Corrected Calibration of Andersson & Braun Type Rem Counter for Divergently Incident Am-Be Neutrons

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An extended procedure is presented to calibrate the Andersson & Braun type neutron rem counter with neutrons from a nearby pointlike Am-Be source. The counter output reading is corrected for the divergent neutrons incident on the counter body since the usual calibration demands the broad monodirectional beam condition. The correction is formulated as a function of source-to-counter distance \( r \) for source neutrons of energy \( E \) in a typical counter, Type AE-2202D of Studsvik Company.

The corrected calibration coefficient defined as the ratio of the dose equivalent rate to the corrected output reading is introduced. Here the dose equivalent rate is assumed to be predicted by the inverse square law at the center of the body.

For the Am-Be source it turns out that (1) for \( r \geq 100 \) cm the corrected coefficient goes into the usual coefficient defined as the ratio of the dose equivalent rate to the observed output reading only, which is virtually unity, and (2) for \( 50 \) cm \( \leq r < 100 \) cm where the above assumption holds approximately, the corrected coefficient will be made equal to unity if the correction is calculated appropriately.

Thus the counter can be calibrated in the distance range beyond \( r = 50 \) cm using such a correction applied to the output reading for the divergence effect of incident neutrons.

KEYWORDS: calibration, Andersson & Braun type neutron rem counter, Am-Be source, divergent neutrons, broad monodirectional beam, corrected calibration coefficient, dose equivalents, inverse square law, neutron sources

I. INTRODUCTION

The Andersson & Braun type neutron rem counter is an instrument for protection survey measurement around reactors, accelerators and other neutron sources.

For calibrating the counter with neutrons of a given energy, it is usually placed at positions very far from the pointlike steady source emitting isotropically these neutrons. Neutrons are then incident on the counter body in an almost broad monodirectional beam. The dose equivalent rate is described accurately by the inverse square law, and the "usual" calibration coefficient defined as the ratio of the dose equivalent rate to the output reading of the counter is well determined.

However, for calibrating with the source of weak strength, the counter must be brought enough close to it to obtain the accurate result of output readings. Neutrons tend to be incident on the body in a divergent way depending on the counter size. The inverse square law is no longer applicable to the prediction of the expected dose equivalent rate.

To perform the calibration in such a case, an extended procedure is presented.

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The source-to-counter distance to be used is generally small as compared with that necessary for the whole body to be exposed to a broad monodirectional beam of neutrons.

We thus introduce the “corrected” calibration coefficient defined as the ratio of the dose equivalent rate given by the inverse square law to the output reading corrected for divergently incident neutrons. Here the correction must be applied to the reading to take account of the divergence effect for incident neutrons particularly remarkable near the periphery of the body.

To demonstrate the effectiveness of the present procedure, a typical rem counter, Type AE-2202D of Studsvik Co., was calibrated with a pointlike Am-Be neutron source. The correction to be applied to the output reading is formulated as a function of source-to-counter distance for the source neutrons. The quantitative relation between the usual and corrected calibration coefficients is pursued as a function of the distance. The restriction to the distance range where the latter coefficient holds is discussed.

II. PRINCIPLE OF EXTENDED CALIBRATION PROCEDURE

1. Definition of Corrected Calibration Coefficient

For a monoenergetic isotropic point source the neutron flux density at distance \( r \) from the source is given by

\[
\phi_p(r) = \frac{Q_s}{4\pi r^2},
\]

where the source emits \( Q_s \) neutrons of energy \( E \) per second. The attenuation of neutrons by the air between the source and the point of observation is neglected.

For the usual calibration the counter is placed at distances very far from the source until the following conditions are met inside the body:

1. A broad monodirectional beam of neutrons is incident on the counter body.
2. The dose equivalent rate is given by the inverse square law, that is,

\[
D_p(r, E) = \phi_p(r) F(E) = \left(\frac{Q_s}{4\pi r^2}\right) F(E),
\]

where \( F(E) \) is the conversion factor that is defined according to the ICRP Publication 21 for the flux density under the parallel beam condition (1).

The behavior of neutrons incident on the body is explained in Fig. 1(a). In general, no consideration is required for the divergent neutrons outside the body since they do not contribute to the counter output reading \( N_{mea}(r, E) \). The usual calibration coefficient of the counter is written in a mathematical form as

\[
\kappa(E) = \lim_{r \to \infty} \left[ \frac{D_p(r, E)}{N_{mea}(r, E)} \right],
\]

which depends on \( E \) only.

If the counter is positioned too near the source, neutrons will be incident on the whole body in a very divergent way, as shown in Fig. 1(b). The conditions (1) and (2) do not hold. Equation (2) can no longer be used to predict the dose equivalent rate. The calibration coefficient of Eq. (3) becomes inaccurate.

However, an extended calibration procedure is expected when the counter is placed between the two extreme positions in Figs. 1(a) and (b). Suppose that the solid angle subtended at distance \( r \) against the source by a unit area (1 cm²) perpendicular to the distance is so small that the neutrons passing through that area per unit time run almost parallel with the distance. Then, at the center of the body (positioned at \( r \)) the neutrons contributing to \( \phi_p(r) \) are considered parallel, and the associated dose equivalent...
rate is given by Eq. (2).

Under such circumstances there are two distinctive cases depending on the counter size. One is shown in Fig. 1(c). Owing to the small size, the solid angle subtended at distance \( r \) by the main surface of the body is equal to, or smaller than that subtended by the unit area there. The calibration is easily performed in the same way as in Fig. 1(a) since the conditions (1) and (2) are satisfied throughout the body.

The other is given in Fig. 1(d). The size of counter body is much larger than that shown in Fig. 1(c). Divergent neutrons are incident on the periphery of the body. Hence the output reading \( N_{\text{mea}}(r, E) \) must be corrected for this divergence effect. The correction is given by

\[
C(r, E) = \frac{N(r, E)}{N_{\text{mea}}(r, E)},
\]

where \( N(r, E) \) is the counter output that would be obtained if the whole body were traversed by the broad monodirectional beam of neutrons having the density \( \phi_p(r) = Q_s/4\pi r^2 \), as shown in the dotted arrows of Fig. 1(d). The counter will then be calibrated in the same way as in Figs. 1(a) and (c), if we use the following corrected calibration coefficient:

\[
\kappa(r, E) = \frac{D_p(r, E)}{N(r, E)} = \frac{D_p(r, E)}{C(r, E)N_{\text{mea}}(r, E)}.
\]

For calibrating the counter near the source \( C(r, E) \) should be formulated as a function of \( r \) in such a way that \( \kappa(r, E) \) is made equal to \( \kappa(E) \) within the distance range where the inverse square law holds at the body center. It is evident from Eqs. (3) and (5) that \( C(r, E) \) goes to unity for \( r \to \infty \), apart from its detailed functional form.

In Sec. II-3 an attempt will be made to express \( C(r, E) \) as a function of \( r \) for a typical neutron rem counter.

2. Neutron Rem Counter

In the present work a neutron rem counter, Type AE-2202D of Studsvik Co. (Sweden), was used. The original principle of the counter is described by Andersson & Braun.(2)

The counter is a compact assembly consisting of a counter unit and an electronic measuring device mounted together. A cylindrical design is used for the counter unit (Fig. 2). A BF₃ proportional counter tube is surrounded by an inner polyethylene layer with walls \( d_1(=a-b)=2.39 \text{ cm} \) thick. This layer is covered with a thin boron plastic cover on the surface. Holes are drilled in the cover to obtain the required rem response mentioned below. The outer polyethylene layer is \( d_2(=R-a)=6.92 \text{ cm} \) thick. The counter is \( 2R=21.5 \text{ cm} \) in diameter and \( h=23.0 \text{ cm} \) long. It weighs 10.9 kg including batteries.
In case a broad neutron beam is incident at right angle to the main axis of the counter unit, the measured neutron sensitivity expressed in cps/cm²·s⁻¹ fits close to the required ICRP response in the energy range between about 1 and 5 MeV, but deviates somewhat from the latter response in the energy ranges 0.025 eV < E < 1 MeV and 5 MeV < E < 17 MeV. The situation is worsened somewhat for the case in which the beam is incident on the body in parallel with the axis and for the isotropic case. However, for neutrons in the energy range of 1~5 MeV the difference in response curve between the measurement and the ICRP prediction may practically be neglected regardless of neutron incidence conditions.

3. Formulation of Correction

The correction \( C(r, E) \) is formulated by considering the physical events occurring inside the body. They are as follows:

1. The flux density is not practically uniform inside the body so that its average value differs from the flux density given by Eq. (1).
2. The intrinsic detection efficiency of the counter is a function of \( r \).

The correction \( C(r, E) \) is written as the product of two factors, \( C_1(r) \) and \( C_2(r, E) \). The subscripts 1 and 2 refer to the events (1) and (2), respectively. Thus,

\[
C(r, E) = C_1(r)C_2(r, E). \tag{6}
\]

(1) Correction Factor \( C_1(r) \) Arising from Nonuniformity of Flux Density Inside Counter

The correction factor \( C_1(r) \) is defined as

\[
C_1(r) = \frac{\phi(r)}{\bar{\phi}(r)}, \tag{7}
\]

where \( \bar{\phi}(r) \) is the average flux density in the counter unit, i.e.

\[
\bar{\phi}(r) = \frac{\int \phi(r)dr}{\int dr}. \tag{8}
\]

To calculate \( \bar{\phi}(r) \) from Eq. (8) it is necessary to specify beforehand the spatial region inside the unit over which Eq. (8) is integrated. As such a region we consider the sensitive part of each main component of the unit. The word “sensitive” means that only the neutrons entering such part can produce the required counter response. We shall thus treat the problem of determining which component part constitutes the relevant region.

Unfortunately, there is no definite criterion on which the determination is to be based. Consequently, the two convenient models are presented to approximate the sensitive part in the unit.

The first model is the line approximation (abbreviated with “L”). The sensitive part is assumed to be the main axis of the following components of the unit.

One component is the inner polyethylene layer (1). The reason for adopting the layer is that, as will be seen later in connection with Eq. (14), the neutrons which are
scattered from the layer are regarded as counted. In Fig. 3(a) the axis $\overline{AB}$ is considered as such a representative part. The average flux density is

$$\left[\bar{\phi}(r)\right]_{L1} = \frac{Q_s}{4\pi} \int_0^{l_1} \cos \theta \, d\theta \int_0^{l_2} \frac{Q_s}{4\pi} r \, \sqrt{r^2 + \frac{l^2}{4}}, \quad (9)$$

where $d^2 = r^2 + \frac{l^2}{4}$ and $\cos \theta = r / d$.

In Eq. (9) the subscript $L1$ indicates the application of the line approximation $L$ to the main axis of the inner polyethylene layer (1). The factor $\cos \theta / d^2$ is the solid angle subtended by a unit area perpendicular to this paper at the line element $dx$. Thus, the integrand $Q_s(\cos \theta / 4\pi d^2)$ is the number of neutrons passing through the unit area after being emitted from the source at position $P$; it is just the neutron flux density at the sensitive line element $dx$.

Next, it is possible to choose the BF$_3$ counter tube (2) as another component since neutrons are just detected there. In Fig. 3(b) the axis $\overline{CD}$ is taken to be such a part. If the lower and upper limits, zero and $l/2$, are replaced with $-l_1$ and $l_2$ in Eq. (9), respectively, the average flux density will be

$$\left[\bar{\phi}(r)\right]_{L2} = \frac{Q_s}{4\pi} \left( \frac{l_1}{\sqrt{r^2 + l_1^2}} \right) \left( \frac{l_2}{\sqrt{r^2 + l_2^2}} \right) / (l_1 + l_2) \, r. \quad (10)$$

The second model is the cross section approximation $C$. Here the sensitive part is assumed to be the cross section of each unit component. The components to be considered are the same as before.

First, consider the cross section of the inner polyethylene layer (1) in Fig. 4(a). The average flux density taken over its quarter section area $ABOF$ is

$$\left[\bar{\phi}(r)\right]_{C1} = \frac{Q_s}{4\pi} \int_{ABOF} \frac{\cos \theta}{4\pi d^2} \, dx \, dy / \int_{ABOF} \frac{dx \, dy}{d^2}$$

$$= \frac{Q_s}{4\pi} \int_{ABOF} \frac{r \, dx \, dy}{(r^2 + a^2 + y^2)^{3/2}} / \frac{a^2}{2} = \frac{Q_s}{2\pi a l} \tan^{-1} \left( \frac{at}{2r \sqrt{r^2 + a^2 + l^2}} \right) \left( \frac{b_1}{\sqrt{r^2 + b_1^2 + l_1^2}} \right) + \tan^{-1} \left( \frac{b_2}{\sqrt{r^2 + b_2^2 + l_2^2}} \right) / b (l_1 + l_2). \quad (11)$$

Here the subscript $C1$ has the meanings that the cross section of the inner polyethylene layer (1) is taken as the sensitive part.

Similarly, the average flux density over the upper half of the cross section of the BF$_3$ counter tube (2), $ABEF$, is written, with reference to Fig. 4(b), as

$$\left[\bar{\phi}(r)\right]_{C2} = \frac{Q_s}{4\pi} \int_{ABEF} \frac{\cos \theta}{4\pi d^2} \, dx \, dy / \int_{ABEF} \frac{dx \, dy}{d^2}$$

$$= \frac{Q_s}{4\pi} \left\{ \tan^{-1} \left( \frac{b_1}{r \sqrt{r^2 + b_1^2 + l_1^2}} \right) + \tan^{-1} \left( \frac{b_2}{\sqrt{r^2 + b_2^2 + l_2^2}} \right) \right\} / b (l_1 + l_2). \quad (12)$$

(2) Average Intrinsic Detection Efficiency $\tilde{p}(r, E)$ for Estimation of Correction Factor $C_2(r, E)$
In evaluating the correction factor $C_2(r, E)$ it is of primary importance to express the intrinsic detection efficiency $\bar{p}(r, E)$ averaged over the volume of counter unit as a function of $r$ since the variation of $\bar{p}(r, E)$ with $r$ provides the basis for calculation of $C_2(r, E)$.

The starting point in this direction is the Andersson et al.'s theory(2), which was developed to describe the performance of their original rem counter. All the neutrons which enter the counter and make their first collision in the outer polyethylene layer are assumed to be absorbed in the boron plastic cover of the inner polyethylene layer. On the other hand, all the neutrons which make their first collision in the inner layer are regarded as counted in the counter with a probability $k$.

With these assumptions the probability of obtaining a pulse from a neutron of energy $E$ incident normally to the axis of the counter unit, i.e. the intrinsic detection efficiency $p(E)$, is

$$p(E) = k \{ \exp \left[ -\Sigma_s(E) d_2 \right] \} \{ 1 - \exp \left[ -2\Sigma_s(E) d_1 \right] \}, \quad (13)$$

where $\Sigma_s(E)$ is the macroscopic total scattering cross section of polyethylene and $d_1$ and $d_2$ are the thicknesses of inner and outer polyethylene layers, respectively.

In the present work an attempt is made, however, to correct Eq. (13) for the isotropic emission of source neutrons. The counter unit is approximated by the cross section in Fig. 5(a). The path length of neutrons traversed by the cross section differs depending on the angle of incidence, $\eta$, so that the intrinsic detection efficiency becomes a function of $r$. For calculation the angle $\eta$ is divided into seven groups which are denoted with Roman numerals I, II, ..., VII.

![Fig. 5 Division of angle of incidence $\eta$ into seven groups in counter unit](image)

The scheme of the counter unit for detecting neutrons is the same as in Eq. (13) on the whole. However, it is assumed that any neutrons scattered from the nuclei in the inner layer after penetrating the outer layer are detected with equal probability $k$. In addition, we suppose that there is little (or no) interaction of neutrons with the material of two holder pipes attached to the BF$_3$ counter tube on both sides. These pipes are considered as void in the inner layer in the following calculation since they are essentially the very thin cylindrical pipes of copper.

The intrinsic detection efficiency averaged over the total region, $\bar{p}(r, E)$, is

$$\bar{p}(r, E) = kQ(r, E). \quad (14)$$
Here the factor \( Q(r, E) \) is given by
\[
Q(r, E) = \sum_{i=1}^{\infty} q_i(r, E) \int_{-\eta_8}^{\eta_1} d\eta = \left\{ \frac{2[ q_1(r, E) + q_8(r, E) ] + \sum_{i=1}^{\infty} q_i(r, E) }{2\eta_1} \right\},
\]
where \( \eta_1 = \eta_8 = \tan^{-1}[l/2(r-a)] \). The component function \( q_i(r, E) \) appearing in \( Q(r, E) \) is as follows.

1. The function \( q_1(r, E) \) is given, with reference to Fig. 5(b), as
\[
q_1(r, E) = \int_{-\eta_8}^{\eta_1} \left\{ \exp \left[ -\Sigma_s(E) \frac{A_1A_2}{R} \right] \right\} \left\{ 1 - \exp \left[ -\Sigma_s(E) \frac{A_1A_2}{R} \right] \right\} d\eta = \int_{-\eta_8}^{\eta_1} S_1(r, \eta, E) d\eta,
\]
where \( \eta_1 = \tan^{-1}[l/2r] \),
\[
S_1(r, \eta, E) = \left\{ \exp \left[ -\Sigma_s(E) R - a \sec \eta \right] \right\} \cdot \left\{ 1 - \exp \left[ -\Sigma_s(E) (R-a) \sec \eta \right] \right\}.
\]

The functions \( q_{II}(r, E) \) through \( q_{V}(r, E) \) will be formulated with reference to Fig. 5(c).

2. \( q_{II}(r, E) \) through \( q_{IV}(r, E) \) will be formulated with reference to Fig. 5(c).

3. \( q_{III}(r, E) \) is given, with reference to Fig. 5(c), as
\[
q_{III}(r, E) = \int_{-\eta_8}^{\eta_1} \left\{ \exp \left[ -\Sigma_s(E) \frac{A_1A_2}{R} \right] \right\} \left\{ 1 - \exp \left[ -\Sigma_s(E) \frac{A_1A_2}{R} \right] \right\} d\eta.
\]

4. The component functions in the regions VI and VII are expressed as

\[
q_4(r, E) = \int_{-\eta_6}^{\eta_5} \left\{ \exp \left[ -\Sigma_s(E) \frac{D_1D_2}{R} \right] \right\} \left\{ 1 - \exp \left[ -2\Sigma_s(E) \frac{D_1D_2}{R} \right] \right\} d\eta
\]

where \( \eta_6 = \tan^{-1}[l_4/r] \),
\[
S_4(r, \eta, E) = \left\{ \exp \left[ -\Sigma_s(E) R - a \sec \eta \right] \right\} \cdot \left\{ 1 - \exp \left[ -2\Sigma_s(E) (a-d) \sec \eta \right] \right\}.
\]

5. The component functions in the regions VI and VII are expressed as

\[
q_5(r, E) = \int_{-\eta_6}^{\eta_5} S_5(r, \eta, E) d\eta
\]

where \( \eta_6 = \eta_5 = \tan^{-1}[l_3/R] \).

6. The component functions in the regions VI and VII are expressed as

\[
q_6(r, E) = \int_{-\eta_6}^{\eta_5} S_6(r, \eta, E) d\eta = q_1(r, E)
\]

by noting that \( \eta_6 = \eta_5, \eta_7 = \eta_2 \) and \( \eta_8 = \eta_1 \) in Fig. 5(a).
The procedure for deriving the correction factor \( C_2(r, E) \) from Eq. (14) will be found in the following chapter.

### III. RESULT OF CORRECTED CALIBRATION COEFFICIENT

1. Calculation of Correction

   (1) Average Flux Density \( \bar{\phi}(r) \) and Correction Factor \( C_1(r) \)

   First, the average flux density \( \bar{\phi}(r) \) was calculated using the various approximations to counter sensitive parts. The result is given in Fig. 6. Since it is of interest to know how far \( \bar{\phi}(r) \) deviates from \( \phi_p(r) \), the deviation fraction defined as

   \[
   100 \times \frac{[\bar{\phi}(r) - \phi_p(r)]}{\phi_p(r)} = 100 \times \{1 - \frac{1}{C_1(r)}\} \%
   \]

   is plotted against \( r \).

   In Fig. 6 the deviation fraction is negative in all the cases; \( \bar{\phi}(r) \) is always smaller than \( \phi_p(r) \) for every approximation to sensitive part. In addition, the deviation fraction for the inner layer (1) is larger than that for the BF\(_3\) counter tube (2) regardless of the approximations at fixed \( r \)-values. This is due to the large volume of the inner layer in comparison with that of the BF\(_3\) counter tube. It is interesting to note that the cross section approximation always gives the larger fraction value than in the line approximation. However, as \( r \) increases, all the fraction curves approach to the abscissa, \( \bar{\phi}(r) - \phi_p(r) = 0 \).

   In Fig. 7 the correction factor \( C_1(r) \) is plotted against \( r \). The variation of \( C_1(r) \) with \( r \) is similar to that of the flux deviation shown in Fig. 6.

   (2) Correction Factor \( C_2(r, E) \)

   It is necessary for calculating \( C_2(r, E) \) to express the position-dependent factor \( Q(r, E) \) of Eq. (15) as a function of \( r \) in advance. The component functions \( q_i(r, E) \) in \( Q(r, E) \) were computed using a 10-point Gaussian quadrature formula in Eqs. (16) through (21). The scattering cross section of polyethylene in these equations was taken to be a mean value of \( \Sigma_s(E) \) over the Am-Be neutron spectrum, i.e. \( \Sigma_s(E) = \ldots \).
0.19 cm\(^{-1}\), since an Am-Be neutron source was used here, as will be seen later. 

**Figure 8** gives the plot of \(Q(r, E)\) against \(r\) thus calculated.

From Fig. 8 it is seen that the factor \(Q(r, E)\) is an increasing function of \(r\) up to \(r=100\) cm, but it reaches a constant value of 0.140 beyond \(r=100\) cm. This saturation effect can be understood from Fig. 7. Since \(C_2(r)=1\) (or \(\bar{q}(r)=\bar{q}_p(r)\)) for \(r>100\) cm regardless of approximations to the sensitive part of the counter, any assumed parts will go into a perfect point for \(r\to\infty\). In other words, all neutrons entering the counter could be regarded as being incident normally to the axis of any unit components. This is just the condition under which Eq. (13) is formulated.

In Eq. (13) the factor \(\{\exp[-\Sigma_s(E) \cdot d_2]\} \{1-\exp[-2\Sigma_s(E) d_2]\} (=p(E)/k)\) is 0.15, which is in good agreement with the saturated value of \(Q(r, E)\) (=\(p(r, E)/k\)), i.e., 0.140 obtained at points far from the source.

Thus, for \(r\to\infty\) we obtain

\[
\lim_{r\to\infty} Q(r, E) (\equiv Q(100, E)) = 0.140
\]

and, by noting that Eq. (14) goes into Eq. (13) in this case,

\[
\lim_{r\to\infty} \bar{p}(r, E) (\equiv \bar{p}(100, E)) = p(E).
\]

Accordingly, the correction factor \(C_2(r, E)\) is defined as

\[
C_2(r, E) = \left[ \lim_{r\to\infty} \bar{p}(r, E) \right] / \bar{p}(r, E)
= \left[ \lim_{r\to\infty} Q(r, E) \right] / Q(r, E)
= 0.140 / Q(r, E).
\]

The variation of \(C_2(r, E)\) with \(r\), which is inversely proportional to \(Q(r, E)\) is plotted in Fig. 8.

(3) Calculation of Correction \(C(r, E)\)

The correction \(C(r, E)\) was calculated from Eq. (6) using the results given in Figs. 7 and 8, and the result is shown in Fig. 9.

2. Result of Corrected Calibration Coefficient

(1) Measurement of Corrected Calibration Coefficient \(\kappa(r, E)\)

For measurements of \(N_{mea}(r, E)\), which are needed to derive \(\kappa(r, E)\), we used an
Am-Be neutron source, 17.4 mm dia. x 19.4 mm high, of the Radiochemical Centre. The source strength is $Q_s = (2.30 \pm 0.05) \times 10^4 \text{s}^{-1}$. Neutrons are emitted from the source isotropically with an effective energy of $E = 4.5 \text{MeV}$.

The experimental arrangement between the source and the rem counter is shown in Fig. 10. The source was put on an aluminum holder with the center at a height of 1 m. The counter was put on another aluminum holder with the center of the outer polyethylene layer of the counter unit at a height of 1 m.

The counter unit was set on the counter holder with the main axis $EF$ perpendicular to $AO=r$. To confirm the condition $AO \perp EF$, three nylon fishing lines $AA'$, $BB'$ and $CC'$ were dropped from the source position $A$ and the centers in the front and back edges of the holder plate, $B$ and $C$, respectively. These lines were kept firmly strain by attaching the lead weights to their tips $A'$, $B'$ and $C'$. The condition could then be established when we saw the enlarged images of the lines overlapping each other in the finder field of a single-eye reflex camera at position $D$. The distance $r$ was taken to be an average of the measured distance $A'B'$ and $A'C'$.

As the source strength was weak, the accuracy of the dose equivalent rate obtained with the measuring meter was generally low except near the source. The pulse counting method was adopted to reduce the reading error. The output of the counter was fed to an amplifier, discriminator and scaler. The measured counting rate was corrected for the scattering of neutrons from the wall, floor and other objectives around the source by the standard method, and divided by the counter sensitivity $\bar{s}(E) = 3.6 \text{cps/mrem} \cdot \text{h}^{-1}$ to obtain $N_{\text{mea}}(r, E)$ in mrem·h$^{-1}$.

The error in $N_{\text{mea}}(r, E)$ includes the statistical error in counts and the uncertainty in $r$ due to finite source dimensions. The latter uncertainty was estimated by quadratical addition of the measured displacement fractions of counts across the source in the directions up and down, to and fro, and forward and backward. This was less than a few percent even near the source because of the small size. The total error in $N_{\text{mea}}(r, E)$ did not exceed several percent throughout the distance range used.

The experimental result of $N_{\text{mea}}(r, E)$ is given in Fig. 9. For convenience $D_p(r, E)/N_{\text{mea}}(r, E)$ is plotted against $r$ on the right ordinate. (The conversion factor $F(E)$ necessary to calculate $D_p(r, E)$ from Eq. (2) is taken to be $3.9 \times 10^{-8} \text{mrem/cm}^{-2}$ from the reference.) Hence $D_p(r, E)$ is expressed in mrem·h$^{-1}$.) By dividing the ratio by the calculated value of $C(r, E)$ in Fig. 9, the coefficient $\kappa(r, E)$ is obtained from Eq. (5). The result is presented in Fig. 11.

Result

In Fig. 11 some interesting features of the distance behavior of $\kappa(r, E)$ are noticed.

(1) From Fig. 9 it is evident that $C(r, E)$ is almost unity for $r \geq 100 \text{cm}$. This means that the broad monodirectional beam of neutrons is incident on the body as if it
came from the point source placed at $r \to \infty$. Correspondingly, $\kappa(r, E)$ should go into $\kappa(E)$.

In Fig. 11 the observed fact that $\kappa(E)=1$, or $N_{\text{mea}}(r, E)=D_p(r, E)$ for $r \geq 100$ cm, shows that the counter is well calibrated for Am-Be neutrons under the parallel beam condition.

(2) For $50$ cm $\leq r < 100$ cm $\kappa(r, E)$ still remains to be unity in any approximations used to derive $C(r, E)$. Here the inverse square law, Eq. (2), is assumed to hold at the center of the body because the largest solid angle subtended at $r=50$ cm by the unit surface perpendicular to the distance is only $4 \times 10^{-4}$ sr. The observed fact assures that the calibration can be achieved by using any $C(r, E)$ values in the distance range from $r=100$ cm down to $r=50$ cm.

(3) For $r < 50$ cm $\kappa(r, E)$ deviates from unity, and the deviation increases rapidly as $r$ decreases. This distance behavior is brought about mainly by the fact that the solid angle subtended by the unit area at distance $r$ increases rapidly with decreasing $r$-value. In addition, the difference in $\kappa(r, E)$ among the various approximations becomes much more marked than at distances beyond $r=50$ cm. It is inappropriate, therefore, to use the distance range ($r<50$ cm) for calibration purposes.

IV. DISCUSSION

First, the accuracy of counter sensitivity $s(E)$ is checked. This is closely related to the reproducibility of the ideal rem dose response. To assure good reproducibility, we used the plot of $s(E)$ against $E$ that was provided by the Studsvik Co., and averaged it over the Am-Be neutron spectrum. The obtained value of $s(E)=3.5$ cps/mrem·h$^{-1}$ is considered reliable in the present work since the counter response is expected to be satisfactory with the Am-Be source neutrons of energies in the order of MeV, as is evident from Sec. II-2. No further check on this point was thus attempted.

Second, there is the possibility of introducing an alternative calibration coefficient to be employed near the source instead of $\kappa(r, E)$. One way is to define it as $\kappa'(r, E)=D(r, E)/N_{\text{mea}}(r, E)$. Here $D(r, E)$ is the dose equivalent rate obtained on the basis of the conversion factor to be calculated under the condition that the source neutrons of energy $E$ are “actually” incident on the standard phantom at distance $r$. In general, the accurate determination of $D(r, E)$ is difficult at distances very near the source.

It must be noticed that, however, except at $r \to \infty$ the practical use of $\kappa'(r, E)$ is
strictly restricted to the very position at which the counter is placed. Accordingly, it is not suitable to use $k'(r, E)$ for the usual calibration under the parallel beam condition. The formulation of $k'(r, E)$ was not attempted here.

Finally, it is hoped that the present method will be extended to measurements with other neutron sources having different energies and with other counters of different size.

V. CONCLUSION

The following conclusion is obtained when the Andersson & Braun type neutron rem counter (Type AE-2202D of Studsvik Co.) is calibrated with neutrons from a pointlike Am-Be source.

1. The counter is well calibrated for $r \geq 100\,\text{cm}$ where the broad monodirectional beam condition is met with good accuracy. (The usual calibration coefficient $k(E) = 1$)

2. The counter can be calibrated in the distance range from $r=100\,\text{cm}$ down to $r=50\,\text{cm}$ by using the correction $C(r, E)$ to the observed output reading $N_{\text{mea}}(r, E)$. (The corrected calibration coefficient is $k(r, E) = k(E) = 1$ for $50\,\text{cm} \leq r < 100\,\text{cm}$ almost regardless of any approximations used to derive $C(r, E)$ under the assumption of the inverse square law at the center of the counter body.)

REFERENCES