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CALIBRATION TECHNIQUES FOR NEUTRON PERSONAL DOSIMETRY

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Abstract–Techniques for calibrating devices used to estimate neutron dose equivalent are discussed. Procedures are recommended for making such calibrations, and for correcting them for effects such as neutron scattering in air and in the walls of the calibration room. Appropriate neutron source and detector combinations, source anisotropy, and optimum source-detector distances for calibrations are discussed. Corrections for neutron scattering using measurements with shadow cones and fitting procedures for detector response as a function of distance are considered, as are corrections predicted by means of simple analytic expressions.

INTRODUCTION

This article discusses techniques for calibrating devices used to estimate neutron dose equivalent received by workers in radiation areas. The word "calibration" is used here to mean one or more measurements by means of which the reading of a device is related to the maximum dose equivalent that would be produced in a tissue equivalent cylindrical phantom by the neutron field at the same location, in the absence of the device. The calibration factor should be a unique property of the device and the neutron source spectrum, and should *not* be a function of the characteristics of the calibration facility. Procedures are recommended for making such measurements and correcting them for effects such as neutron scattering in the walls of the calibration room. Although a calibration may require only a single measurement, many measurements may be required to determine the corrections which must be applied to that measurement. Where appropriate, procedures for making these preliminary measurements and determining correction factors are discussed. This article is not concerned with the measurement of response of a device to monoenergetic neutrons, although knowledge of the response function derived from such measurements may be necessary for calculating some corrections.

SOURCES

Standard sources

Radioactive neutron sources can be divided into three categories: (α,n) sources, employing one of the actinide isotopes as an alpha emitter; (γ,n) sources, using a radioisotope gamma ray emitter; and spontaneous fission sources. They can be further subdivided according to whether they are used "bare", or moderated. Recent reviews of radioactive neutron sources have been given by Knoll[1], Geiger[2], and Blinov[3]. An earlier, but still valuable, review was given by Kluge *et al*[4]. Griffith *et al*[5] have discussed a very complete set of moderated sources, and Schwartz and Eisenhauer[6] and Harvey and Bending[7] have suggested the use of particular moderated sources for calibrating neutron personnel dosemeters.

While it is true that many laboratories use Sb-Be(γ,n) sources, and that the primary standards at the national laboratories of the United States, the United Kingdom, and the Soviet Union are Ra-Be(γ,n) sources, the high ratio of gamma-to-neutron dose equivalent ($\sim 10^4$) intrinsic to (γ,n) sources makes them difficult to use for routine calibrations. We therefore do not recommend that any (γ,n) sources be used as standards for calibrating neutron personnel protection devices.

Among the (α,n) sources, probably the most widely used is Pu-Be. In many countries, however, plutonium is classified as a "special nuclear material" and has thus become very difficult to obtain, with many administrative and procedural difficulties hindering its use: thus, the only actinide neutron sources which we recommend as standards are those employing ^{241}Am as the α emitter. The highest neutron yield is obtained using beryllium as the target material, with boron the second highest. Although Am-F and Am-Li sources have also been used, their yields are, respectively, 20 and 50 times lower than Am-Be. Hence, following the recent ISO recommendations[8], we recommend that the (α,n) sources be limited to ^{241}Am-Be and ^{241}Am-B.

The only practical spontaneous fission neutron source is ^{252}Cf.

Two moderated sources have been advocated for use as calibration standards: Sb-Be moderated by 4 cm (radius) of water or plastic, surrounded by a 1mm thick shell of ^{10}B[7], and ^{252}Cf moderated by 15 cm of heavy water[6], covered with cadmium. A typical Sb-Be source gives a gamma dose equivalent approximately 10^4 times greater than the neutron dose equivalent. The moderator significantly lowers the neutron dose equivalent without much change in the gamma dose. Hence, the gamma dose equivalent for moderated Sb-Be is approximately 10^5 times the neutron dose equivalent[7], making its use very difficult. The only recommended moderated source is therefore D_2O-moderated ^{252}Cf.

It was noted in a recent paper[8] that four standard sources have been proposed in a recent ISO TC85 draft standard of the International Standards Organisation. We recommended the use of these four sources for calibration of neutron instruments. Table 1 lists the properties of the recommended neutron sources.

Choice of source type

The bare ^{252}Cf neutron source 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[3,9]. Sources are available in any reasonable strength and are physically small (approaching a point source) and relatively lightly encapsulated. The small size and light encapsulation mean that the neutron emission is close to isotropic (see section below on Source anisotropy). Finally, the gamma contamination is low. The principal disadvantage of ^{252}Cf is its relatively short half-life (2.6 y), which requires that it be replaced periodically. Whether to use "bare" ^{252}Cf or moderated ^{252}Cf is determined by the type of device to be calibrated and the neutron spectrum to which it (and the worker) are expected to be exposed, as discussed in the section on calibration considerations.

The only advantage of Am-Be or Am-B source is their long half-life (432 y), so that the sources need not be replaced. Their main disadvantage is that it may be difficult to get such sources (particularly Am-B) intense enough to test remmeters in their higher ranges. Specifically, most commercial remmeters will read up to 20 to 50 $mSv.h^{-1}$. This means that they should be calibrated in fields in the range of 10 to 40 $mSv.h^{-1}$. From Table 1, and assuming a minimum source-detector distance of 30 cm we see that this would require at least a 2×10^{12} Bq (~ 50 Ci) source, which is close to the upper limit of available source strengths.

Source emission rate

For doing any neutron calibrations, the neutron source emission rate ("source strength") must be accurately determined. For calibrating personnel dosemeters, however, one generally has a great deal of flexibility in choosing the appropriate source strength. It is only necessary to ensure that the source is not so weak that the irradiations become inordinately long (e.g., several days) nor so strong that the irradiation times become so short (i.e., a few minutes) that timing uncertainties may become important.

The choice of source emission rate is much more important for calibrating remmeters, however, since a remmeter should generally be calibrated at not less than one point for each decade of scale. A high dose equivalent rate may be achieved, of course, by simply moving the instrument close to the source. At small

Table 1. Reference radioactive neutron sources for calibrating neutron measuring devices.

Source	Half-life (y)	Neutron yield	Neutron dose equivalent rate constant	Photon dose equivalent rate constant	Mean neutron fluence-to-dose equivalent conversion factor
		$(s^{-1}.g^{-1})$	$(Sv.h^{-1}.g^{-1}.m^2)$	$(Sv.h^{-1}.g^{-1}.m^2)$	$(Sv.m^2)$
^{252}Cf with D_2O (moderator sphere $\Phi = 30$ cm)	2.65	2.1×10^{12}*	5.4	0.9	9.1×10^{-15}
^{252}Cf	2.65	2.3×10^{12}	22	1.1**	3.33×10^{-14}
		$(s^{-1}.Bq^{-1})$	$(Sv.h^{-1}.Bq^{-1}.m^2)$	$(Sv.h^{-1}.Bq^{-1}.m^2)$	
^{241}Am-B(α,n)	432	1.6×10^{-5}	1.8×10^{-16}	7×10^{-16}	3.93×10^{-14}
^{241}Am-Be(α,n)	432	6.6×10^{-5}	7.2×10^{-16}	7×10^{-16}	3.81×10^{-14}

*Yield for Cd covered sphere.

**Dose equivalent rate for 2.7 mm thick steel source encapsulation.

distances, however, the field no longer follows the $1/r^2$ law, since the remmeter is not a point detector. As a rule of thumb, the centre-to-centre distance from source to detector should always be at least twice the equivalent radius of the detector, and the appropriate corrections applied[10,11] (see section on Source-detector distance).

To obtain low dose equivalent rates, one obviously moves the instrument further away. The limit is set by the distance at which the room-scattered neutrons make an unacceptably large contribution to the instrument reading. Depending upon the size of the room, it may therefore be necessary to use two or more sources with different emission rates.

Much more intense sources are required for calibrating with D_2O-moderated ^{252}Cf than with bare sources, for two reasons. First, the fluence-to-dose equivalent conversion factor is almost exactly a factor of four lower for the moderated ^{252}Cf source as compared to the bare ^{252}Cf source (Table 1); second, the source is no longer a "point" source, and there are deviations from the $1/r^2$ law and changes in the neutron spectrum at distances closer to the centre of the source than ~ 30 cm[12,13]. As a rule of thumb, the minimum source-detector centre-to-centre distance should be greater than the sum of the diameters of the source and detector. For a remmeter of 20 cm diameter this means a minimum distance of ~ 50 cm. To allow for the decay, one should start out with a source at least two to three times more intense than the minimum required; hence for a rate of 15 $mSv.h^{-1}$ a source emission rate of $\sim 2 \times 10^9$ s^{-1} would be desirable. While such sources are readily available, they are expensive and difficult to handle.

An alternative to using such intense sources is calibrating the remmeter with bare californium, and then determining the ratio of the bare to moderated response at one or more convenient dose equivalent rates.

In order for a detector to be properly calibrated, it must be exposed to a source of known emission rate and spectrum. The emission rates of the recommended "bare" neutron sources are usually determined by calibration in a manganous sulphate bath. The emission rate of a moderated ^{252}Cf source is obtained by multiplying the emission rate of the ^{252}Cf fission source by 0.885, the calculated fraction of neutrons emerging from the cadmium shell of the moderated source[12,14]. The fluence rate at any point can be determined from the emission rate of the source, the anisotropy factor, and the distance from the source to the point at which the detector is to be placed. This is generally assumed to be the geometrical centre of the device and corrections are applied for the finite size of the detector and for the fact that the neutron field is divergent rather than monodirectional (see section on Source-to-detector distance).

Source anisotropy

Commercially manufactured radioactive neutron sources are generally cylindrical and doubly encapsulated in order to prevent any leakage. The neutrons emitted from the internal radioactive components undergo both elastic and inelastic scattering, so the emission varies with the effective path length through the encapsulation, and hence is not isotropic. The larger the ratio of the cylinder length to the diameter of the source, the greater the anisotropy, and so these effects should be minimised by ensuring, where possible, that this ratio is close to unity. Also the source-support structure should be as light as possible in order to minimise the correction for neutrons scattered in that structure.

For cylindrical sources having rotational symmetry, the neutron flux emitted into a small solid angle $d\Omega(\theta,\alpha)$, see Figure 1, centred about the direction Ω and characterised by the angles θ and α, should not depend upon the azimuthal angle α, but only upon θ. Since the neutron emission varies least in the direction perpendicular to the cylindrical axis (that is, $\theta = 90°$) this orientation should be used wherever practicable.

The neutron fluence rate in vacuum, in a direction θ, at a distance r, from the geometric centre of a source whose absolute total emission rate is Q, is then given by $QF(\theta)/4\pi r^2$, where $F(\theta)$ is the anisotropy factor[15]. This may be determined experimentally with a neutron device whose response is energy independent, such as a precision long counter (PLC), in the following way. The count-rate, $C(\theta)$ is

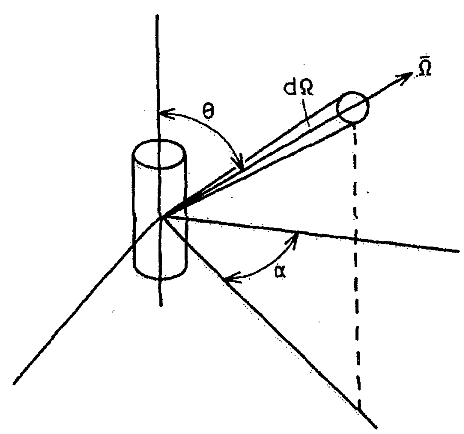

Figure 1. Neutron emission from a cylindrical source in a system of spherical coordinates r, θ, α.

determined as a function of the emission angle θ, and the anisotropy factor is calculated using

$$F(\theta) = \frac{2C(\theta)}{\int_0^{\pi} C(\theta)\, \sin\theta d\theta} \qquad (1)$$

Measurements should be made in increments of ten degrees or less.

For lightly encapsulated sources, with the cylinder length equal to the diameter, the anisotropy factor is very close to unity. Table 2 presents a summary of published[(15)] and unpublished[(16,17)] measured anisotropy factors determined in a direction perpendicular to the cylindrical axis, F(90°), for commercially available sources. It should be noted that these values are for guidance only, and that, for any accurate calibration work, these factors should be determined for the particular source.

Source spectrum

The source spectrum for a ^{252}Cf source is defined as the spectrum generated by the active ^{252}Cf. Any scattering in the encapsulation should be treated as an effect for which a correction must be made. Since the spectrum of scattered neutrons is generally different from that of the source neutrons, the correction is different for each detector response function. Most californium sources used for calibration purposes are lightly encapsulated so that the scattering is small and the spectrum change is very small. Thus, the difference in the correction factor between a fluence measuring device (e.g., long counter) and a dose equivalent measuring device is ≤1% for conventional Amersham or Savannah River encapsulations. The available experimental evidence indicates that the same is probably true for an Amersham Am-Be or Am-B source, although for highest accuracy the scattering should be measured explicitly.

For sources with large anisotropy factors, Equation 1 should be modified to allow for changes in the source spectrum due to both scattering within the encapsulation and to room return scattering within the calibration hall.

The source spectrum for the D_2O-moderated ^{252}Cf configuration is defined to be the spectrum of the current of neutrons leaking from the exterior of the Cd shell surrounding the sphere. No corrections are necessary for interactions in the D_2O, iron, or cadmium of the moderating sphere, since these interactions have already been taken into account in the calculated spectrum.

GENERAL CALIBRATION CONSIDERATIONS

Matching source energy distribution to detector response

The choice of the most appropriate source for calibration of a device depends both upon the spectra in the fields where the instrument is to be used and

Table 2. Anisotropy factors, (90°), for typical commercial neutron sources.

Neutron source type	Supplier	Capsule material	Approx. mass or activity of source	Capsule type	Overall diameter (mm)	Overall height (mm)	Overall wall thickness (mm)	Anisotropy factor F(90°)	Reference
^{252}Cf	Amersham	Stainless steel	<100 μg	X1	7.8	10.0	1.6	1.012	(15)
^{252}Cf	Monsanto	Zircalloy or stainless steel	<10 mg	2765	9.4	37.6	1.7	–	
		Pt-Rh alloy and zircalloy or stainless steel		SR-Cf-100				1.037	(16)
^{241}Am-B(α,n)	Amersham	Stainless steel	≤1 Ci	X3	22.4	31	2.4	1.035	(16)
^{241}Am-Be(α,n)	Amersham	stainless steel	≤1 Ci	X3	22.4	31	2.4	1.030	(16)
			≤10 Ci	X14	30.0	60.0	2.4	~1.04	(17)

upon the energy-response function of the measuring device. Ideally, the choice of instrument should be determined by how large an overlap exists between the energy response region of the detector and the neutron spectrum that is to be measured. If the choice of instrument has already been made, it is then highly desirable to choose a calibration source that has a significant fraction of its neutron spectrum in the energy range where the detector has a significant response. For example, if the device to be calibrated is an albedo neutron dosemeter – with its relatively weak response to neutrons above 1 MeV – then the bare ^{252}Cf source spectrum is not a good choice for a calibration source (see Figure 2). Only the high energy "tail" of the response function overlaps the low energy end of the bare ^{252}Cf spectrum, so that testing with a bare ^{252}Cf source would not necessarily give a good indication of its performance. Moderated ^{252}Cf is therefore preferred for testing albedo neutron dosemeters.

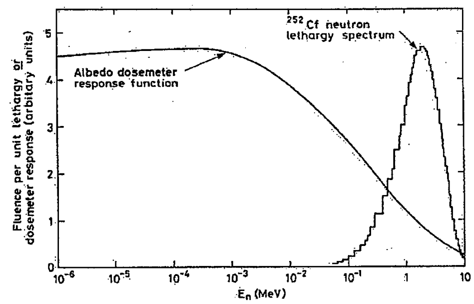

Figure 2. Fluence per unit lethargy for a bare ^{252}Cf source, and the albedo dosemeter response function.

Source-to-detector distance

There can be no single recommended source-to-detector distance for calibrating remmeters, since they should generally be calibrated over their entire working range. This covers, typically, a factor of $\sim 10^3$ in dose equivalent rate, and hence in influence rate, which means that several different distances must be used, as well as, possibly, more than one source.

The irradiation of dosemeters mounted on a phantom, however, is done at a single distance. The optimum value for that distance is a compromise between conflicting requirements. Too great a distance can lead to large room-scatter corrections (especially for albedo dosemeters) as well as, possibly, inconveniently long irradiation times. Too small a distance leads to non-uniform irradiation of the phantom, variation in the spectrum (for the moderated source), and uncertainty in the "effective depth" (see below), introducing a relatively large uncertainty in the calibration factor. Typically, distances between 50 cm and 1 m are generally used. Thus, the American Health Physics Society Standards Committee[18] recommends a 50 cm source-to-phantom distance. Increasing the distance to, say, 75 cm, would improve the unformity of illumination of the phantom, particularly if a large (40 cm × 40 cm) phantom is used.

The definition of distance for an albedo dosemeter exposed on a phantom is somewhat ambiguous, since the phantom is part of the albedo detector system. Measuring to the front face of the phantom is a convention, which has the great advantage of being well defined and easily reproduced. 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[19,20] that are consistent with an effective depth of 1 to 3 cm for albedo dosemeters irradiated with a ^{252}Cf source, we prefer to define the calibration distance as that from the source centre to the front 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 minimised if all measurements are made at the same distance.

For a spherical detector and a point isotropic neutron source, Axton[10] showed, using geometrical arguments, that the response of the device is increased by a factor of approximately $(1 + \delta a^2/4r^2)$ above that expected according to the inverse square law, where a is the radius of the sphere, and r is the distance between the geometric centres of the source and detector. The term $a^2/4r^2$ is the additional fractional number of neutrons entering the detector volume, and the parameter δ attempts to account for the relative effectiveness of these extra neutrons in producing a response in the detector. Axton[10] argued that δ is probably energy dependent, but independent of a/r and should have a value between 0 and 1. It was suggested that a value of 2/3 would generally be appropriate for all sphere sizes and neutron energies. Subsequently, Harrison[11] demonstrated, using the Monte Carlo technique, that these conclusions are substantially correct, even for devices with a relatively large detector at the centre to detect the thermal neutrons.

The above geometry factor contains only the first term of an expansion in terms of $(a/r)^2$, and the higher order terms become more important as the ratio a/r approaches unity[10,11]. It follows from Axton[10] that the exact expression for the geometry factor $F_g(a,r)$ is given by

$$F_g(a,r) = 1 + \delta\left\{\frac{2r^2}{a^2}\left[1-\left(1-\frac{a^2}{r^2}\right)^{1/2}\right]-1\right\} \quad (2)$$

Recent measurements by Johnson[21] and by Hunt[22,23] with physically small californium sources, have demonstrated that this relationship accurately relates the response obtained at very close distances, with a/r as large as 0.96, to that obtained at large separation distances. Although the value of δ is independent of a/r, it appears to be a function of the sphere radius a. For the 3" and 10" diameter spheres, δ has a value of about 0.4, but peaks at a value of approximately 0.65 for a 5" sphere[23].

One can minimise the effect of the uncertainty in δ by limiting the shortest source-detector spacing r to the diameter of the sphere (i.e., a/r = 0.5) and assuming an average value of δ of (0.5 ± 0.25) for all sphere sizes up to 45 cm diameter. For this case the first order correction factor, $1 + \delta a^2/4r^2$, is equal to 1.03 ± 0.02.

For cylindrical remmeters, where the geometry is clearly more complex, it has been found by one of the authors (J.B.H.) that the inverse-square law is obeyed down to a separation distance of 30 cm between the source and the remmeter axis for an irradiation perpendicular to the cylindrical axis. For a calibration with the cylindrical axis parallel to the source remmeter axis, the situation is very similar to the calibration of the long counter, and accurate calibrations will depend upon determining the (energy-dependent) effective centre[15], which will not necessarily correspond to the physical centre.

The geometry correction for a spherical, isotropic, neutron source (e.g., D_2O-moderated ^{252}Cf) irradiating a point detector is analogous to that for the point source and spherical detector, and Ing and Cross[24] have derived a geometrical correction factor similar to Equation 2. In addition, for the particular case of D_2O-moderated ^{252}Cf, spectral changes at distances close to the moderating sphere require that the detector be no closer than $\sim$ 30 cm from the sphere centre.

We are not aware of either calculations or systematic measurements for the combination of a spherical source and a spherical detector. A reasonable estimate might be obtained from a product of two factors of the type shown in Equation 2, using the source radius in one factor and the detector radius in the other factor. However, in the absence of experimental data, we would recommend as a rule-of-thumb that the centre-to-centre distance be greater than the sum of the two sphere diameters.

Dose equivalent

Calibration laboratories may specify the dose equivalent rate at the detector position. This is obtained by weighting the fluence spectrum with "fluence-to-dose-equivalent" conversion factors such as those recommended by the ICRP[25]. These spectrum-averaged conversion factors are quoted for the four reference sources in Table 1. If the recommended conversion factors change, new averaged dose equivalent rates must be calculated, even though the fluence rate may not have changed.

CALIBRATION TECHNIQUES

For an ideal irradiation facility in free space with no background due to air and room scattering and no source anisotropy a detector would exhibit what we call a "free-field response". In practice, air scattering generally amounts to only a few per cent, and the source anisotropy 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 dosemeter may be significant, particularly if the dosemeter 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. Calibrations of the same dosemeter at different laboratories will then give the same results, within the experimental uncertainties.

There are many techniques that have been used to evaluate scattering corrections necessary for proper calibration of neutron personnel instruments. These can generally be grouped into two categories. The first involves measurement of the total response to all neutrons followed by measurement of the scattered contribution by means of a shadow cone placed between source and detector. With a shadow cone in place, the detector is exposed only to neutrons scattered from air, the surfaces of the calibration room, and any structures in the room. This detector response can then be subtracted from the response measured with no shadow cone, to obtain the response from neutrons coming directly from the source. This method has the advantage that it makes use of an actual measurement of the scattered radiation. It has been used extensively at laboratories such as the National Physical Laboratory (NPL), U.K., and Physikalisch Technische Bundesanstalt (PTB), in Germany. Details of this technique are given in the next section.

In other techniques, one measures only the total response to all neutrons. A combination of calculations and subsidiary measurements is then used to correct the observed response to a response from source neutrons alone. These techniques are described in detail in later sections.

SHADOW-CONE TECHNIQUE

This technique has often been used with long counter detectors[15,27], and has recently been shown to be applicable to both spherical and cylindrical remmeters[23]. In order to apply this method accurately, the properties of the shadow-cone have to be well understood, and its shape must be matched to the particular source-detector geometry. This leads to a set of shadow-cones designed specifically for each type of detector to be calibrated and for each range of calibration distances.

Design of typical shadow-cone

The general configuration and size for a typical set of shadow-cones have been given by Hunt[15]. Each cone consists of two parts, a 20 cm long conical front end made entirely of iron and a 30 cm long rear section made of polyethylene, or a hollow truncated cone filled with paraffin wax. A shadow-cone constructed in this way has a negligible transmission for neutrons emitted by the recommended radioactive neutron sources. The diameter of the smaller front end should be larger than the longest linear dimension of any of the neutron sources used for calibrations. The cone half-angle is designed so that the instrument to be calibrated is completely shadowed at the calibration position. In order to avoid the possibility of "overshadowing", the solid angle subtended by the shadow-cone should be less than twice the solid angle subtended by the device under test.

Position of shadow-cone

The position of the shadow-cone within the source-detector geometry is very important[15]. At very small separation distances between the front end of the cone and the neutron source, the detector response to inscattered neutrons is low, because the cone itself does not allow neutrons emitted in the forward hemisphere, centred about the detector axis, to scatter into the detector. If the separation distance is increased, the detector response increases and then remains constant over a range of distances. The midpoint of this range is the optimum separation distance. Further increasing the source-to-cone separation distance produces a rapidly increasing response as the cone no longer fully shadows the detector.

If the detector is too close to the rear of the shadow-cone, then the base of the cone shadows the detector to incoming scattered neutrons, thereby reducing the response due to these neutrons. The closest distance between the cone and detector at which consistent measurements can be performed is difficult to determine experimentally. It has been found by experience that if the cone-detector distance is at least equal to the overall length of the cone, then a reliable estimate of the effect of the inscattered neutrons can be obtained. Any support system used with the shadow-cone should be left in position throughout the calibration.

With these considerations in mind, the minimum source detector separation distance, using the previously described shadow-cones, is approximately one metre. Although the technique has been shown to agree very well with the inverse-square law from this minimum distance to greater than five metres[15,23,28], it is recommended that separation distances near the minimum should be used in order to reduce the effects due to the inscattered neutrons.

Inverse square law measurements

The dose-equivalent rate at a distance r is obtained by multiplying the source emission rate by $F(\theta)\bar{h}_\Phi/4\pi r^2$, where $\bar{h}_\Phi$ is the mean fluence-to-dose-equivalent conversion factor. The shadow-cone technique determines the effects due to room-return neutrons and air inscattering, but does not account for air outscatter. This latter effect reduces the dose-equivalent rate at r. The relationship between the measured responses and the distance between the geometric centres of the source and the detector, r, is given by

$$(R_T - R_S)\,F_A(r) = D_o/r^2 \tag{3}$$

where R_T is the total response observed in open geometry, R_S is the observed response due to inscattered neutrons measured with the shadow cone in position and $F_A(r)$ is the air attenuation correction factor discussed in the next section. The quantity D_0, the response at unit distance due to the source neutrons alone, may be obtained by measuring both the total and inscattered responses as a function of distance, and applying a linear least squares analysis to the equation

$$\left[(R_T - R_S)\,F_A(r)\right]^{-1/2} = (D_0)^{-1/2}\, r \tag{4}$$

The gradient of the fitted line is then equal to $D_0^{-1/2}$. For non-spherical devices, consideration must be given to the possibility that the effective centre of the device may not be at the geometric centre. The overall consistency of the data should be tested by observing the change in the response D_0 as a function of the range of distances included in the analysis[15,29]. The response D_0 should be independent of either the minimum or maximum distance included in the analysis, or the overall range of distances included.

From Equation 3, the product $(R_T - R_S)\ F_A(r)\ r^2$ should be a constant for all values of r. The effects of both the inscattered and outscattered neutrons can be seen in Figure 3. In this case, the products $R_T r^2$, $(R_T - R_S)\ r^2$, and $(R_T - R_S)\ F_A(r)\ r^2$ are plotted as a function of the square of the separation distance r. These data were taken with a 3″ diameter Bonner sphere and a bare ^{252}Cf source in the low-scatter facility at the National Physical Laboratory[15]. Even in this very large room, with the source at least six metres from the floor or walls, the contribution due to inscattered neutrons for this particular source-detector combination is large: 35% at one metre and 115% at two metres, compared with that due to the source neutrons only. Despite these large corrections, the fully corrected product $(R_T - R_S)\ F_A(r)\ r^2$, (case iii) and hence the response D_0, is independent of the separation distance r.

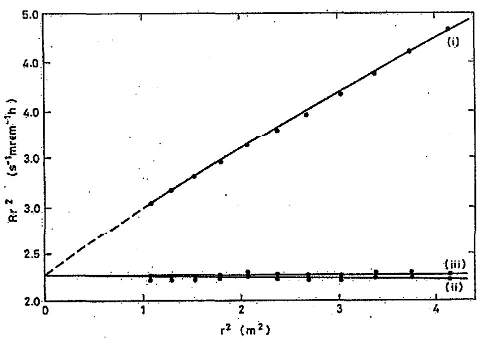

Figure 3. Response R times the square of the source-detector distance r for a ^{252}Cf fission neutron source and a 3″ diameter Bonner sphere in the NPL "scatter-free" calibration room. (i) $R_T r^2$, total response. (ii) $(R_T - R_S)r^2$, total response corrected for inscatter only. (iii) $(R_T - R_S r^2\ F_A(r)$, total response corrected for both inscatter and air-outscatter. Note suppressed zero.

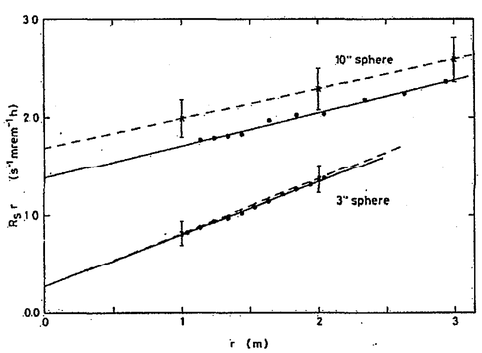

Figure 4. Inscatter response R_S times source-detector distance r, plotted against r, for a ^{252}Cf fission neutron source in the NPL "scatter-free" calibration room. The points are the values of the inscatter as measured with shadow cones, and the solid line is a fit to the measured points. The dashed lines are the values of inscatter derived from polynomial fits to the total response data. The error bars are the statistical uncertainties associated with the polynomial fitting technique (see text). (i) 3 inch diameter Bonner sphere, (ii) 10 inch diameter Bonner sphere.

Air attenuation correction factor

The air between the source and the detector wil scatter some neutrons away from the detector. The air attenuation correction factor, $F_A(r)$, is just the reciprocal of the neutron transmission of the air, i.e.,

$$F_A(r) = \exp\ (\bar{\Sigma}_{air}\ r') \qquad (5)$$

where r′ is the distance between the source and the front face of the device, and $\bar{\Sigma}_{air}$ is the spectrum-averaged macroscopic neutron total cross section of air. In order to obtain the appropriate spectrum-averaged cross section for the recommended sources, both the oxygen and nitrogen cross sections are folded over the neutron source spectrum. The resulting calculated macroscopic cross sections are given in Table 3 for air at 21°C, pressure 10^5 Pa, and 50% relative humidity.

GENERALISED POLYNOMIAL RELATIONSHIP

It has been pointed out before that for isotropic neutron sources at, or near the centre of a calibration room, the room-return component should be approximately constant in a region near the source[30]. Similarly, the air in-scattered component should be inversely proportional to the separation distance[31]. Combining these two relationships leads to the following expression for the inscatter as a function of distance

$$R_S = M + L/r \qquad (6)$$

where M is the room-return component and L is the air-scattered component. Shadow-cone determinations of inscatter, using cones matched to the source-detector geometry, for spherically symmetric devices, have recently been shown to follow this behaviour[23]. By applying the weighted least squares technique to the following equation

$$R_S r = M\,r + L \qquad (7)$$

the coefficients M and L are obtained.

Figure 4 shows the inscatter data obtained with 3″ and 10″ diameter Bonner spheres and a ^{252}Cf neutron source. This demonstrates that the inscattered response is predicted by Equation 7. For cylindrical devices, the data obtained with an Andersson-Braun remmeter, irradiated either "side-on" or "end-on", does not give as good agreement. This may be due to either the nonisotropic response of the device, or to the mismatch between the circularly symmetric cone and the rectangularly symmetric detector, in the "side-on" geometry.

Having demonstrated that Equation 3 adequately describes the total and inscattered data as a function of distance, and that Equation 6 describes the behaviour of the inscattered data alone, then these can be combined into a general relationship. Since $\Sigma r'$ is small and $r' \simeq r$, the air attenuation correction factor, from Equation 5 can be written

$$F_A(r) = \exp(\bar{\Sigma} r') \simeq 1 + \bar{\Sigma} r' \simeq 1 + \bar{\Sigma} r \simeq 1/(1-\bar{\Sigma} r) \quad (8)$$

Substitution of Equations 6 and 8 into Equation 3 leads to

$$R_T r^2 = D_0[1 + (L' - \bar{\Sigma})r + M'r^2] \quad (9)$$

where

$$L' = L/D_0 \quad \text{and} \quad M' = M/D_0 \quad (10)$$

A second order polynomial, with the mathematical form of Equation 9, has been shown to fit the measured data extremely well (within ± 3%) both for spherically symmetric and for cylindrical devices[23]. The response to inscatter alone can be derived from Equations 9, 10, and 6. Again, there is fairly good agreement between the inscatter response determined by the polynomial fit and that measured with shadow cones.

Figure 4 demonstrates this for both the 3″ and 10″ diameter spheres irradiated by a ^{252}Cf source in the "scatter free" area at the National Physical Laboratory. Table 4 gives an indication of the agreement between the shadow-cone technique, using Equations 2 and 3, and the polynomial expression, Equation 9. This gives the ratio of the inferred direct response D_0 at unit distance, using the two techniques for both a 3″ diameter and 10″ diameter Bonner sphere and the Andersson-Braun remmeter "side-on". The uncertainties are from statistical sources only, and are mainly associated with the polynomial fitting technique.

SEMI-EMPIRICAL TECHNIQUE FOR SUBTRACTION OF SCATTERING BACKGROUND

As an alternative to the methods discussed in the previous sections, the following paragraphs suggest a semi-empirical approach to making scattering corrections. This approach allows one to predict the scattering effects for a particular room design by means of a simple semi-empirical analytic expression. On the basis of this result decisions can then be made about the necessity for more time-consuming measurements or calculations.

Table 3. Macroscopic neutron total cross section of air, $\bar{\Sigma}_{air}$.

Radioactive Source	^{252}Cf with 15 cm radius D_2O moderater	^{252}Cf	^{241}AmB (α,n)	$^{241}AmBe$ (α,n)
Macroscopic cross section $\bar{\Sigma}\,10^{-5}\,m^{-1}$	3000	1060	820	880

Table 4. Ratio of the response D_0 derived from the polynomial technique to that obtained using the shadow-cone technique.

Device	3″ diameter Bonner sphere	10″ diameter Bonner sphere	Andersson-Braun remmeter "side-on"
Ratio	0.99±0.03	0.984±0.007	1.014±0.010

Table 5. Net increase in response due to air scatter.

	Increase per metre for (%)	
	Bare ^{252}Cf	Moderated ^{252}Cf
NTA film, polycarbonate track etch dosemeter	0.5	0.9
Dose equivalent detector	1.0	1.5
9 inch spherical remmeter	1.0	2.3
Albedo dosemeter	1.1	3.0
Fluence detector	1.2	4.0
3 inch sphere	1.7	4.5

Air scattering

Air transport calculations have very recently been made by McCall[32] using the Morse Monte Carlo code. His results show that air inscattering 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 the 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 5, are derived from McCall's air scatter calculations[32] and Hankins measurements of detector response functions[33]. Detector readings should be decreased by these percentages to obtain free-field values,

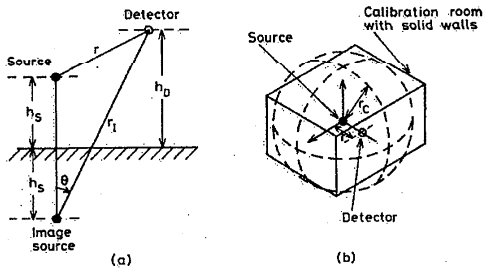

Figure 5. Schematic diagram showing parameters associated with the analysis of room-return neutrons. (a) Scattering by a single reflecting surface indicating the postulated image source, and (b) scattering in an enclosed room indicating the postulated radius r_C of the equivalent spherical cavity.

although the correction is clearly negligible in many cases. An estimated factor of 0.8 has been applied to the in-scattered neutrons for the two dosemeter listings in the Table to account for their anisotropic angular response. This factor is based on an analysis of recent measurements by Johnson[19]. The responses of the spheres and the ideal fluence and dose equivalent detectors are assumed to be isotropic. The latter two responses are included only for purposes of comparison. In this technique, corrections are not applied to the calculated fluence or dose equivalent, but are applied rather to detector readings. Similar calculations are being made for Am-Be and Am-B sources, but results are not yet available. The corrections are expected to be similar to those for bare ^{252}Cf.

Room return

Single-surface reflection

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. The problem can be divided into two limiting cases. First, consider just a single reflecting surface, such as shown in Figure 5(a). 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[34] 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

$$\frac{R_r}{R_0} = 2\alpha g \frac{\sigma_r}{\sigma_0} \cos\theta \left(\frac{r}{r_I}\right)^2 \qquad (11)$$

where R_r/R_0 is the relative response of the detector to the reflected and the source neutrons,

- α is the albedo of the reflecting surface,
- g is the factor to account for anisotropic detector response,
- σ_r and σ_0 are the spectrum-averaged responses for the reflected and source neutrons, respectively,
- r is the source-to-detector distance.

If $h_S = h_D = h$, then the specular angle θ is given by $\tan\theta = r/2h$; and

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

For $r << h$, Equation 11 simplifies to

$$\frac{R_r}{R_0} = \frac{\alpha}{2} g \frac{\sigma_r}{\sigma_0} \left(\frac{r}{h}\right)^2 \qquad (12)$$

(The value of R_r/R_0 calculated from Equation 11 differs from that obtained from Equation 12 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 ~ 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. The behaviour predicted by Equation 11 has recently been verified in an experiment by Li Lin Pei[35] for the case where source and detector are nearly on a vertical line ($\cos\theta \approx 1$). His measurements were made with a fission ionisation chamber containing ^{235}U foils.

Calculated values for the quantity $g\sigma_r/\sigma_0$ for various instruments are given in Table 6. A value of unity was assumed for g for all responses except the albedo dosemeter. For this detector g was set equal to 0.5, based on measurements by Johnson[19] of the relative response at 90° compared with the response in the forward direction. The value of (σ_r/σ_0) for an ideal dose equivalent detector is calculated and that for an ideal fluence detector is unity by definition.

Reflection from surfaces of a room

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 ~ 2½ traversals of the room before being captured[36]. A theory for this case has been given in a series of publications[36-38]; hence only the results will be presented here. (A very similar development had also been given earlier by Savinskii and Filyushkin[39].) It has been shown that the room scattered neutrons are essentially uniformly distributed throughout the central portion of the room, and that for bare californium in a concrete room

$$\frac{R_r}{R_0} = 5.6\,g\frac{\sigma_r}{\sigma_0}\left(\frac{r}{r_c}\right)^2 \qquad (13)$$

with

$$4\pi r_c^2 = \Sigma A_i \qquad (14)$$

where A_i is the area of the ith 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 (see Figure 5(b)). The other symbols have the same meaning as in Equation 11. (The expression for moderated californium is identical except that the numerical coefficient is 4.5 rather than 5.6).

Table 7 lists some values of $(g\sigma_r/\sigma_0)$ for bare and for moderated californium sources in an enclosed concrete room. Values for the ideal fluence and dose equivalent detectors are calculated. The other values are determined from measurements of the quantity R_r/R_0 and then solving Equation 13 for $g\sigma_r/\sigma_0$.

The relative room return can also be obtained directly from measurements. Since the fluence of room return neutrons is approximately uniform throughout the central portion of the room and the fluence of the source neutrons varies as $1/r^2$, the total response, R_T^C, corrected for air scatter is given by

$$R_T^C = R_0 + R_r = \frac{D_0}{r^2} + R_r \qquad (15)$$

where D_0, the response at unit distance to the source neutrons alone, is the main quantity to be determined. Comparison with Equations 9 and 10 shows that R_r is equivalent to $M = M'D_0$. However R_r and M may have different values because they are estimated in different ways. Equation 15 is quite general, and similar expressions have been given before[37-40].

Equation 15 can be written as

$$R_T^C r^2 = D_0(1 + Sr^2) \qquad (16)$$

where

$$S \equiv R_r/D_0 \qquad (17)$$

Thus, plotting R_T^C as a function of r^2 should give a straight line whose intercept is D_0, the desired quantity. The slope R_r is the constant room return correction. The quantity S is, physically, the fractional room return correction at unit source-detector distance. It is equivalent to M' in Equation 9. Typical data are shown in Figure 6 for measurements taken with the Hankins albedo dosemeter and a bare ^{252}Cf source in the Lawrence Livermore National Laboratory (LLNL) and the National Bureau of Standards (NBS) calibration rooms. The ordinate in this figure is the ratio of the detector response to the calculated dose equivalent due to source neutrons alone. Comparison of the data in Figure 6 shows that the value of D_0 obtained in the two facilities is the same to within 3% (0.090 vs 0.092) even though the room return corrections at one metre are 30% and 20% in the respective rooms.

Room return corrections can thus be estimated either by calculation, using Equations 13 and 14, or

Table 6. Calculated values of the factor $g\sigma_r/\sigma_0$ for single-surface reflection.

	Bare ^{252}Cf	Moderated ^{252}Cf
NTA film, polycarbonate track etch dosemeter	0.2	0.3
Dose equivalent detector	0.37	0.6
9-inch spherical remmeter	0.68	0.75
Albedo dosemeter	1.0	0.6
Fluence detector	1.0	1.0
3-inch sphere	1.8	1.1

Table 7. Values of $(g\sigma_r/\sigma_0)$ for enclosed concrete room.

	Bare ^{252}Cf	Moderated ^{252}Cf
3-inch cadmium covered sphere	2.9	1.4
Albedo dosemeter	2.1	0.58
Fluence detector	1.0	1.0
9-inch spherical remmeter	0.52	0.86
Andersson-Braun remmeter	0.22	
Dose equivalent detector	0.35	0.49

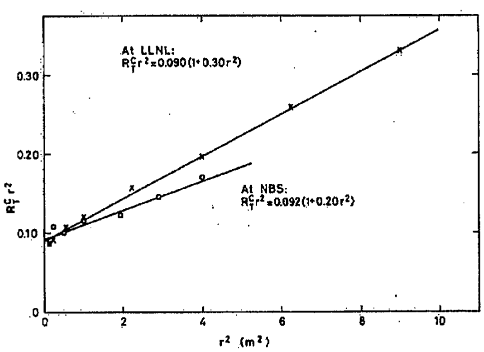

Figure 6. Air-scatter-corrected, response (R_T^C) times the source-detector distance (r) squared for a ^{252}Cf fission neutron source and the Hankins albedo dosemeter in: (i) the Lawrence Livermore National Laboratory calibration room, and (ii) the National Bureau of Standards calibration room.

by making response measurements as a function of distance and fitting to Equation 16. From Equations 13 to 17 it can be seen that the calculated value of the relative slope is given by

$$S = 5.6\,g\,\frac{\sigma_r}{\sigma_0}\cdot\frac{4\pi}{\Sigma A_i} \qquad (18)$$

While our experience indicates that the use of Equation 18, with the values tabulated in Table 7, will give the value of S to within 20% to 25%, there are two drawbacks to this approach. First, data are lacking for several popular dosemeter types; most notably for track etch dosemeters. (We would estimate that the response ratios for polycarbonate track etch dosemeters, 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[38]. In addition, the simple formulas probably don't apply to irregularly shaped rooms. Therefore the values of room return calculated from Equation 18 and Table 7 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 dosemeters irradiated with bare californium), each laboratory should do its own set of measurements and, using Equation 16, experimentally determine its own room return correction. The measurements should be taken at several different distances, from ~ 30 cm out to two or three metres. The data should first be corrected for air scattering (where significant) by subtracting the amount suggested at the start of this section. The corrected data should then be plotted as indicated above, and the value of S obtained.

COMPARISON OF METHODS

Equivalence of methods

Mathematically, the two expressions given in Equations 9 and 16 are equivalent, as can be seen from the following arguments. When the air scattering component is small compared with the room return (see previous section), we may re-write the polynomial in Equation 9 as

$$R_T r^2 = D_0(1 + M'r^2)[1 + (L' - \Sigma)r]$$

The total response, corrected for air scatter, is therefore given by

$$R_T^C r^2 = \frac{R_T r^2}{[1 + (L' - \Sigma)r]} = D_0(1 + M'r^2) \quad (19)$$

This is the mathematical form given in Equation 16.

The two methods should be totally equivalent provided two conditions are satisfied. First the 1/r term is entirely due to air-scatter, that is $(L - \Sigma)r$ is given by the values quoted in Table 5, and secondly, the room-return component is constant throughout the range of measurement distances covered.

Experimental verification

For most types of dose-measuring instruments, there is no "right answer" known *a priori* for the calibration factor. Therefore, the only experimental way to check the various calibration methods is to ascertain that data measured as a function of distance follow the expected functional form, and that the same value for the calibration factor is obtained by different techniques or by measurements under different circumstances, e.g., at varying distances from the source or in different rooms. The data supporting the different types of calibration methods have been discussed in the appropriate sections of this paper. One other set of measurements requires particular mention, however.

H. Kluge[28] of the Physikalisch-Technische Bundesanstalt (PTB) has calibrated a spherical remmeter, using shadow cones, in both the small PTB "Bunker" – a nearly cubical concrete room 7 m on a side – and in the PTB large experimental hall (24 m × 30 m × 14 m). (This experiment is to be the subject of a forthcoming paper by Kluge, and hence we shall not discuss it in detail.) The data were first analysed by shadow-cone analysis (see appropriate section). The "total" data (i.e., the readings taken without the shadow cone) were then analysed using the semi-empirical technique. The values of D_0 obtained by the two methods for the "Bunker" data agreed to within ~ 1½%, and the value of S obtained from the slope of the fit to Equation 16 agreed to within ~ 20% with that predicted from Equation 18 and the values in Table 7.

Shadow cone analysis of the data taken in the large experimental hall gave essentially the same value for D_0 as obtained from the "Bunker" data. The "total" data taken in the large hall did not, however, have the form predicted by Equation 16: a plot of Rr^2 vs r^2 was not a straight line, but was curved in the same way as curve (i) in Figure 3. Since we have observed this same failure to follow the form predicted by Equation 16 for data taken in other very large calibration rooms (most notably the 25 m × 18 m × 18 m hall at NPL) we must conclude that the semi-empirical method, while successful in small and intermediate-sized calibration rooms, breaks down in very large rooms. We estimate that the dividing line occurs for rooms with average linear dimensions of approximately 10-12 m; the method works well for smaller rooms, but not for larger ones. At the time of writing, we do not understand the reason for this behaviour.

Choice of method

In this section we will summarise the advantages and disadvantages of the various calibration methods discussed in the earlier sections.

Shadow cones

The shadow cone technique has a long history of giving consistent, reproducible, results. It has the great advantage of directly measuring the effect of the scattered neutrons, so that the response to the scattered neutrons may be unambiguously subtracted from the total reading. While this technique can be used in any size room, the fact that the minimum source-detector distance is ~ 1 m suggests that shadow cones are best suited for larger calibration rooms; in a small room the room scatter at 1 m may be already quite large, and thus the attempt to get far enough away from the source to measure the scatter may make the scatter unacceptably large. Another drawback of the 1 m minimum distance arises from the fact that to obtain a dose equivalent rate of, say, ~ 20 mSv h^{-1} at 1 m requires a (californium) source emission rate of $\sim 2 \times 10^9$ s^{-1}. Finally, there are no data for shadow cone calibrations of very large detectors (e.g., 40 cm $\times$ 40 cm phantom), or for calibrations using physically large sources (e.g., 30 cm diam., D_2O moderated californium). Shadow cones for such situations would have to be very large and cumbersome, and the specific techniques previously described would not necessarily be appropriate.

Generalised polynomial fit

We have shown, based on data taken in the NPL low-scatter room, that the generalised polynomial method gives results in excellent agreement with those obtained by the shadow cone method. At the start of this section we showed that the semi-empirical method and the generalised polynomial method were mathematically equivalent, but then we pointed out that the semi-empirical method does not work in the large NPL or PTB rooms. This contradiction is caused by the fact that while the $(L' - \bar{\Sigma})r$ term is formally identified with air-scatter, the numerical values of $(L' - \bar{\Sigma})$ obtained from analysis of data taken in the very large rooms turn out to be five to ten times larger than those listed in Table 5. The reason for this is not at all understood, since it is very unlikely that the values for air-scatter listed in Table 5 are very much in error. In view of this problem, one must consider the polynomial fit method as just that – a two-parameter fit to the data, where the physical significance of the parameters may not be obvious.

In principle, the polynomial fit method can be used in any size room, but in practice is limited to rooms sufficiently large for $(L' - \bar{\Sigma})$ not to be too much smaller than M' in Equation 9. In smaller rooms, where M' is the dominant term, experimental uncertainties can then lead to large uncertainties in determining the $(L' - \bar{\Sigma})$ term, in turn leading to large uncertainties in the derived value of D_0. The method does permit working at small source-detector distances; in fact, for spherical detectors, the source can be as close as one sphere radius to the surface of the device if the geometry correction discussed earlier is included in the polynomial formulation[23]. This method is the method of choice for calibrating large detectors or using large sources in a large calibration hall. It must be borne in mind, however, that Equation 9 is fairly general, and that there is essentially no theoretical guidance for the values of the coefficients of the r and r^2 terms, and thus no internal checks for consistency. Hence, before this method can be used in a particular laboratory for routine calibration, it must be carefully checked against another method, such as the shadow cone method. Note also that if the device being calibrated suffers from such defects as non-linear response or drift, these faults may be masked by the fitting procedure. Thus, the method must be used with great care, and only for devices which are known to be reasonably stable and linear in response.

Semi-empirical method

As indicated above, this method should not be used in very large rooms. It has, however, been used extensively for calibrations in smaller rooms. It has the great advantage that, using Equation 18 and the data in Table 7 (or, for single-surface reflection, Equation 12 and Table 6) one can, to first order, calculate the expected room scatter without making any measurements at all. This can be very useful to guide the design of new facilities, and, in general, to determine whether or not a serious scatter problem exists for a particular facility. In addition, Equation 18 allows one to scale values of S, determined in one room or for one type of detector, to determine the scattering response expected in a different sized room or with a different detector.

For maximum accuracy, S should be determined in each facility, for each detector type, by making measurements as a function of distance and fitting Equation 16. Once this is done, the value of S so obtained can be used to correct readings of other instruments of the same type, without redoing the fitting procedure. The method can be used for any size source or detector, and, as with the polynomial fit method, can be used quite close to the source as long as the appropriate correction is made.

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