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Procedures for Calibrating Neutron Personnel Dosimeters

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Foreword

This report was prepared as part of the U.S. Department of Energy Neutron Dosimetry Upgrade Program, and is intended as a guide to recommended procedures for calibrating neutron personnel dosimeters and other neutron protection instruments. Although intended specifically for use by DOE laboratories, the procedures should be generally applicable in any laboratory doing these types of calibrations.

We would like to thank the U.S. Department of Energy, and in particular, Mr. Edward J. Vallario, Division of Operational Safety, DOE, for supporting this work.

Abstract

Procedures are given for routine testing and calibration of neutron dosimeters and remmeters with radioactive neutron sources. The issues addressed include: the choice of neutron source; phantom construction; fluence to dose equivalent conversion; and corrections for air scatter, room return, and anisotropic-neutron emission. Explicit, semi-empirical, analytic expressions are given for the room return correction, and calculated numerical values are given for air scatter.

Key words: air scatter; calibration; californium; dose equivalent; dosimeter; neutron; remmeter; room return.

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I. Introduction

In this report we shall discuss a technique for routine calibration and testing of neutron dosimeters and remmeters with radioactive neutron sources. For the sake of simplicity, we will generally refer to dosimeter calibrations, but most of the procedures apply equally well to active instruments, such as remmeters or Bonner spheres. In principle, it is a very simple procedure: the dosimeter is placed at a convenient distance from a neutron source of known emission rate, and irradiated for a known time. From the emission rate of the source, the distance, and the time, the neutron fluence at the dosimeter is calculated. Using a conventional fluence-to-dose-equivalent* conversion factor, we calculate the dose equivalent to which the dosimeter has been exposed. The dosimeter is then processed, and the reading corrected for the background from air and room scattering. The calculated dose equivalent, divided by the corrected reading, is then the dosimeter calibration factor for that source.

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*Note Concerning Units. The special SI unit for dose equivalent is the sievert (Sv).

$$1\ \text{Sv} = 1\ \text{J kg}^{-1} = 100\ \text{rem}.$$

The sievert, however, is not in general use in DOE laboratories, and the authors are not aware of any instrument calibrated in sieverts. Hence, to avoid confusion, we shall use rem (or millirem) in this report.

Similarly, it would seem to be needless pedantry to refer to the well-known 9-inch spherical remmeter as a "22.86 cm spherical remmeter."

In general, there are several possible ways of performing each of these steps, leading to dosimeter calibrations which are not unique. This report recommends detailed procedures to be followed in performing the calibrations. Our goal is to outline "correct" procedures; at least as far as our present knowledge allows. It is more important, however, that everyone use the same procedure, so that dosimeter calibrations will be a function only of the dosimeter type and the source energy spectrum, and not depend upon such factors as the source-detector distance or the room size. This is the only way in which dosimeters from different laboratories can be fairly compared, and the only way in which new dosimeter types can be sensibily evaluated.

II. Neutron Sources

The recent ISO TC85 draft standard[1] proposes four neutron sources: D_2O-moderated ^{252}Cf, ^{252}Cf, ^{241}Am-B, and ^{241}Am-Be. Other sources which have been used for calibrations include PuBe, Pu-Li, and Am-Li, although these sources may no longer be generally available from suppliers.

Leaving aside, for the moment, the moderated californium source, the clear winner among the other sources is ^{252}Cf. It has the following advantages as compared with the other sources: the neutron spectrum, which is similar to that from ^{235}U fission, has been carefully evaluated and is very well known;[2,3,4] sources are available in any reasonable strength, are physically small (approaching a point source) and relatively lightly encapsulated; the neutron emission is close to isotropic; and the gamma contamination is lower than for any of the other sources.

The principal disadvantage of ^{252}Cf is its relatively short half-life (2.6 years), which requires that it be replaced periodically. While this can be a problem in some laboratories, it should not be a serious handicap to DOE laboratories.

Whether to use bare ^{252}Cf or moderated ^{252}Cf is determined by the type of dosimeter to be calibrated and the neutron spectrum to which it (and the wearer) are expected to be exposed. (Note that in this report "moderated californium" will always refer to a ^{252}Cf source in the center of a D_2O sphere of 15 cm radius,[5] covered with 0.020" thick cadmium). For calibrating albedo dosimeters, particularly if they are to be used in the relatively soft spectra found in reactor environments, moderated californium is clearly preferred.[6,7] We have shown[7] that for other common dosimeter types (film, CR-39, polycarbonate) there are not very great differences (less than a factor of 2) in calibration factors between bare and moderated ^{252}Cf. Thus, the moderated ^{252}Cf is the more versatile of the two sources, since it is appropriate for all of the commonly used dosimeter types. It is also the only neutron source given in the July 1981 Draft Standard developed by the Health Physics Society Standards Committee (HPSSC), "Criteria for Testing Personnel Dosimetry Performance." On the other hand, if workers are exposed primarily to neutrons with fission energy (or higher energy), it is simpler and more logical to use a bare californium source. This report will thus consider calibrations done with both bare and moderated californium. Discussion will be limited to these two sources, although most of the arguments can be readily extended to other sources.

In any case, the source should be accurately calibrated before being put into use. NBS calibrates sources to an accuracy of $\pm$ 1.2%, (1σ) for emission rates between $\sim 10^6$ n/s and $\sim 5 \times 10^9$ n/s.

For calibrations in a closed room, the source should be placed at, or near, the center of the room. For outdoor calibrations, the source should be placed as high off the ground as can reasonably be done. Analytic expressions are given in Section VI of this report for predicting the effects of scattered neutrons in these configurations.

III. Phantoms

Albedo dosimeters obviously must be mounted on a phantom and, following the HPSSC Draft Standard, we recommend that all dosimeters be irradiated on a phantom.

While Hankins[8] found no difference in albedo dosimeter readings for irradiations using phantoms of polyethelene, Lucite (poly (methyl methacrylate)), or water, the HPSSC Draft Standard explicitly recommends methyl methacrylate. This recommendation was made largely because methyl methacrylate ($CH_2=C(CH_3)COOCH_3$) is closer in chemical composition to tissue than is water. (In addition, a Lucite phantom is less likely to become a puddle on the floor.)

Hankins[8] found, however, that albedo dosimeter readings did depend on the shape of the phantom, and Nash and Johnson[9] showed that the readings would be too low if the dosimeter were placed too close to the edge of the phantom face. To permit simultaneous irradiations of several dosimeters, the HPSSC Draft Standard therefore specifies that the phantom be a rectangular parallelepiped, 40 cm x 40 cm x 15 cm thick (rather than the earlier specified 30 cm x 30 cm x 15 cm) and that no portion of the dosimeter be closer than 10 cm to the phantom edge. This is a safe practice, but it may be unduly conservative, since the experimental evidence[9,10] indicates that the "edge effect" is determined only by the position of the sensitive element in the albedo dosimeter (e.g., the TLD chip itself).

We recommend that phantoms be built to the specifications of the HPSSC Draft Standard: 40 cm x 40 cm x 15 cm Lucite or Plexiglas. Temporarily, existing phantoms of water or polyethelene, no smaller than 30 cm x 30 cm x 15 cm, may be used, but they should be replaced with the recommended phantom as soon as possible. Cylindrical phantoms should not be used, even on a temporary basis.

In any case, the phantom should be placed on a low mass stand for minimum scattering, and should be the same height off the floor as the source.

IV. Source-to-Detector Distance

There are two questions to be considered: first, between what two points is the distance to be measured; and, second, is there an optimum (or, at least, a preferred) value for this distance?

The answer to the first question is: the source-detector distance is to be taken as the distance from the center of the source to the front face of the phantom directly behind the dosimeter. If several dosimeters are to be irradiated at the same time on the same phantom, the sensitive elements should be on the periphery of a circle centered on the face of the phantom, so that the dosimeters are all equidistant from the source. (The face of the phantom should, of course, be perpendicular to the line joining the source and phantom centers.) If this is not possible, explicit corrections should be made for the variation of the distance from the source for each dosimeter.

The fact that the center of the source should be one of the end points seems obvious in the case of small, bare, ^{252}Cf sources. For moderated californium sources, Ing and Cross[11] have shown that the center of the sphere is also the appropriate measuring point, (i.e. the variation of dose rate with distance follows the inverse square law) for distances greater than 30 cm (one sphere diameter).

Measuring to the front face of the phantom is simply a convention, which has the great advantage of being well defined and easily reproduced. Since the phantom is, however, part of the albedo system, the distance to use for calculating the fluence is somewhat ambiguous. An "effective" depth is sometimes

defined as the point in the phantom such that, when distance is measured to that point, the response follows the $1/r^2$ law. While there are data[12,13] which are consistent with an effective depth of 1 to 3 cm for albedo dosimeters irradiated with a Cf source, we prefer to define the distance to the face of the phantom. If definitive data were available, the calibration factor could be corrected to what it would be at great distances; i.e., where neutrons are normally incident on the face of the phantom. In the absence of such data, there will thus be some ambiguity in the calibrations, although the problem is minimized if all measurements are made at the same distance.

The answer to the question of the optimum distance for irradiation is a compromise between conflicting requirements. Too great a distance leads to very large room scatter corrections (especially for albedo dosimeters) as well as, possibly, inconveniently long irradiation times. Too short a distance leads to non-uniform illumination of the phantom and serious departure from the $1/r^2$ law for the moderated source. With all of the above in mind, the HPSSC Draft Standard recommends a 50 cm source-to-phantom distance, and we suggest that this recommendation be followed.

For a spherical detector (e.g., Bonner sphere, spherical remmeter) and a point neutron source, Axton[14] and Harrison[15] have shown that one should again measure to the center of the sphere, but that the effective fluence is increased by a factor of approximately $[1 + (r/d)^2/6]$, where r is the radius of the sphere, and d is the distance between the source and the center of the detector. Thus, for a source-detector spacing equal to the diameter of the sphere, $r/d = 0.5$ and the correction factor is 1.04. For a 12" Bonner sphere, a 50 cm spacing would make the correction almost completely negligible (1 1/2%). For an Andersson-Braun remmeter, we have found that the inverse square law is obeyed down to d = 35 cm, where the long axis of the remmeter is perpendicular to the line between the source and the center of the remmeter, and the distance is measured to the remmeter axis.

We are not aware of either calculations or systematic measurements for a spherical source and a spherical detector. In the absence of such data, we would recommend as a rule-of-thumb that the center-to-center distance be greater than the sum of the two sphere diameters.

V. Fluence to Dose Equivalent Conversion

The dose equivalent for a particular spectrum is calculated by convoluting the spectrum with the recommended energy-dependent fluence-to-dose-equivalent conversion factors.

For calculations involving the bare ^{252}Cf spectrum, we recommend the Grundl-Eisenhauer spectrum evaluation.[2,3] This evaluation seems to be generally accepted by the community of californium users, and calculations based on this spectrum (in areas such as reactor materials dosimetry) have generally given excellent agreement with measured values.[16] The evaluated spectrum is given in the Appendix, along with a 44-group representation generated from the evaluation.

A recent re-calculation by Ing and Cross[11] of the moderated Cf spectrum gives results which are in substantial agreement with their 1977 calculation.[17] We should like to thank Dr. Ing for permission to use his latest values prior to their formal publication.

The existence of several different "recommended" sets of fluence to dose equivalent conversion factors has been duly noted, and deplored, in the literature.[18,19,20] The position within the DOE community was given by Hankins in 1977,[21] when he recommended that the procedure in NCRP Report No. 38[22] be followed, including the recommendation for linear interpolation between neighboring values. Recent calculations by Cross[23] and by Chilton,[24] however, give values which are more consistent with the ICRP recommendations[25] (which specify log-log interpolation) than those of the NCRP. We assume that these recent results are more accurate than the older ICRP or NCRP conversion factors. The agreement between the new calculations, and the ICRP recommendations, is taken as a verification

of the ICRP-recommended conversion factors. We therefore recommend that the ICRP procedure be followed, including log-log interpolation. This has the further advantages of eliminating the non-physical cusps in the curves of conversion factor as a function of energy (see Fig. 1 of ref. 18), and of putting us in consonance with our European colleagues. We do not recommend use of the Cross[23] (or the Chilton[24]) values, because we do not feel that it is appropriate at this time to introduce yet another set of "recommended" conversion factors.

Using the ICRP conversion factors, the Grundl-Eisenhauer ^{252}Cf spectrum, and the 1981 Ing and Cross spectrum for moderated californium, we recommend the following conversion factors:

Bare ^{252}Cf:

Dose Equivalent Conversion = 3.33×10^{-5} mrem cm^2;

$$\text{Dose Equivalent Rate} = \frac{3.33 \times 10^{-5}}{4\pi} \times 3600 \frac{Q}{r^2}$$

$$= 9.54 \times 10^{-3} \, Q/r^2 \text{ mrem/hr},$$

Moderated ^{252}Cf:

Dose Equivalent Conversion = 9.3×10^{-6} mrem cm^2;

$$\text{Dose Equivalent Rate} = \frac{9.3 \times 10^{-6}}{4\pi} \times 3600 \times 0.89 \, Q/r^2$$

$$= 2.37 \times 10^{-3} \, Q/r^2 \text{ mrem/hr},$$

where Q is the bare source emission rate, in neutrons/second,
r is the source-detector distance in centimeters, as defined in §§ 4.

(The factor 0.89 in the expression for the dose equivalent rate from the moderated source takes into account the ∿ 11% loss of neutrons which are moderated in the D_2O to below the cadmium cut-off.)

The fluence to dose equivalent conversion factor for bare ^{252}Cf is not a sensitive function of credible variations in the spectrum shape. We have calculated that the uncertainty in the dose equivalent conversion, due to the uncertainty in the spectrum shape, is 0.5% (1σ). Thus, the uncertainty in the dose equivalent rate will be determined mainly by the uncertainty in the value of Q.

While the bare ^{252}Cf spectrum has been verified experimentally,[16] the moderated spectrum has not. Although for the moderated californium, the dose equivalent conversion is not a sensitive function of the spectral shape, the lack of experimental confirmation of the shape leads us to recommend that an uncertainty of 7% be assigned to the conversion factor for moderated ^{252}Cf.

VI. Corrections

A. Principles

We have thus far tacitly assumed an ideal irradiation facility in free space, so that dividing the source emission rate by $4\pi r^2$ gives the flux density at the dosimeter, and multiplying by the appropriate conversion factor gives the dose equivalent rate. In fact, we refer to these quantities as the "free field flux density" and the "free field dose equivalent rate," respectively, and their time integrals as the "free field fluence" and "free field dose equivalent." That is, they are the quantities which would exist if the irradiations were done in free space with no background due to air and room scattering and no source asymmetry. In practice, air scattering generally amounts to only a few percent, and the source asymmetry may be very small. However, since the albedo of fast neutrons from concrete and other building materials is greater than 0.5,[26] the contribution of room-reflected neutrons to the response of the dosimeter may be significant, particularly if the dosimeter is sensitive to the low energy neutrons resulting from room scatter.

These scattered neutrons have a different spectrum and a different variation with distance from the source. Therefore, they must not be considered a proper part of the calibration field, but should rather be considered a type of background, and appropriate corrections made. This follows from our fundamental point of view: the calibration factor should be a unique property of the dosimeter type and the neutron source spectrum, and should not be a function of the characteristics of the calibration facility. Thus, all calibrations should refer to the "free field" quantities, so that calibrations of the same dosimeter at different laboratories will give the same result, within the experimental uncertainties.

Several authors have been concerned with these problems for many years. For example, Schraube et al.[27] discussed them in their 1972 paper, and many laboratories have appropriate computer codes for dealing with them. As an alternative to computer calculations, the following paragraphs suggest a semi-empirical approach to making these corrections. While this approach makes use of computer calculations, it offers physical insight into the problem without, in many cases, requiring further significant calculations.

B. Air Scattering

Air transport calculations have very recently been made by R. C. McCall[28] using the Morse Monte Carlo code. This method is more appropriate for the problem than the earlier moments calculation of Simmons and Eisenhauer[29] which we previously used to estimate corrections for air scattering.

The results show that air in-scattering is approximately twice the out-scattering, so that the net effect is always to increase the fluence at the detector. The inscattered spectrum is, however, shifted to lower energies due to energy dependence and kinematics of elastic-scattering in nitrogen and oxygen. The effect of the in-scattered neutrons is represented by an

integral over the energy and angular response of the detector. The recommended corrections, listed in Table I, are derived from McCall's air scatter calculations[27] and Hankins energy response measurements.[30] An estimated factor of 0.8 has been applied to the in-scattered neutrons, for the two dosimeter listings in the Table to account for their anisotropic angular response. This factor is based on an analysis of recent measurements by T. L. Johnson.[12] The response of the spheres is assumed to be isotropic. For the purposes of this section, we will treat the quantities "fluence" and "dose equivalent" as a type of isotropic response.

Table I -- Net Increase in Response Due to Air Scatter

	Increase per Meter for	
Type of Response	Bare ^{252}Cf	Moderated ^{252}Cf
NTA Film, Polycarbonate Track Etch Dosimeter	0.5%	0.9%
Dose Equivalent	1.0%	1.5%
9" Spherical Remmeter	1.0%	2.3%
Albedo Dosimeter	1.1%	3.0%
Fluence	1.2%	4.0%
3" Sphere	1.7%	4.5%

Detector readings should be decreased by these percentages to obtain free-field values, although the correction is clearly negligible in many cases.

C. Room Return

Scattering from the room walls, ceiling and floor, or "room return," is not a new problem, and has been investigated at many laboratories in the past. We can divide the problem into two limiting cases. First, consider just a single reflecting surface. This would be the case for calibrations done out of doors, or in a room with, say, a concrete floor but with thin walls and roof. It has been shown[31] that the response to reflected neutrons from a source at height h can be predicted by postulating an image source at a distance h below the floor. If the distance from the image source to the detector is denoted by r_I, the relative response of the detector to the reflected and the source neutrons is given by

$$\frac{R_r}{R_o} = 2\alpha g \frac{\sigma_r}{\sigma_o} \cos\theta \left(\frac{r}{r_I}\right)^2 \quad , \qquad (1)$$

where R_r/R_o is the relative response of the detector to the reflected and the source neutrons,

α is the albedo of the reflecting surface,

g is a factor to account for anisotropic detector response,

σ_r and σ_o are the spectrum-averaged responses for the reflected and source neutrons, respectively,

r is the source-to-detector distance,

the specular angle θ is given by $\tan\theta = r/2h$; and

$r_I^2 = (2h)^2 + r^2$.

For $r \ll h$, eq (1) simplifies to

$$\frac{R_r}{R_o} = \frac{\alpha}{2} g \frac{\sigma_r}{\sigma_o} \frac{r^2}{h^2} \quad . \qquad (2)$$

(The value of R_r/R_o calculated from eq (1) differs from that obtained from eq (2) by less than 4% for $h>3r$.)

For epi-cadmium neutrons, α has the value of 0.54 for concrete and is about the same for dry soil, decreasing by $\sim$ 20% for saturated soil.[26] The value of g for reflection from a single surface will be determined primarily by the ratio of the response of the detector in the direction perpendicular to the surface and the response in the direction of the source.

Calculated values for the quantity $g\sigma_r/\sigma_o$ for various instruments are given in Table 2. A value of unity was assumed for g for all responses except the dosimeters. In this case g was set equal to 0.5, based on measurements by T. Johnson[12] of the relative response at 90° compared to the response in the forward direction.

Table 2 --Calculated Values of the Factor $g\sigma_r/\sigma_o$ for Single-Surface Reflection

Type of Response	$g\sigma_r/\sigma_o$ Bare ^{252}Cf	$g\sigma_r/\sigma_o$ Moderated ^{252}Cf
NTA Film, Polycarbonate Track Etch Dosimeter	.2	.3
Dose Equivalent	.37	.6
9" Spherical Remmeter	0.68	0.75
Albedo Dosimeter	1.0	0.6
Fluence	1.0	1.0
3" Sphere	1.8	1.1

Values in Table 2 can be substituted in eqs (1) or (2) to obtain the relative detector response due to single-surface reflections.

As an example, consider a 3" sphere and moderated californium source, 2 m above a concrete floor. For a 50 cm source-dosimeter spacing, eq (1) predicts R_r/R_o = 0.018; i.e., a 1.8% correction. Although eq (1) has not been explicitly verifed experimentally, the predictions are consistent with Monte Carlo calculations by McCall.[28]

Room return in the other limiting case, that of a completely enclosed concrete room, is a much more serious problem. Not only are there now six reflecting surfaces rather than one, but, on the average, each neutron makes $\sim$ 2 1/2 traversals of the room before being captured.[32] A theory for this case has been given by the present authors in a series of publications,[32,33,34] and hence only the results will be presented here. (A very similiar development had also been given earlier by Savinskii and Filyushkin.[35]) It has been shown that the room scattered neutrons are essentially uniformly distributed throughout the room, and that for bare californium in a concrete room:

$$\frac{R_r}{R_o} = 5.6\, g \frac{\sigma_r}{\sigma_o} \left(\frac{r}{r_c}\right)^2 \quad , \tag{3}$$

$$\text{with } 4\pi r_c^{\,2} = \Sigma A_i \quad , \tag{4}$$

where A_i is the area of the i^{th} surface of the room, and the summation is taken over the six room surfaces. The quantity r_c is the radius of a spherical cavity which has the same surface area as the actual calibration room. The other symbols have the same meaning as in eq (1). (The expression for moderated californium is identical except that the numerical coefficient is 4.5 rather than 5.6.)

Since the fluence of room return neutrons is approximately uniform throughout the room and the fluence of the source neutrons varies as $1/r^2$, if we first correct for air scattering, we can, in general, write for the total response, D:

$$D \equiv R_o + R_r = \frac{D_o}{r^2} + R_r \quad , \tag{5}$$

where D_o is the response at unit distance to the source neutrons alone. The quantity D_o is the quantity which we are trying to determine. Eq (5) is quite general, and similar expressions have been given before.[35,36]

Combining eqs (3), (4) and (5) gives

$$Dr^2 = D_0(1+Sr^2) \tag{6}$$

where $S \equiv 5.6\ g\frac{\sigma_r}{\sigma_0}\cdot\frac{4\pi}{\sum A_i}$. (7)

Thus, plotting Dr^2 as a function of r^2 should give a straight line whose intercept is D_0, the desired quantity. The slope will be D_0S, with S given by equation 7. The quantity S is, physically, the fractional room return correction at unit source-detector distance. Typical data are shown in Figures 1-3 for measurements taken with the Hankins albedo dosimeter. Figures 1 and 2 are data taken with bare ^{252}Cf in the LLNL and the NBS calibration rooms, respectively. Figure 3 shows data taken in the NBS room with the moderated source. The ordinate in these figures is the detector response per unit dose equivalent. Comparison of Figures 1 and 2 show that the value of D_0 obtained in the two facilities is the same to within 3% (.090 vs. .092) even though the room return corrections at one meter are 30% and 20% in the respective rooms. Comparison of Figures 2 and 3 shows that the room return correction for the albedo dosimeter is almost a factor of 4 less for the moderated source than for the bare source (5.4%/m^2 vs. 20%/m^2). (Figures 2 and 3 also show that the sensitivity (response per unit dose equivalent) of this dosimeter is more than twenty times as high for the moderated source than for the bare source (2.05 vs. .092).)

Room return corrections can thus be made either by calculation, using eqs (3) and (4), (or, equivalently, eqs (6) and (7)) or by making response measurements as a function of distance and fitting to eq (6). To calculate the room return by eq (3) (or (6)), Table 3 lists some values of $(g\sigma_r/\sigma_0)$ for bare and for moderated californium in an enclosed concrete room.

Table 3 -- Values of $(g\sigma_r/\sigma_o)$ for Enclosed Concrete Room

	Bare Cf	Moderated Cf
3" Cd. covered sphere	2.9	1.4
Albedo Dosimeter	2.1	.58
Fluence	1.0	1.0
9" spherical remmeter	.52	.86
Andersson-Braun Remmeter	.22	
Dose Equivalent	.35	.49

The values of $(g\sigma_r/\sigma_o)$ for dose equivalent is calculated, and that for fluence is unity by definition. The other values are determined from measurements of the quantity S and then solving eq (7) for $g\sigma_r/\sigma_o$. In general the measured values of S are in satisfactory agreement with calculated values.

While our experience indicates that the use of eqs (3) and (4), with the values tabulated in Table 3, will give the relative response to within 25%, there are two drawbacks to this approach. First, data are lacking for several popular dosimeter types; most notably for track etch dosimeters. (We would estimate that the response ratios for polycarbonate track etch dosimeters, or NTA film, would be approximately 80% of the response ratios for dose equivalent. This has not been verified experimentally.) Second, particular calibration facilities may differ in the scattering produced. For example, an iron-lined room gives considerably less room return than bare concrete.[32] In addition, the simple formulas probably don't apply to irregularly shaped rooms. Therefore the values of room return calculated from the data given here should be considered only as a first approximation. Where the calculations indicate that the correction will be significant (this will usually be the case for albedo dosimeters irradiated with bare californium), each laboratory should do its own set of measurements and experimentally determine its own room return correction. The measurements should be taken at several different distances, from $\sim$ 30 cm out to two or three meters. The data should first be corrected for air scattering (where significant) by subtracting the amount suggested in Section VI.B. The corrected data should then be plotted as indicated above, and the value of S obtained.

D. Anisotropic Emission and Scattering by Source Encapsulation

Neutron emission from californium itself is intrinsically isotropic, with negligible scattering. The californium must, however, be encapsulated, and there is a finite amount of scattering, both elastic and inelastic, from the encapsulation. In the usual case of cylindrical encapsulation, the ratio of in-to-out scattering will vary as a function of orientation and thus the emission will no longer be isotropic. The flux density at a distance r from a source whose absolute total emission rate is Q is then usually given as $Q/4\pi r^2 \cdot F(\theta)$, where $F(\theta)$ is the anisotropy factor. Since, however, the anisotropy is caused by both elastic and nonelastic processes, in general the anisotropy factor will be energy dependent and its effect will vary with detector response.

For a lightly encapsulated source, $F(\theta)$ is very close to unity. The NBS californium sources,[37] for example, are embedded in an aluminum pellet $\sim$ 6 mm in diameter by $\sim$ 6 mm high, placed in a stainless steel capsule with 0.5 mm thick walls. The californium sources sold by Amersham[38] are slightly larger: 8 mm in diameter by 10 mm high, and the Savannah River SR-Cf-100 series encapsulation is 9.4 mm in diameter and 33 mm high.[39] Recent calculations by one of the authors (CME) show that in the direction perpendicular to the cylinder axis, $F(\theta) = 1.01$ for the NBS sources; that is, in-scatter predominates over out-scatter to give a 1% increase in flux density. Hunt[40] has reported a measured anisotropy factor of $F(\theta) = 1.012$ for his Amersham californium sources, in good agreement with the calculated value for the similar-sized NBS source. The situation for the SR-Cf-100 series is less clear, since different combinations of type 304 stainless steel, 90% platinum -10% rhodium alloy, and zircalloy 2 are used for these doubly encapsulated sources. (Zircalloy 2 is a 98% zirconium, 1.5% tin, alloy.) The most common types of encapsulation are listed in the table below, in estimated order of increasing scattering and hence of increasing anistropy.

SR-Cf-100 Encapsulations

	Supplier	Inner Capsule	Outer Capsule
1)	Monsanto Research Corp.	Zircalloy	Zircalloy
2)	Monsanto Research Corp.	Stainless Steel	Stainless Steel
3)	Savannah River	Pt-Rh	Zircalloy
4)	Savannah River	Pt-Rh	Stainless Steel

Hunt has recently reported[41] a measured anistropy of $F(\theta) = 1.037$ for the Pt-Rh-Zircalloy capsule (number 3). We do not, at this time, have accurate measurements or calculations for the anisotropies of the other encapsulations, but we estimate that numbers 1 and 2 should be somewhat less than 3, and 4 possibly somewhat more. (We would like to thank Dr. Hunt for supplying us with the result of his anisotropy measurement.)

For work of the highest accuracy, the anisotropy factor should be applied as a correction to the readings of any device which measures fluence (e.g., long counters) or is sensitive to low energy neutrons (e.g., albedo dosimeters). Since, however, some of the inscattered fluence consists of neutrons which have been inelastically scattered to lower energies, calculations indicate that the effects of in-scatter and out-scatter more nearly balance for instruments which are less responsive to lower energy neutrons. Hence, for all practical purposes, it is probably not necessary to make any anistropy corrections for devices such as remmeters or polycarbonate track etch dosimeters.

It must be emphasized that these results only apply to small, lightly encapsulated sources. Hunt,[40] for example, reports a measured anisotropy factor $F(\theta) = 0.76$ for a large Am-Li source, viewed end-on. Hence, for large sources, calculations or measurements should be made for the specific source, and the correction factor applied to the detector response.

E. Summary of Correction Procedures.

We reiterate that the only way in which calibrations can be made comparable between one laboratory and another, and the only way in which new devices can be fairly compared to existing ones, is to reduce the calibrations to "free-field" conditions. This means that the fluence, or dose-equivalent, delivered to the device is calculated assuming a "free field." The various scattering contributions are then treated as backgrounds which are subtracted from the reading of the device under test. There are three sources of scattering background, each of which usually tends to <u>increase</u> the reading. Two of these, air scatter and source scatter, are often negligibly small, but room return is often very large. Some laboratories can readily make these corrections by Monte Carlo calculations. Other laboratories should do the corrections following the methods discussed earlier in this section, which are here briefly summarized.

1. Source Scatter (Section VI D)

This correction is independent of distance, and amounts to between $\sim$ 1% and $\sim$ 3% for lightly encapsulated sources and albedo dosimeters, and is essentially zero for remmeters or track etch dosimeters. For heavier encapsulations it must be determined by either measurement or calculation.

2. Air Scatter (Section VI B)

The relative contribution from air scatter increases linearly with source-detector distance. The numbers given in Section VI B may be used to estimate this correction.

3. Room Return (Section VI C)

The relative contribution of room return varies as the square of the source-detector distance, and can become very large for an indoor facility. As a first approximation, eqs (3) and (4) together with table 2 may be used. If this calculation indicates a large correction (say, > 20%), the room return correction should be explicitly measured for that particular facility, using the method suggested in VI C.

In an outdoor facility, "room" return is much less serious and may be calculated from eq (2), together with Table 1.

VII. Conclusions

We have described procedures for dosimeter and remmeter calibrations which will give well-defined results accurate to within the present state-of-the-art. Equally important, adoption of these procedures will assure different laboratories getting the same results for the same dosimeter.

VIII. Acknowledgments

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Appendix

The NBS fission spectrum evaluation of 1975, updated in 1976, is described up to 20 MeV by means of a reference Maxwellian, M(E), modified by four piecewise continuous segments below 6 MeV plus one exponential segment above 6 MeV. The reference Maxwellian is

$$M(E) = 0.667 \sqrt{E} \exp(-1.5E/2.13), \text{ E in MeV},$$

and the evaluated spectrum is $\chi(E) = \mu(E) \cdot M(E)$. The adjustment functions $\mu(E)$ are as follows:

Energy Interval (MeV)	$\mu_{Cf}(E)$
0.0 - 0.25	1 + 1.20E - 0.237
0.25 - 0.8	1 - 0.14E + 0.098
0.8 - 1.5	1 + 0.024E - 0.0332
1.5 - 6.0	1 - 0.0006E + 0.0037
6.0 - 20	1.0 exp[-0.03(E-6.0)/1.0]

A 44 group tabulation of this evaluated spectrum is given in Table A-1.

Table A-1

NEUTRON FLUENCE SPECTRUM OF ^{252}CF

E_{Hi}*	Fluence per Unit Lethargy	E_{Hi}*	Fluence per Unit Lethargy
50 keV	3.32×10^{-4}	3.0 MeV	4.29×10^{-1}
100	1.06×10^{-2}	3.4	4.02×10^{-1}
200	3.16×10^{-2}	3.7	3.67×10^{-1}
250	6.27×10^{-2}	4.2	3.26×10^{-1}
300	8.34×10^{-2}	4.6	2.78×10^{-1}
400	1.12×10^{-1}	5.0	2.40×10^{-1}
500	1.51×10^{-1}	5.5	1.99×10^{-1}
600	1.88×10^{-1}	6.0	1.61×10^{-1}
700	2.23×10^{-1}	6.5	1.27×10^{-1}
800	2.53×10^{-1}	7.0	9.90×10^{-2}
1 MeV	2.98×10^{-1}	7.5	7.64×10^{-2}
1.2	3.52×10^{-1}	8.0	5.86×10^{-2}
1.4	3.94×10^{-1}	8.5	4.45×10^{-2}
1.5	4.20×10^{-1}	9.0	3.38×10^{-2}
1.6	4.32×10^{-1}	9.5	2.53×10^{-2}
1.8	4.47×10^{-1}	10	1.90×10^{-2}
2.0	4.59×10^{-1}	11	1.24×10^{-2}
2.2	4.64×10^{-1}	12	6.84×10^{-3}
2.3	4.63×10^{-1}	13	3.72×10^{-3}
2.4	4.61×10^{-1}	14	2.01×10^{-3}
2.6	4.55×10^{-1}	16	8.31×10^{-4}
2.8	4.43×10^{-1}	18	2.30×10^{-4}

Normalized to one source neutron

Grundl, J. and Eisenhauer, C., "Fission Rate Measurements for Materials Neutron Dosimetry in Reactor Environments," Proceedings First ASTM-EURATOM Symposium on Reactor Dosimetry, EUR5667 e/f, Commission of the European Communities, Petten (September 1975).

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*Upper limit of energy interval.

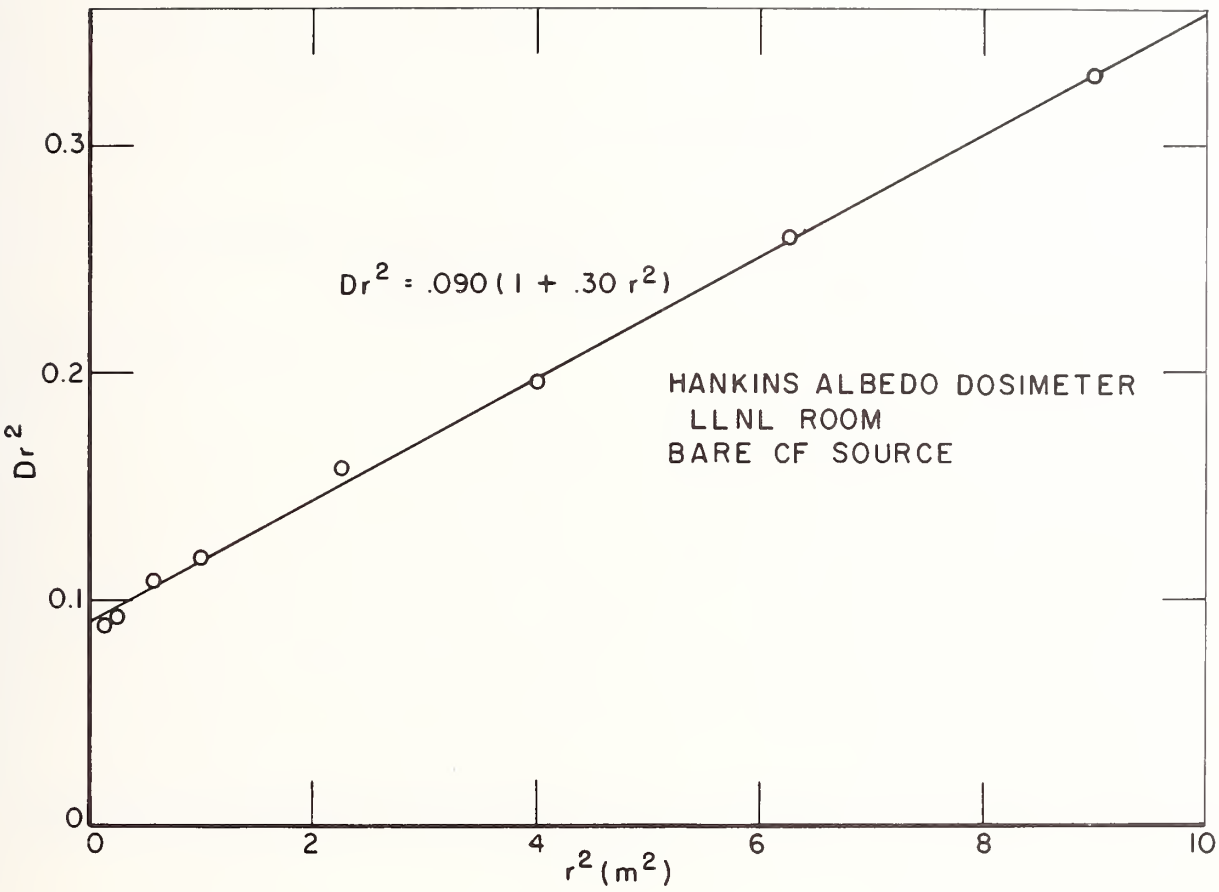

Figure 1 - Response of the Hankins Albedo Dosimeter per unit dose equivalent as a function of distance from the neutron source. The measurements were taken with a bare ^{252}Cf source in the LLNL calibration room. The data are fitted to an equation of the form

$$Dr^2 = D_0\,(1+Sr^2),$$

where D is the measured response at a source-to-detector distance r. The quantity D_0 (in this case equal to 0.090) is the response per unit dose equivalent at one meter, to the source neutrons alone, and is thus the reciprocal of the calibration factor. The quantity S (in this case equal to 0.30) is the fractional room return at one meter.

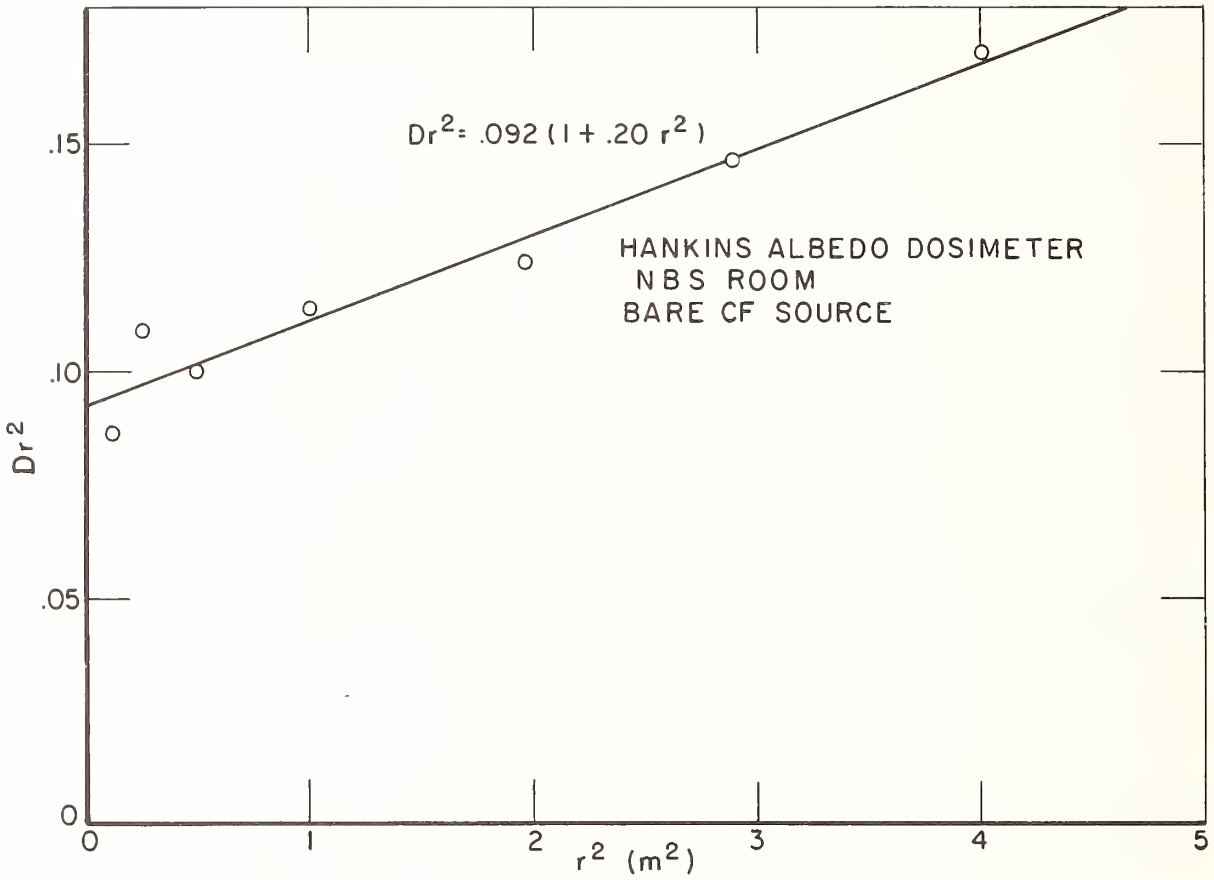

Figure 2 - Response of the Hankins Albedo Dosimeter per unit dose equivalent as a function of distance from the neutron source. The measurements were taken with a bare ^{252}Cf source in the NBS calibration room. The data are fitted to an equation of the form

$$Dr^2 = D_o\ (1+Sr^2),$$

where the quantities have the same meaning as in Figure 1.

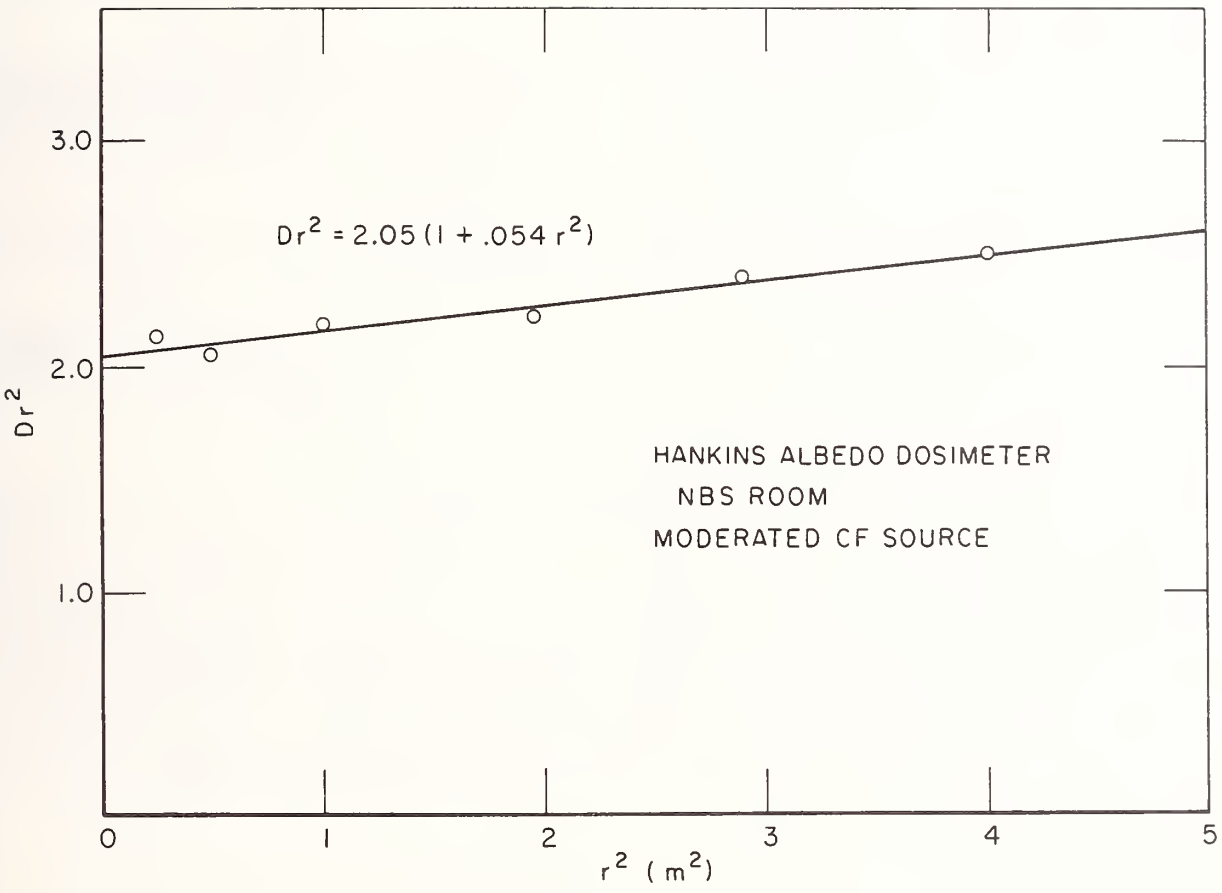

Figure 3 - Response of the Hankins Albedo Dosimeter per unit dose equivalent as a function of distance from the neutron source. The measurements were taken with a moderated ^{252}Cf source in the NBS calibration room. The data are fitted to an equation of the form

$$Dr^2 = D_o\,(1+Sr^2),$$

where the quantities have the same meaning as in Figure 1.

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Procedures are given for routine testing and calibration of neutron dosimeters and remmeters with radioactive neutron sources. The issues addressed include: the choice of neutron source; phantom construction; fluence to dose equivalent conversion; and the corrections for air scatter, room return, and anisotropic-neutron emission. Explicit, semi-empirical, analytic expressions are given for the room return correction, and calculated numerical values are given for air scatter.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

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