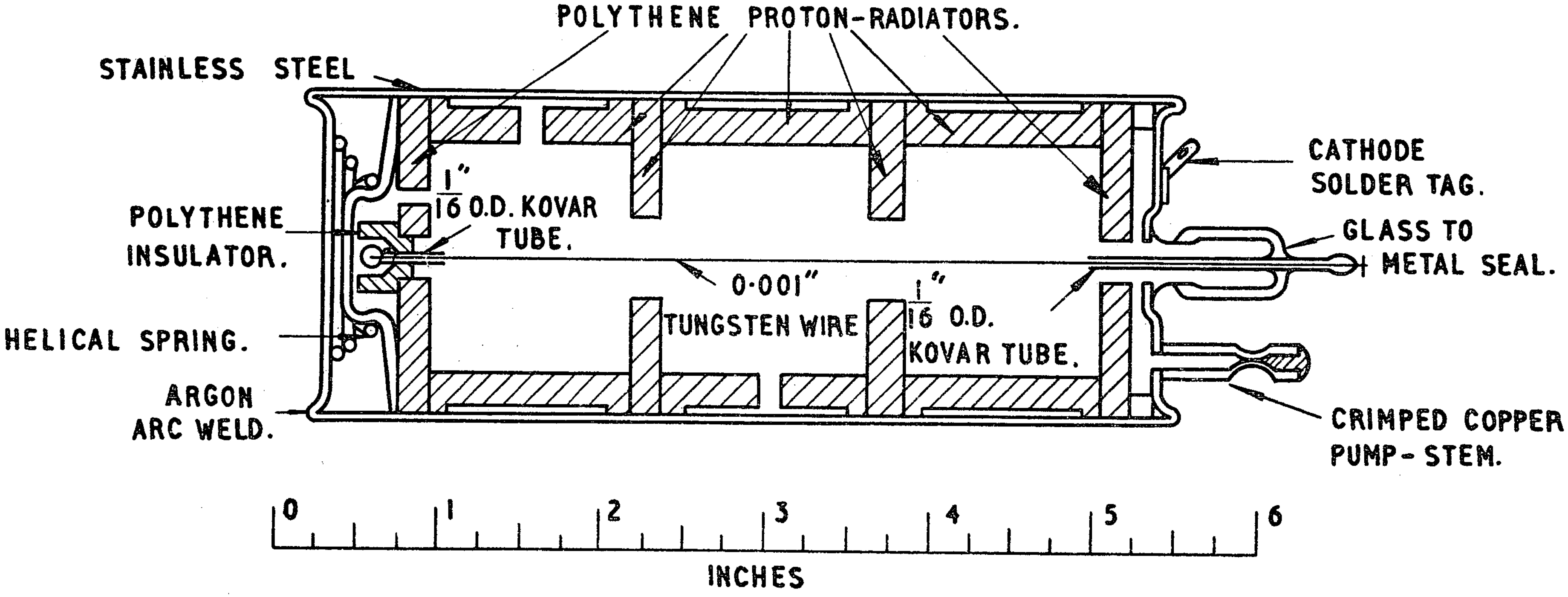
Type of Counter	No. of Cells	Distance of Centre of Counting Volume from the Seal End. cm.	Counting rate at Operating Bias c.p.m.	Neutron Sensitivity c/sec/m.p.l.
FN2/3	3	6.5	176 118	0.9 0.7
FN2/6	6	12	289	1.8
FN2/12	12	23	346	3.6

(2) Setting up the operating bias level of a three-cell counter using a calibration jig type 1546A

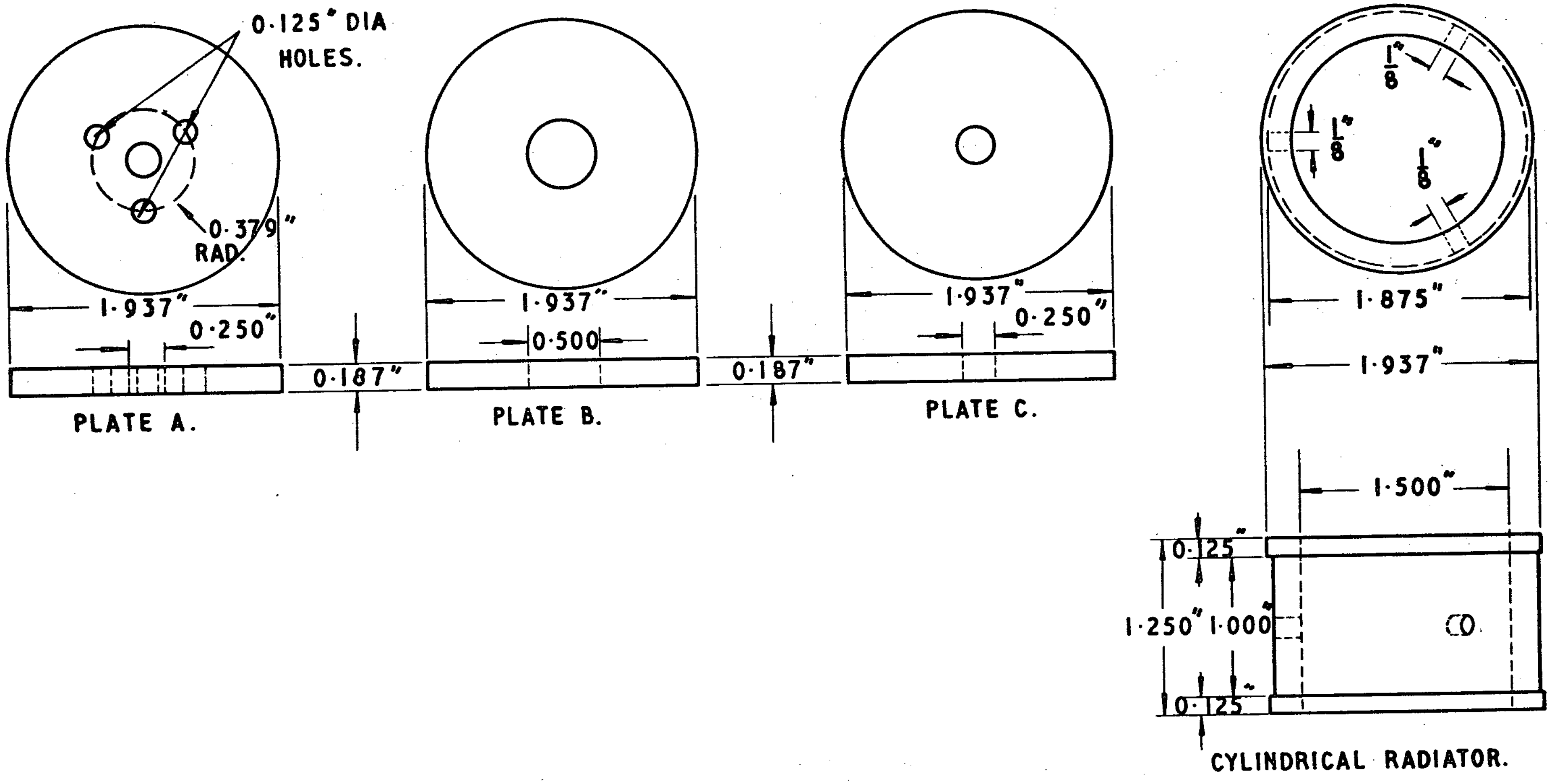
Portable fast neutron monitors containing a three-cell counter are more easily set up by using the Calibration Jig Type 1546A which contains a 5 mC Ra-Be source. The position of the source has been adjusted so that, when a three-cell counter is placed in the jig in the position shown in Fig. 9, a counting rate of 120 c.p.m. is obtained for a neutron sensitivity of 0.9 c/sec/m.p.l., or 100 c.p.m. for a sensitivity of 0.7 c/sec/m.p.l. For reasons which have been outlined above, it is recommended that battery-operated equipments are set-up to the lower sensitivity. In the case of the 1407C Portable Fast-Neutron Monitor, the required counting rate in the jig is obtained by means of the preset controls in the side of the equipment.

(3) Testing for gamma sensitivity

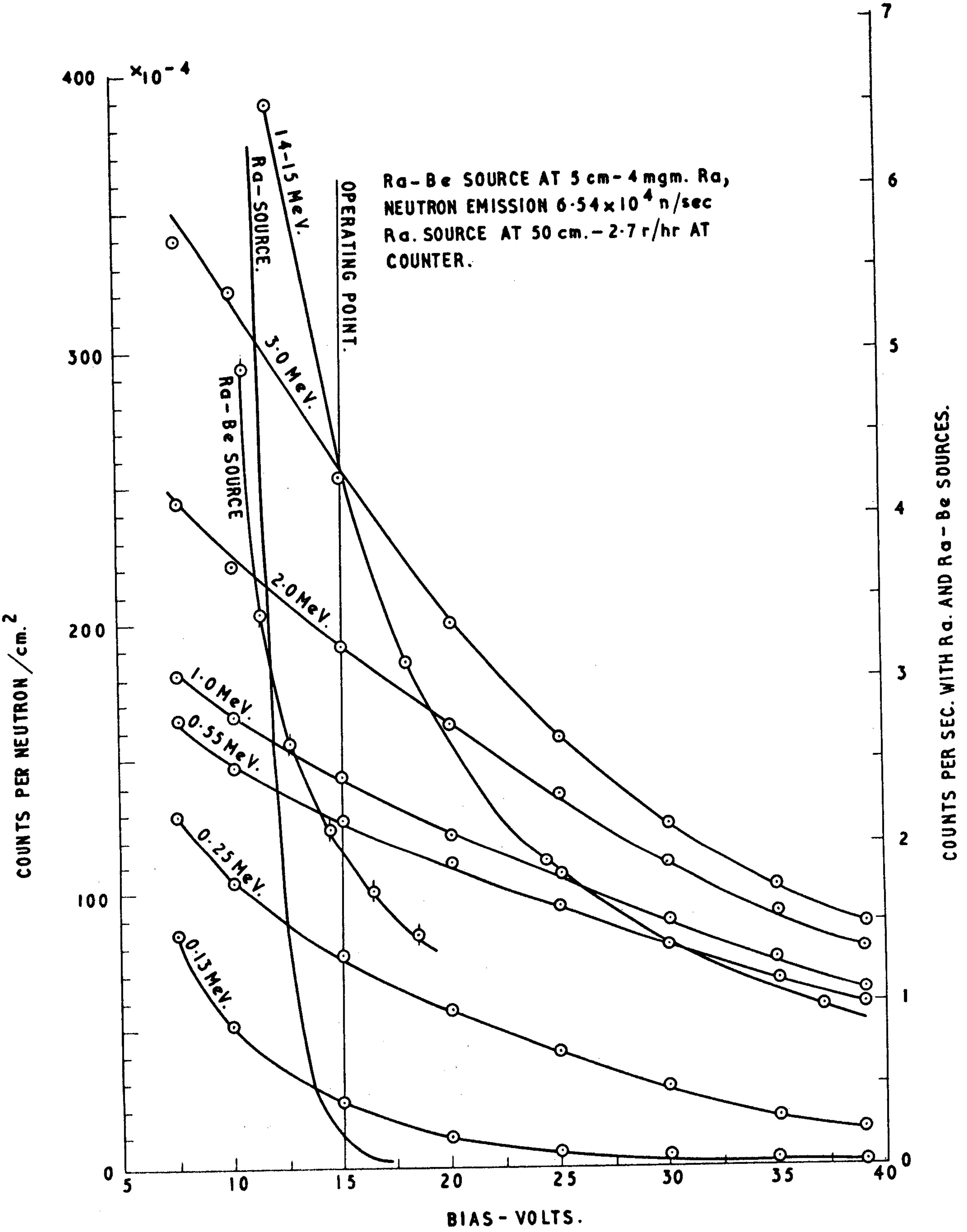
After the bias level of the equipment has been set to the operating point by one of the procedures described above, the gamma sensitivity may be tested. A simple test is to place a 1 mC Radium needle with its centre 1 cm from the side of the counter in a plane which intersects the axis of the counter at right angles and passes through the centre of the counting volume; the axis of the Radium needle should be in the plane and at right angles to the line from the needle centre to the axis of the counter. With the Radium needle in this position the counting rate will not exceed 7 c.p.m., unless there is a fault in the counter or equipment.



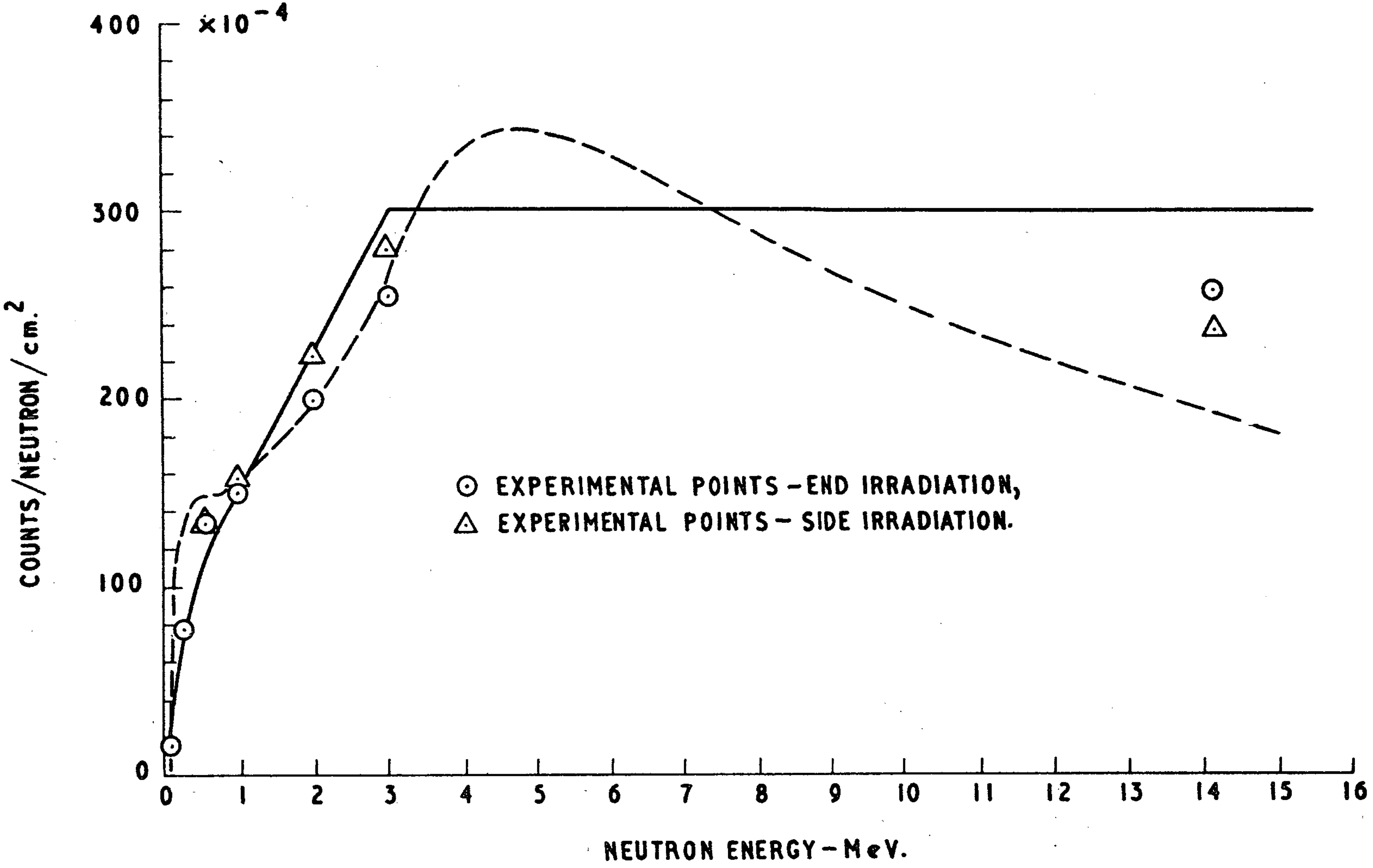
A.E.R.E. R.3302. FIG. 1. CUT-AWAY VIEW OF A THREE CELL COUNTER, TYPE FN2/3.



A.E.R.E. R.3302. FIG. 2. DETAILS OF POLYTHENE RADIATORS.

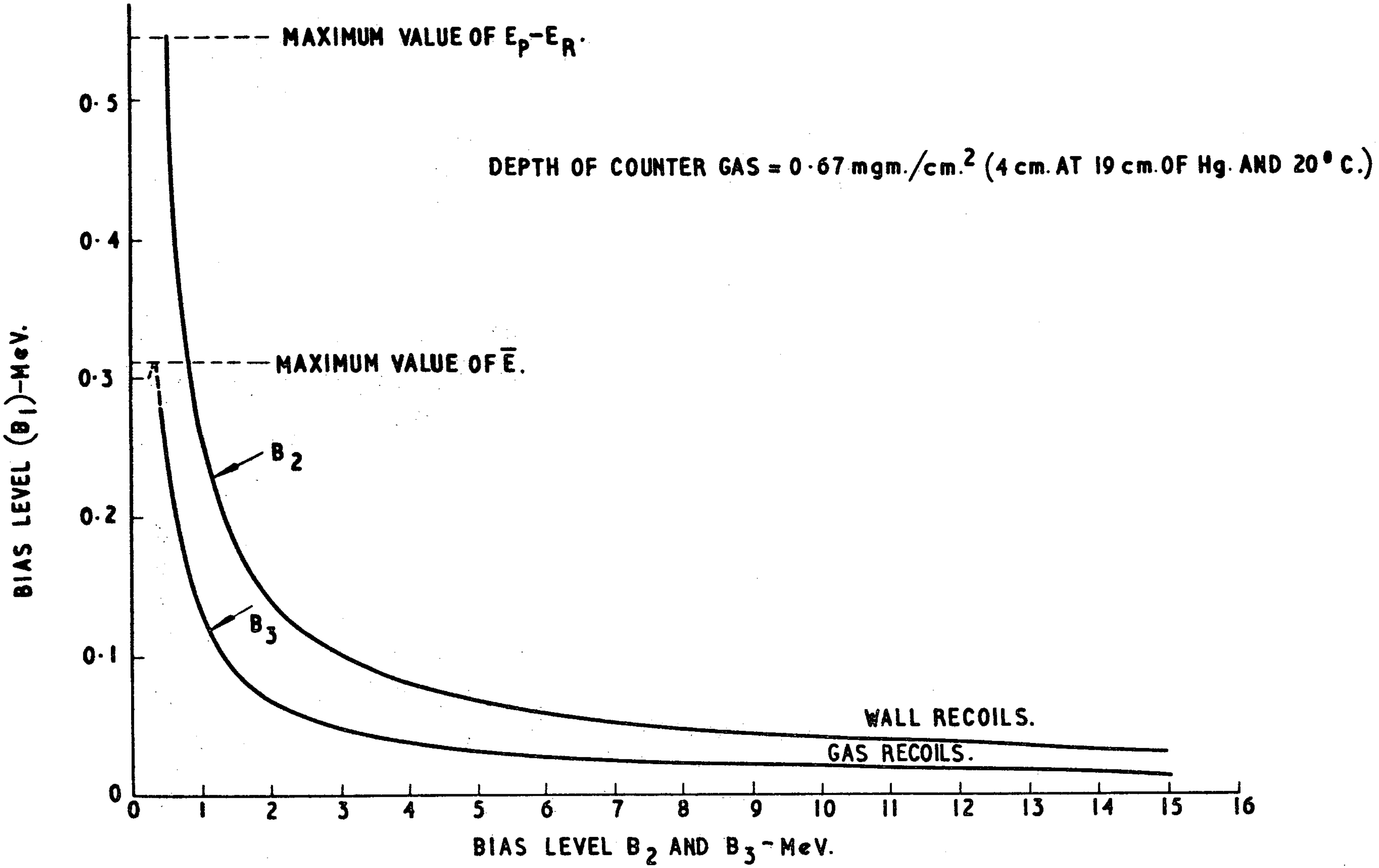


A.E.R.E. R.3302. FIG.3. INTEGRAL BIAS CURVES FOR MONOENERGETIC NEUTRONS, Ra-Be NEUTRONS AND RADIUM GAMMAS.

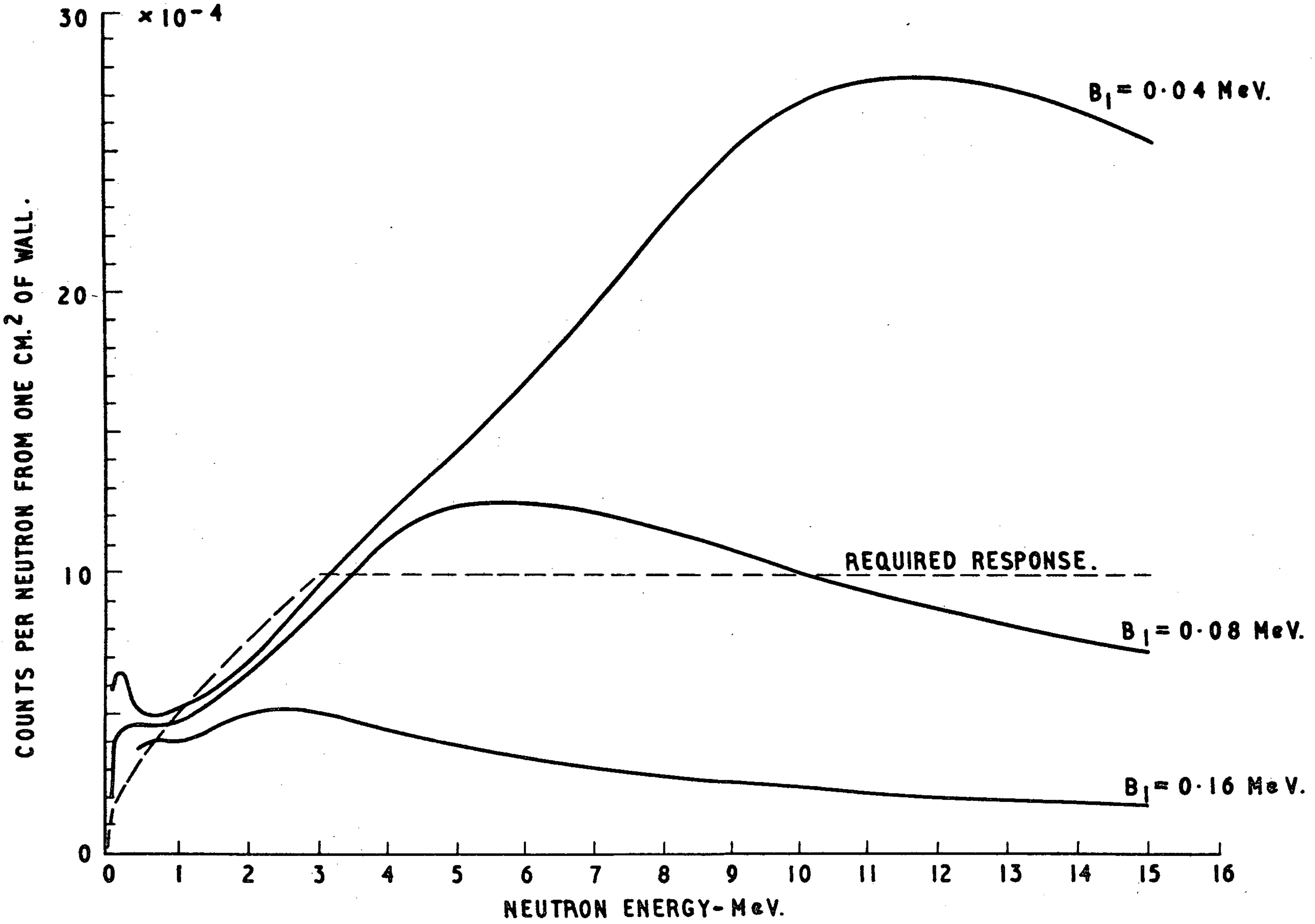


THE SOLID LINE IS THE REQUIRED RESPONSE ACCORDING TO THE I.C.R.P. RECOMMENDATIONS, FOR A COUNTING RATE OF 0·9 c/sec/mpl. THE DASHED LINE IS THEORETICAL RESPONSE OF THE COUNTER FOR END ON IRRADIATION AT A BIAS LEVEL EQUIVALENT TO 0·09 MeV.

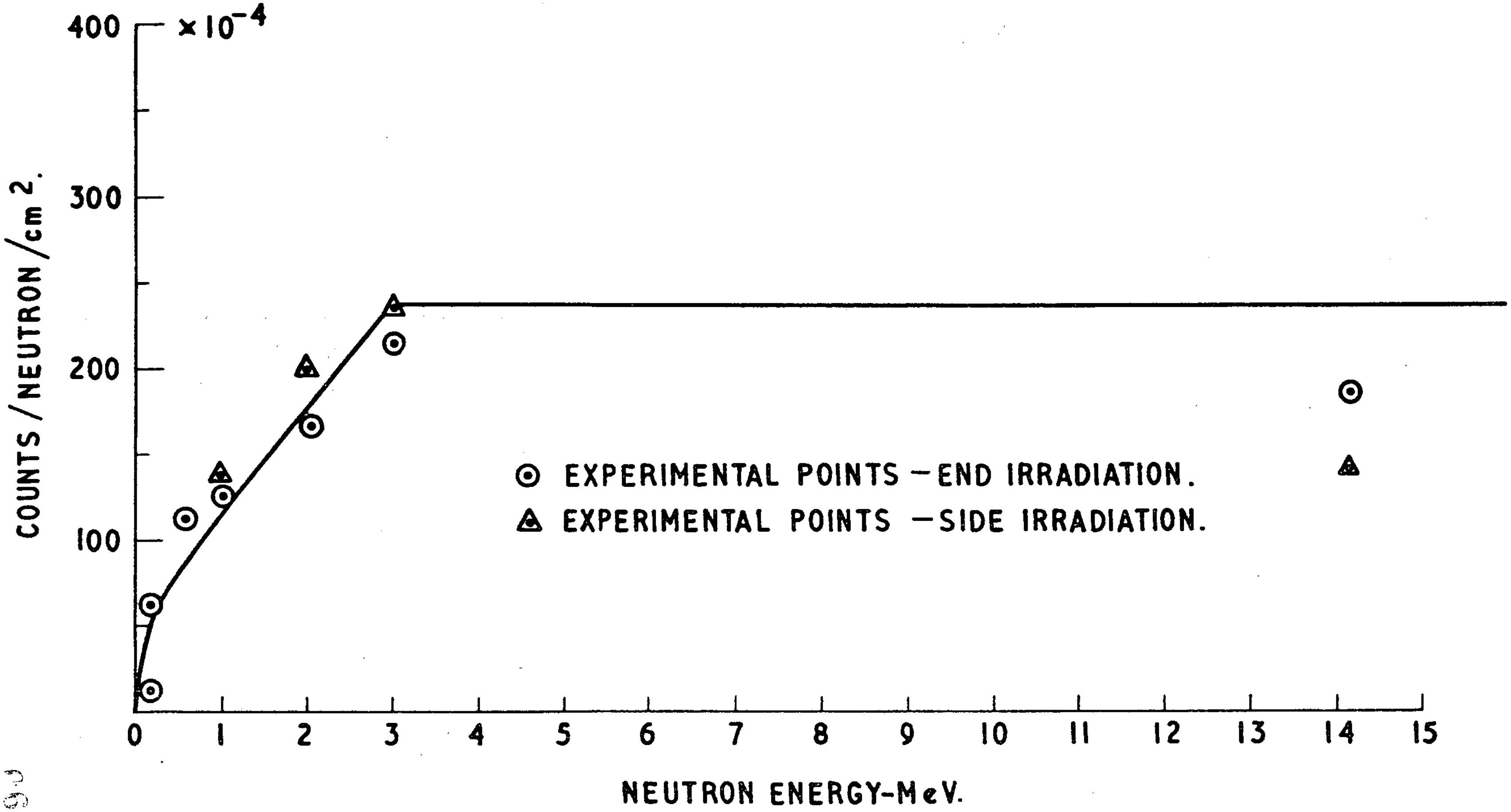
A.E.R.E. R.3302. FIG. 4. AVERAGE RESPONSE OF THREE TYPE FN 2/3 COUNTERS AS A FUNCTION OF NEUTRON ENERGY.



A.E.R.E. R.3302. FIG. 5. MAXIMUM PROTON ENERGY B_2 FOR A THICK HYDROGENOUS SLAB AND B_3 FOR METHANE, FOR WHICH THE ENERGY DEPOSITED IN THE CHAMBER IS GREATER THAN THE DISCRIMINATOR BIAS LEVEL B_1.

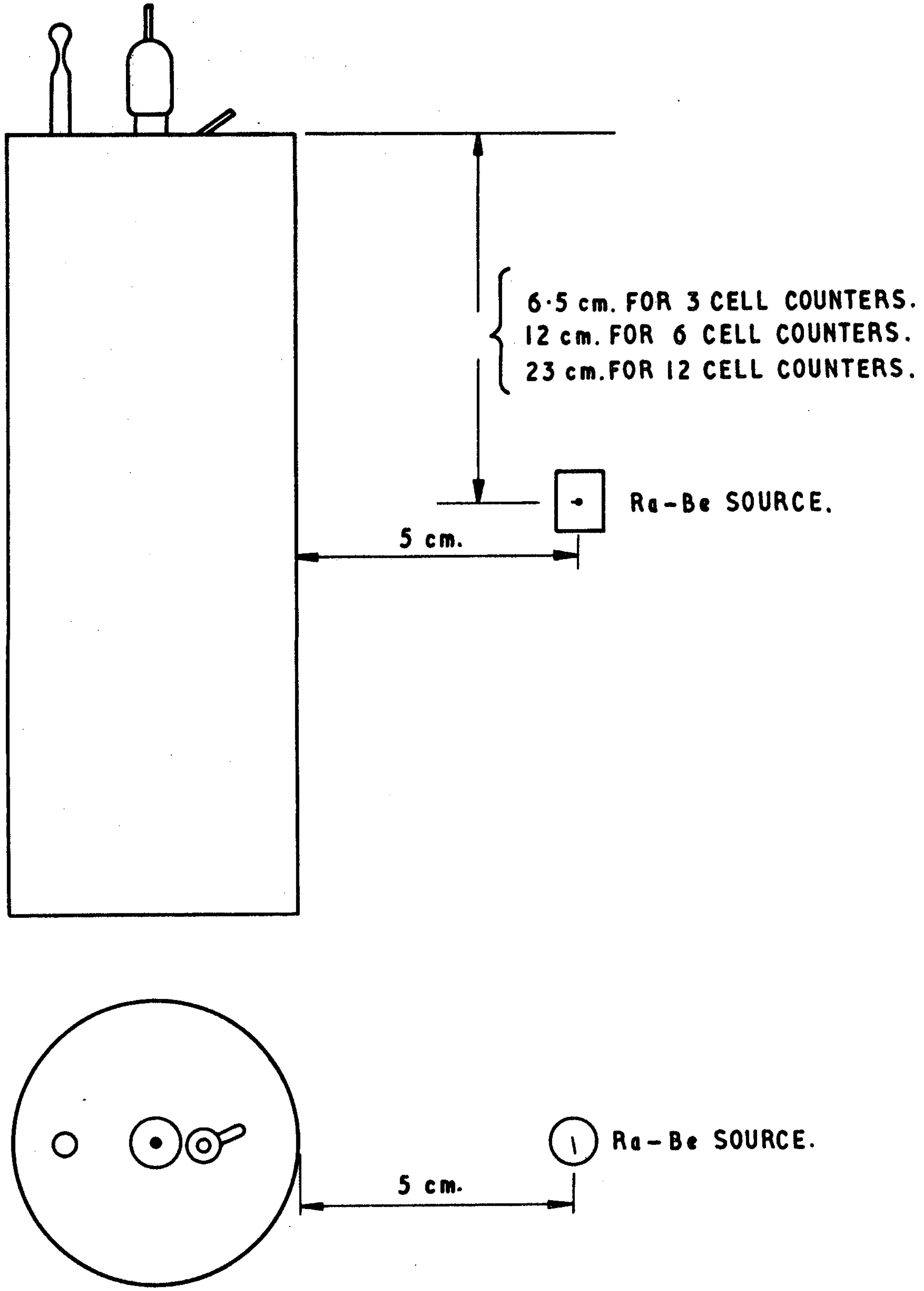


A.E.R.E. 3302. FIG. 6. COMBINED RESPONSE OF HYDROGENOUS WALL AND GAS FOR DIFFERENT BIAS LEVELS AND NEUTRON ENERGIES, ACCORDING TO THE SIMPLE THEORY.

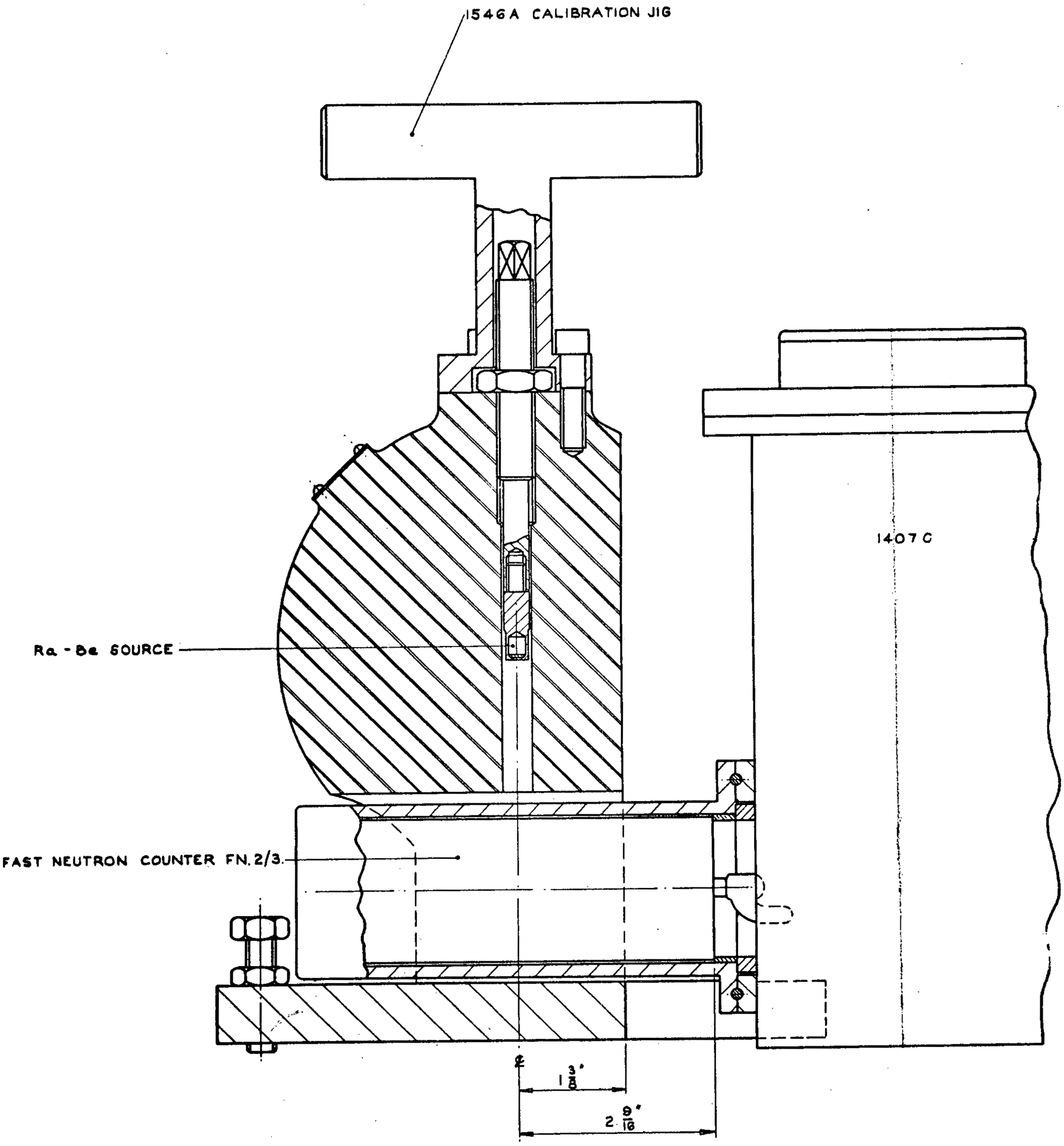


THE SOLID LINE IS THE REQUIRED RESPONSE FOR A SENSITIVITY OF 0·7 c./sec./m.p.l.

A.E.R.E. R.3302. FIG. 7. RESPONSE OF A THREE CELL COUNTER, TYPE FN2/3, FOR 0·7 c./sec./m.p.l. AND REDUCED GAMMA SENSITIVITY.



A.E.R.E. R.3302. FIG. 8. SOURCE POSITION FOR THE SETTING UP OF THE OPERATING BIAS LEVEL.



A.E.R.E. R.3302. FIG. 9. COUNTER POSITION FOR THE SETTING UP OF THE OPERATING BIAS LEVEL USING A 1546A CALIBRATION JIG.

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