No. 49

Measurement

Good Practice Guide

The Assessment of Uncertainty in Radiological Calibration and Testing

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Abstract

A brief summary of the principles of the treatment and expression of uncertainty is given. The evaluation of uncertainty in several key areas of radiological measurement is illustrated by examples showing the application of those principles to photon dosimetry, neutron area survey monitoring and radioactive surface contamination monitoring.

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Foreword

The need for an internationally-accepted procedure for the treatment and reporting of uncertainties in measurement has been recognised for some time. In 1981 the Comité International des Poids et Mesures (CIPM) approved outline recommendations from national standards laboratories and the ISO was asked to develop a guide applicable to all levels of metrology. A working group (ISO/TAG4/WG3) was set up and, as a result, the ISO *Guide to the Expression of Uncertainty in Measurement* [1] was published in 1993.

Prior to this time, a working group of the United Kingdom Accreditation Service (UKAS) produced the NAMAS publication B0825, *The Expression of Uncertainty in Radiological Measurements* [2], although this contained no advice specific to radiological measurements. UKAS published M 3003, *The Expression of Uncertainty and Confidence in Measurement* [3] in 1997. This is consistent with the ISO *Guide* and contains examples of the application of the theory for several fields of measurement but excluding radiological measurements.

Recognising the need to revise the guidance set out in B0825 to bring it in line with the ISO *Guide* and M 3003, the Ionising Radiations Metrology Forum (IRMF) set up a working group in 1996 to advise UKAS on how best to revise B0825. However, with the decision by UKAS to withdraw B0825 altogether, it was decided to produce the present good practice guide, whose main purpose is to augment existing guidance in M 3003 with examples for several areas of radiological measurement.

It is not intended to describe all possible sources of uncertainty in these areas; nor is it intended to tell users which ones they must put into their uncertainty budgets. Nor is this document intended either to be a guide on how to make measurements. The values used in the examples are for illustrative purposes only; each laboratory must evaluate the values applicable to the conditions concerned.

For convenience, a brief summary of the theory is given in the present publication. This is based on publication M 3003, which, along with the ISO *Guide*, is strongly recommended as further reading for detailed background information and for coverage of additional topics. The examples in this guide are based partly on experience gained with the IRMF comparisons of calibrations in the areas of gamma dose monitoring, neutron area survey monitoring and surface contamination monitoring. These exercises have underlined the need for a consistent approach to the treatment of uncertainties in those areas. The format of the examples in this guide follows that of the examples in M 3003.

In accordance with IRMF policy, it is intended to formally review this guide within five years of publication. The IRMF will appoint a working group to carry this out. In the meantime, readers may send any comments or corrections to the *Secretary, IRMF*, at the National Physical Laboratory. These will be considered and incorporated if appropriate.

The definitive version of the guide is the version maintained on the IRMF website (part of the NPL website). Any changes, as a result of comments and corrections notified to NPL since the document was first published are shown in red within the text and are also listed at the end of the website version.

The IRMF consists of representatives of a wide range of UK organisations involved in the measurement of ionising radiation. One of the major aims of the Forum is the promotion of good measurement practice through the production of guidance material based on what is currently considered by practitioners in this field to be good practice. A further activity is the organisation of measurement comparisons in the UK.

The Assessment of Uncertainty in Radiological Calibration and Testing

Contents

Glossary

The following terms are used in this document:

Bias	Constant error that produces a consistent deviation from true value.
Calibration	Procedure to establish a quantitative relation between the response of an instrument and the quantity to be measured.
Calibration Coefficient	Coefficient by which a reading is multiplied to obtain the quantity being measured. Reciprocal of response.
Calibration Factor	Factor by which a reading is multiplied to obtain the quantity being measured. The term *factor* is used instead of *coefficient* when the reading and quantity have the same dimension.
Confidence Level	Number expressing degree or level of confidence in the result. Usually expressed as a percentage or as a number of standard deviations.
Coverage Factor (k)	Number that is multiplied by the combined standard uncertainty to give an expanded uncertainty for a given confidence level.
Divisor	Number by which an uncertainty is divided in order to obtain the associated standard uncertainty
Degrees of Freedom	The number of terms in a sum minus the number of constraints on the terms of the sum.
Error	A deviation from the true value.
Expanded Uncertainty	The standard uncertainty (or combined standard uncertainty) multiplied by a coverage factor for a given confidence level
Probability Distribution	A function giving the probability that a random variable takes any given value.
Repeatability	Intrinsic instrument variability – a measure of the agreement between repeated measurements of the same quantity under unchanged conditions of measurement.
Reproducibility	A measure of the agreement between repeated measurements of the same quantity under changed conditions of measurement.
Response	Ratio of the observed reading of an instrument to the true value of quantity producing the reading. Reciprocal of calibration coefficient
Sensitivity coefficient (c_i)	Coefficient by which the uncertainty of an input parameter is multiplied to give the corresponding uncertainty component of the quantity being measured.

Standard Deviation	Positive square root of the variance.
Standard Deviation of the Mean (SDOM)	Standard deviation of mean of a series of results of measurements of the same quantity made under unchanged conditions. Formerly known as Standard Error of the Mean.
Standard Uncertainty	Uncertainty of a measurement expressed as a margin equivalent to plus or minus one standard deviation
Traceability	Ability to relate measurements to national or international standards through an unbroken chain of calibrations that are carried out in a technically sound manner.
Uncertainty	Parameter associated with the result of a measurement that characterises the dispersion of the values that could reasonably be attributed to the quantity being measured.
Variance	A term used to describe the dispersion of a set of observations with respect to its arithmetic mean. Variance is equal to the mean square deviation from the arithmetic mean.

1 Treatment of Uncertainties

The expression of the value of the result of a measurement, y, is incomplete without a statement of its evaluated uncertainty, U. This characterises the range in which the "true value" is estimated to lie with a given level of confidence. The measured value (or output quantity) is determined as a function $f(x_i)$, of input parameters x_i that must be either known, measured or otherwise estimated.

The uncertainty associated with a measurement is due to a combination of the uncertainties, δy_i, arising from those of the input quantities, δx_i. There is no fundamentally "correct" method of combining these uncertainties. This section describes an internationally-accepted procedure for the treatment and expression of uncertainty. It is based on the published ISO *Guide to the Expression of Uncertainty in Measurement* [1].

1.1 Basic Concepts

Each x_i has an associated uncertainty δx_i that is a parameter characterizing the spread of values within which x_i is believed to lie. If x_i may lie anywhere within a specified range of values with equal probability, it is said to have a rectangular probability distribution and the uncertainty is expressed in terms of the value for the semi-range. Alternatively, the probability distribution can be normal (i.e. Gaussian), and the standard deviation (or a given multiple of the standard deviation) may be used.

An uncertainty should always be expressed in terms of a numerical value with an associated level of confidence. The type of probability distribution should also be given.

Each uncertainty may be expressed as a standard uncertainty, $u(x_i)$, that may be derived by dividing δx_i by a number that depends on the probability distribution of δx_i. The standard uncertainty is equivalent to one standard deviation and is a key quantity in the combination of uncertainties (see 1.4 below).

Some common types of probability distribution associated with uncertainties along with the parameters usually chosen, the confidence levels and the divisors are shown in Table 1.1.

Table 1.1 Common types of uncertainty

Distribution	Parameter	Confidence level	Divisor
Normal	1 standard deviation	67.7%	1.0
Normal	2 standard deviations	95.5%	2.0
Normal	3 standard deviations	99.7%	3.0
Rectangular	semi-range	100%	$\sqrt{3}$
Triangular	semi-range	100%	$\sqrt{6}$

Each $u(x_i)$ gives rise to a corresponding standard uncertainty, $u_i(y)$, in the output quantity. This may be expressed as

$$u_i(y) = c_i\, u(x_i),$$

where c_i is a sensitivity coefficient that is equal to the partial derivative –

$$c_i = |\partial y/\partial \mathbf{x_i}|.$$

To express the standard uncertainty in the output quantity in fractional terms the *relative* sensitivity coefficient is $(\partial y/\partial \mathbf{x_i})/y$. For simple expressions such as

$$y = x_1 / x_2,$$

the standard uncertainties then become $u(x_1)/x_1$ and $u(x_2)/x_2$ in fractional terms. More often, the standard uncertainties are derived in percentage terms as $100.u(x_1)/x_1$ and $100.u(x_2)/x_2$.

Examples of the derivation of sensitivity coefficients are given in Section 4.

1.2 Type A Uncertainties

The traditional classification of uncertainty components as random and non-random (sometimes termed "systematic") has been superseded by a system based on the method used to estimate their values. By definition, Type A uncertainties are those that can be evaluated using statistical techniques and Type B uncertainties are those that are evaluated by other means.

A Type A component of uncertainty is a measure of the repeatability of a result under constant conditions and can usually be assumed to have a normal probability distribution. It can be determined by series of measurements (y_i) in which an estimate, $s(\sigma)$, of the standard deviation, σ, is obtained by a series of n measurements, applying –

$$s(\sigma) = \left(\frac{\sum (y_i - y_m)^2}{(n-1)} \right)^{1/2}$$

where y_m is the mean value of y.

The standard deviation of the mean is $s(\sigma)/\sqrt{n}$. This is the value to be used for the summation in quadrature for obtaining the combined standard uncertainty (see 1.4 below).

1.3 Type B Uncertainties

All uncertainties that are not Type A, that is those that cannot be determined by a series of repeated measurements, are Type B uncertainties. These are effectively uncertainties that remain constant during one or more series of measurements. They arise from a variety of sources and the probability distributions may take a variety of shapes. Practical guidance on evaluating Type B components is given in [1].

The values for some Type B components may be already determined and quoted by an external agency, e.g. the uncertainty for a reference standard is usually given on the certificate issued by the standardising body. The uncertainties of some input quantities or ancillary data used may be found in published documents. The most important source of information on Type B uncertainties is invariably the use of past experience of measurements by the operator to derive informed estimates.

If the value of an uncertainty is not known, conservatively wide limits should be adopted and, where possible, an attempt should be made to quantify it, for example, by measurement.

If the probability distribution of an uncertainty is not known, then further information should be sought, e.g. from the manufacturer. Often a rectangular distribution may be assumed. A more conservative route would be to assume a standard uncertainty with a normal distribution, so that the divisor would be unity.

1.4 Combination of Uncertainties

1.4.1 Combined standard uncertainty

The combined standard uncertainty of the output quantity, *u(y)*, is derived by the summation in quadrature of all Type A and Type B standard uncertainties due to the input parameters:

$$u(y) \quad = \quad [\, \Sigma\, u_i(y)^2\,]^{1/2}$$

The combined standard uncertainty is generally a standard deviation with a normal probability distribution unless one component dominates the combined effect of all others (see below).

The above expression applies only when the input quantities are independent of each other (i.e. a change in one input quantity does not affect another). The ISO Guide [1] should be consulted for a more accurate approach if there are correlations.

1.4.2 Expanded uncertainty

The key uncertainty to be quoted for the output quantity is the expanded uncertainty, *U*, which represents the total uncertainty for a specific level of confidence. It is derived by multiplying the combined standard uncertainty, *u(y)*, by a coverage factor, *k*, that is selected to give the desired level of confidence for a normal distribution. Typical choices for *k* are the integers 1, 2, or 3; which correspond to confidence levels of 67.7%, 95.5% and 99.7% respectively. For most radiological applications, a 95% confidence level, for which $k = 1.96$, is recommended. For convenience, this is rounded upwards to a value of exactly 2.0.

It is recommended that an uncertainty budget be produced listing relevant components and their numerical values, confidence levels, probability distributions, sensitivity coefficients and the corresponding standard uncertainties in the output quantity. Uncertainty budgets are usually in the form of spreadsheets that are used to calculate the expanded uncertainties. Examples are given in Sections 2, 3 and 4. (Note that the output quantity uncertainties in each table are expressed either all in absolute units or all as percentages.)

1.4.3 Coverage factors for non-ideal situations

The choice of $k = 2$ for the coverage factor assumes that the Type A uncertainties are based on a large number of readings so that the distribution is effectively normal. Otherwise the value of k should be derived from a *t*-distribution. As a rule of thumb, if the number of readings is less than 10 and the Type A contribution is more than 50% of the overall uncertainty, the effective number of degrees of freedom, υ_{eff}, should be derived and used in conjunction with *t*-distribution tables to obtain the appropriate *k*-value. Further guidance is given in Appendix 1.

1.4.4 Dominant component

The probability distribution of the expanded uncertainty may be assumed to be normal unless a dominant component such as a large uncertainty with a rectangular distribution is present. In such a situation, the expanded uncertainty may exceed the arithmetic sum of the values of all components because the divisor for the dominant component (√3) is smaller than the *k*-factor used to calculate the expanded uncertainty ($k = 2$ for 95% confidence level).

To avoid this problem, the dominant component, u_{dom}, should not be combined with the other uncertainty components, but should be quoted separately [3]. The expanded uncertainty may be expressed as -

$$U = u_{dom} + U'$$

where U' is derived from the combination of the other components.

1.5 Expression of Uncertainty

The statement of the value of a measured quantity must include the value of the expanded uncertainty. The reported value must be accompanied by a statement giving the method of derivation of the uncertainty and the confidence level employed. This statement could be of the form -

> *The reported uncertainty is based on a standard uncertainty multiplied by a coverage factor k = 2, that provides a level of confidence of approximately 95%.*

If a dominant component is present, this statement could be replaced by one of the form -

> *The reported uncertainty is dominated by the uncertainty due to …………for which a rectangular probability distribution has been assumed.*

1.5.1 Significant digits

The number of significant digits of the value of the uncertainty should be appropriate for the accuracy with which the uncertainty is assessed. The accuracy of a radiological measurement is seldom better than 1% unless an unrealistic effort is made. It is not usually practical to determine an uncertainty with an accuracy better than 10% of the uncertainty itself. Thus, there should be no more than two digits in the uncertainty value; often only one is justified.

It is recommended that -

- uncertainties are reported as either one-digit integers between 3 and 9 or two-digit integers between 10 and 29,
- rounding of uncertainty values should be upwards,
- values of measured quantities should be rounded to the same least significant digit as the uncertainty.

The following result:

95.08 ± 0.29	is reported as	95.1 ± 0.3
95.08 ± 1.25	is reported as	95.1 ± 1.3
95.08 ± 2.9	is reported as	95.1 ± 2.9
95.08 ± 3.1	is reported as	95 ± 4

1.6 Summary of Steps Involved in Deriving an Uncertainty

- Determine Type A uncertainties at one standard deviation.
- Determine Type B uncertainties and their probability distributions.
- Calculate the standard uncertainties $u(x_i)$ by dividing the uncertainties by the divisors appropriate to the probability distributions.
- Derive sensitivity coefficients c_i and calculate $u_i(y)$.

  All $u_i(y)$ should be in the same units (either absolute or percentage)
- Combine Type A and Type B components in quadrature $[\Sigma\, u_i(y)^2]^{½}$ to give the combined standard uncertainty $u(y)$.
- Check for presence of dominant component
- Derive or select coverage factor, k, for the desired level of confidence. The recommended value is $k = 2$, for 95% confidence level.
- Multiply $u(y)$ by coverage factor k to give expanded uncertainty U.
- Round the result to the appropriate number of significant figures.
- Report U, coverage factor and level of confidence.

The final value should always be examined to judge whether it makes sense.

2 Photon Monitoring

This section covers the calibration of gamma-ray and X-ray fields and the calibration of portable radiation protection instruments. It does not explicitly cover radiotherapy applications, although there are similarities in the sources of uncertainty in the two areas.

A photon field is calibrated by measuring the dose delivered by the photon beam at a reference position, using a secondary standard instrument, against the response of an appropriate monitor. For fields produced using X-ray sets or accelerators, the monitor could be a transmission-type of ionisation chamber in the radiation beam. For fields produced using radionuclide sources, the monitoring could be of time since the kerma rate is constant (allowing for decay of the source).

For radiation protection instrument calibration, there is the further step of measuring the response of the instrument being calibrated to a standardised field. The examples below deal with the calibration of a photon field and its use for calibrating portable dose rate meters.

2.1 Calibration of a Photon Beam

A photon field (normally a beam) is calibrated using a secondary standard such as an ionisation chamber to measure air kerma, *K*, (or air kerma rate) at selected reference points along the axis of the radiation beam against the response of a beam monitor [4].

2.1.1 Measurement of air kerma rate using a secondary standard

The direct air kerma on the beam axis is related to the instrument reading by the expression:

$$K = (M_s - M_B)\ C_s\ F_{nl}\ F_r\ F_{dd}\ F_{nu}\ F_{room}\ F_{scim}\ F_{rate}\ F_T\ F_P\ F_H\ F_{Ti}$$

where:
- M_s - reading of (integrating) secondary standard instrument,
- M_B - background reading of secondary standard instrument,
- C_s - calibration coefficient of secondary standard for relevant radiation quality,
- F_{nl} - instrument scale non-linearity correction,
- F_r - instrument range correction factor,
- F_{dd} - instrument directional dependence correction factor,
- F_{nu} - field non-uniformity correction factor,
- F_{room} - correction for room- and air- scatter,
- F_{scim} - correction for scatter from instrument mount
- F_{rate} - rate correction factor,
- F_T - temperature correction factor,
- F_P - pressure correction factor,
- F_H - humidity correction factor,
- F_{Ti} - correction for timer.

The correction factors are normally defined so that they are unity under standard or ideal (e.g. zero scatter) operating conditions.

2.1.2 Uncertainty components for measurement of air kerma

2.1.2.1 Reading of secondary standard instrument, *M*s

The secondary standard normally has a digital display. The uncertainty of the mean reading is the standard deviation of the mean of a series of values provided that the resolution of the display is sufficiently sensitive. This is a Type A uncertainty with a normal distribution. The uncertainties for the various types of outputs and displays are discussed in Section 2.2.3.

2.1.2.2 Reading of secondary standard instrument due to background, M_B

The reading is corrected for background and effects such as leakage currents by subtraction of a reading made with the radiation source switched off or removed. The uncertainty for the background reading is the standard deviation of the mean of a series of readings. This is a Type A uncertainty with a normal distribution. It may be necessary to include the effect of temporal fluctuation of the background.

2.1.2.3 Calibration factor of the secondary standard instrument, $\mathrm{C_s}$

The uncertainty for the calibration factor is reported on the calibration certificate supplied by the standardising laboratory. It is quoted for a 95% confidence level and has a normal distribution. The value is corrected for the change in sensitivity that is revealed as a drift in its response to a check-source since the last calibration. A typical value for drift is around 0.3 %, with an uncertainty of less than 0.1% that is folded into the uncertainty for $\mathrm{C_S}$.

2.1.2.4 Instrument scale non-linearity correction, F_{nl}

This is dependent on the instrument and its value along with the associated uncertainty should be obtained from the manufacturer's data or the calibration certificate.

2.1.2.5 Instrument range correction factor, F_r

This is dependent on the instrument and its value along with the associated uncertainty should be obtained from the manufacturer's data or the calibration certificate.

2.1.2.6 Directional dependence of the ionisation chamber, F_{dd}

This is dependent on the instrument and the relevant information should be obtained from the manufacturer's data.

2.1.2.7 Non-uniformity of field, F_{nu}

Because the ionisation chamber averages kerma over a cross section of the beam, a correction is applied to give the kerma at a point on the beam axis. The intensity profile of the radiation field across this area depends on the collimation of the source, the distance between source and ionisation chamber, and the radius of the latter. The profile is measured on a convenient occasion using a small probe. The correction may amount to 2% (i.e. $F_{nu} = 1.020$) for a large-volume ionisation chamber used at short source distances. It is obtained by folding the profile into the area of the ionisation chamber. The uncertainty is assumed to have a rectangular distribution usually with a semi-range of up to 25% of the correction, e.g. $F_{nu} = 1.016 \pm 0.004$.

2.1.2.8 Scatter from the surroundings, F_{room}

The effect of lower energy room- and air-scattered radiation for the secondary standard depends on the energy dependence of the response. This component should be measured and subtracted, yielding the direct component. In favourable geometries, this correction is usually small and the associated uncertainty is correspondingly low. However, whereas the direct beam component varies with distance from source approximately according to an inverse square law, the scatter component is relatively constant and therefore its effect increases markedly with distance.

The effect of scatter on the response of instruments subsequently calibrated in the field can be similar to that for the secondary standard and the overall uncertainty of the calibration would be lessened accordingly. See Section 2.2.4.3.

2.1.2.9 Scatter from the instrument mounts, F_{scim}

This correction is generally in the region of 1 to 2%, depending on the structure of the table top, with a correspondingly low uncertainty. The effect can be assessed by bringing an extra mount up to the instrument. The same remarks as for the room- and air-scatter correction apply except that it varies in a similar manner to the direct component and the correction is therefore approximately constant with distance.

2.1.2.10 Rate correction factor, F_{rate}

This is dependent on the instrument and the kerma rate. The factor and its uncertainty should be obtained using the manufacturer's data. For typical ionisation chambers the uncertainty due to recombination effects is generally less than 0.1 %, but there can be other effects contributing to this factor such as the performance of any analogue to digital converter.

2.1.2.11 Ambient temperature, F_T

When measuring kerma rate with an unsealed ionisation chamber a correction must be applied for the effect of temperature and pressure on air density. The correction factor for temperature, F_T, is $(T + 273) / 293$ where T is the temperature of ionisation chamber in degrees Celsius. Temperature variation may affect also the calibration of the instrument's electronics.

2.1.2.12 Ambient pressure, F_P

The correction factor for pressure, F_P, is $1013.3/P$ where P is pressure in mbar.
(Note: *1 mbar = 100 Pa; 1 atmosphere = 101.3 kPa*)

2.1.2.13 Humidity correction factor, F_H

The values for the humidity correction factor for relative humidity ranging from 20% to 70% indicate that for a small, typical uncertainty in relative humidity the related uncertainty in the ionisation chamber response is of the order of 0.05%.

2.1.2.14 Time, F_{Ti}

The timer used to set the period for the dose integration must be calibrated against the UK national time standard. Normally the uncertainty in this correction would be negligible. Another uncertainty may arise due to the resolution of the reading of the timing device.

2.1.3 Calibration of beam monitor

In the case of a field produced by a radionuclide source the air kerma measurement may be made with respect to time as the output is constant after allowance is made for source decay. In order to allow for the variation of the output of X-ray sources, the air kerma measurement is made with respect to a monitor fixed in an appropriate position elsewhere in the field. This is usually a transmission-type ionisation chamber.

The monitor response is calibrated in terms of reading per kerma (rate) at reference positions along the beam axis.

2.1.4 Uncertainty components for calibration of beam monitor

These are in addition to those for the measurement of air kerma.

2.1.4.1 Monitor reading

The uncertainties associated with instrument readings are discussed in Section 2.2.3.

2.1.4.2 Position of secondary standard

The uncertainty for a single position is a combination of the uncertainty due to the position of the effective centre of the secondary standard with respect to a reference mark on the stand holding the instrument mount and that in the distance between the reference mark and the source of radiation. Both have rectangular distributions. In order to calculate the associated uncertainty in the calibration, it is sufficiently accurate to assume an inverse square law with distance, s, between source and instrument for the radiation field, although the effect of collimator, air attenuation, background and scatter is to produce a deviation from an inverse square relationship. The sensitivity coefficient for the uncertainty in calibration is thus (2 / s).

Note: *For the calibration of a tertiary instrument using the same stand in the same reference position, the second uncertainty component would be cancelled out. (Refer to Section 2.2.4.7.)*

2.1.4.3 Interpolation for positions between those where kerma is measured

Interpolation is necessary because kerma rate does not follow an inverse square law exactly due to the effects mentioned above. The accuracy depends on that of the kerma measurements and the positions of the secondary standard and is calculated by the fitting program.

2.1.4.4 Ambient conditions

Correction factors may have to be applied for the effects of ambient temperature, pressure and humidity if the ionisation chamber beam monitor is unsealed. The uncertainties associated with the correction factors for ambient conditions are discussed in Sections 2.1.2.11, 12, 13.
Note: If the beam monitor is calibrated using an unsealed secondary standard ionisation chamber, the pressure corrections and also the humidity corrections for both instruments would cancel out. However, the two chambers may be at different temperatures as one could be free-in-air and the other could be located in a machine.

2.1.5 Uncertainty budget for measurement of kerma rate

An example of an uncertainty budget for the calibration of a beam produced by a radionuclide source (^{137}Cs) in terms of air kerma rate at a reference position is given in Table 2.1. The calibration is carried out by measuring air kerma over a set time interval.

A series of ten readings has been made for both beam and background measurements. The uncertainties for these readings are assumed to have normal distributions. The effective number of degrees of freedom has been calculated using the Welch-Satterthwaite formula (given in Appendix 1 of this guide) in order to demonstrate that the effect on the coverage factor of having a relatively small number of readings is negligible in this case.

The formulae for the partial differentials used to derive the sensitivity coefficients, c_i, are given in the table. In line with common practice in this area, the standard uncertainties, $u_i(y)$, are expressed as percentages of the result quantity and the values for the relative sensitivity coefficients are calculated accordingly. Their units are the reciprocal of those of the input quantities to which they correspond.

The values used for the quantities and their uncertainties are for illustration only and should not be assumed for other situations. This example is chosen in order to match the example given in the next section.

2.1.6 Reported result

For the example shown above, the calibration report could state:

> *The ^{137}Cs air kerma rate at the 2,000 mm reference position is (83.4 ± 2.1) µGy h^{-1}*
>
> *The reported uncertainty is based on a standard uncertainty multiplied by a coverage factor of k = 2, which provides a level of confidence of approximately 95%.*

Table 2.1 Uncertainty budget for measurement of kerma rate at a reference position in a ^{137}Cs beam

Quantity	Value	Uncertainty (δx_i)	Probability distribution	Divisor	$(\partial f/\partial x_i) / y$	c_i / y	u_i (%)	v_i or v_{eff}
Mean reading of secondary standard, M_S	28.3	0.2	normal	1	$(M_s - M_B)^{-1}$	100 / 28	0.71	9
Mean background reading, M_B	0.3	0.1	normal	1	$(M_s - M_B)^{-1}$	100 / 28	0.36	9
Secondary standard calibration, C_S	1.000 µGy	0.018 µGy	normal	2	C_S	100	0.90	∞
Non-linearity factor, F_{nl}	1.000	0.002	rectangular	√3	$1 / F_{nl}$	100	0.12	∞
Range correction factor, F_r	1.000	0.001	rectangular	√3	$1 / F_r$	100	0.06	∞
Directional dependence, F_{dd}	1.000	0.002	rectangular	√3	$1 / F_{dd}$	100	0.12	∞
Non-uniformity of beam, F_{nu}	1.016	0.004	rectangular	√3	$1 / F_{nu}$	100	0.23	∞
Room scatter, F_{room}	0.981	0.002	rectangular	√3	$1 / F_{room}$	100	0.12	∞
Scatter from mount, F_{scim}	0.990	0.002	rectangular	√3	$1 / F_{scim}$	100	0.12	∞
Rate effects, F_{rate}	1.000	< 0.001	rectangular	√3	$1 / F_{rate}$	100	0.06	∞
Temperature, T	19.0 °C	0.5 °C	rectangular	√3	$1 / (T+273)$	100	0.10	∞
Pressure, P	1003 mbar	1 mbar	rectangular	√3	$1 / P$	100	0.06	∞
Humidity	50 %	5 %	rectangular	√3	1 / 100	100	< 0.01	∞
Distance, s	2.000 m							
position of effective centre		2 mm	rectangular	√3	$2 / s$	200/ 2000	0.12	∞
distance of stand from source		2 mm	rectangular	√3	2 / s	200/ 2000	0.12	∞
Time, t	1200 s	0.2 s	rectangular	√3	$1 / t$	100 / 600	0.01	∞
Air kerma rate, K	83.4 µGy/h		normal			$u(K)$	1.27	85
Expanded uncertainty for K, (k = 2.09)	2.1 µGy/h		normal			U	2.6	85

$$u_i(y) = (\delta x_i / \text{divisor}) \times (c_i / y)$$

The values used for the quantities and their uncertainties are for illustration only and should not be assumed for other situations.

2.2 Calibration of Portable Dose Rate Meter

This section deals with the calibration of a portable dose rate meter by measuring its response to the radiation field that has been calibrated using a secondary standard, as dealt with in the above section. Owing to the wide variety of quality, sensitivity and display devices of radiation monitors, it is impossible to give the uncertainty of calibration of a 'typical' instrument. Instead, the various effects that are taken into account are listed and the range of uncertainties that may contribute to the overall uncertainty are indicated.

2.2.1 Method

The instrument calibration factor, C_K, in terms of kerma, is derived using the relationship between the kerma, K, (or kerma rate) at the calibration point and the instrument reading –

$$C_K = K \{(M - M_B)(f_{nu} f_{room} f_{scim} f_{rate} f_T f_P f_H)\}^{-1}$$

with: M - dose rate meter reading,

M_B - background reading of dose rate meter.

The f-factors are analogous to the F-factors in section 2.1.

2.2.2 Uncertainty components for calibration of portable dose rate meter

2.2.2.1 Kerma rate, *K*

The assessment of the uncertainty of kerma at the instrument position in the photon beam per unit of beam monitor response is described in section 2.1.

2.2.2.2 Calibration in terms of dose equivalent, *H*

The dose equivalent (or dose equivalent rate) is given by -

$$D = h K$$

The coefficient h converts kerma to the required dose equivalent quantity. The instrument calibration factor in terms of a dose equivalent quantity is equal to $C_K h$.

The value of h varies with photon energy and is derived from radiobiological data. Values are published in a standard [5] that also recommends that the value for any mono-energetic field should be regarded as having no associated uncertainty. In practice however, the spectra from sources like ^{137}Cs and ^{241}Am are not truly mono-energetic, but include scattered radiation, particularly from the source encapsulation. The standard therefore further recommends that an uncertainty, quoted as 2%, is included for calibrations using such sources.

The calibration certificate should state if this component is omitted from the uncertainty budget.

2.2.2.3 Position

The uncertainty in position is a combination of the uncertainty due to the position of the

effective centre with respect to the instrument support stand and that in the position of the stand with respect to the source of radiation. Both have rectangular distributions.
Account should be taken of correlations with uncertainties in the position of the secondary standard instrument. (For example, if the instrument under test is mounted in the same position as the secondary standard the second source of uncertainty would cancel out.) These correlations are relatively small and usually have negligible effect on the overall uncertainty.

2.2.3 Instrument reading, *M*

The reading may be a digital display or an analogue display (LCD or moving needle on a graduated scale) that may be linear or logarithmic. The uncertainty is sometimes referred to as the *resolution* of the instrument.

2.2.3.1 Analogue display: statistical fluctuations

At high, constant dose rates, the meter reading of a dose-rate meter will be reasonably steady and therefore could be averaged accurately by eye. The range of the reading and hence the uncertainty may also be estimated by visual inspection with an accuracy that is comparable with, say, the uncertainties due to scale resolution and parallax. The problem with determining the mean and standard deviation of the mean of eye-averaged readings is that each reading is a subjective judgment. The first estimate of the eye average reading can influence subsequent estimates, especially if the reading is close to a scale division, and result in an underestimate of the true uncertainty of the estimated readings.

At low dose rates the meter indication can fluctuate significantly, and sufficient readings must be taken to enable an average or median value to be derived with the desired accuracy. In order to do this objectively, first the response time (time to reach 90% of final reading) at the dose rate is derived either from manufacturer's instructions or by eye estimate. Then a series of readings is taken over consecutive periods equal to the response time or longer. The mean value and standard deviation of the mean are calculated in the usual manner.

Another method that is widely employed is to note the maximum and minimum readings over a period of time and derive the standard uncertainty from this range. For a constant dose rate, the process is essentially random (stochastic) and therefore a normal distribution should be assumed rather than a rectangular one. The main problem is the assessment of the confidence level to which the maximum and minimum correspond. A long time period would have a greater level of confidence than a shorter one, but a greater range of values would be observed. As a rule of thumb, the total observation time of about twenty times the response time should be used for a confidence level of 95% to be assumed and, in turn, a value of 2 employed for the divisor used to derive the standard deviation of the distribution. The standard deviation of the mean is obtained by dividing this by $\sqrt{n}$, where n is the number of response times in the observation period.

It may be necessary to treat the instrument reading uncertainty as a dominant component (see Section 1.4.4).

Alternatively, this component along with the uncertainty derived by combining all other components may be reported separately. The instrument reading uncertainty could be reported in terms of the minimum and maximum readings observed over a stated period of time. This period should be sufficiently long to ensure a confidence level of about 95%.

2.2.3.2 Analogue display: parallax

If the pointer of a moving-needle display is not very close to the scale, the log-scaled meter of an instrument may read up to 5% high at the top end of the scale and 5% low at the bottom end when viewed by a television camera positioned central to the scale. The error can sometimes be estimated visually and a correction applied for the effect for which the residual uncertainty may be less than ± 1%. The error in linearly-scaled indications can be much higher than this.

Note: This uncertainty can be reduced by mounting the optical axis of the CCTV camera lens on the axis of the meter pivot.

2.2.3.3 Analogue display: instrument scale resolution

The scale resolution can be estimated by visual inspection. For a linear analogue display, the uncertainty of the reading may be about 2% near 90% FSD and about 4% at half-scale.

For analogue quasi-logarithmic scales, the percentage uncertainty of observation may be no better than ± 10% and even as high as ± 20% if several decades are compressed into a short scale length. The uncertainty tends to be dominated by the sparseness or otherwise of the scale markings which tend to be closer for readings of around 7, 8, 9, than around 10, 15, 20.

2.2.3.4 Digital display

The electronics of most units display the reading to the selected precision and ignore the other digits, i.e. the reading is usually rounded downwards. Thus, for example, a reading of 30 units would mean that the value lies between 30 and 31 with equal probability. The uncertainty is equal to half of the resolution and has a rectangular distribution [1]. Therefore the result would be 30.5 ± 0.5.
Note: *In some instruments the last digit displayed is not the least significant digit.*

If the reading wavers between readings of 30 and 31, a fairly accurate estimate of the value may be obtained by taking the mean values of a series of readings made at fixed time intervals (and if necessary, adding 0.5 as above). The interval should be equal to or greater than the response time. The reading must be recorded for all intervals in the series - even when it does not change between consecutive intervals. The uncertainty is a combination of the standard deviation of the mean (SDOM) of the set of readings and the resolution uncertainty as defined above. This is discussed in [6].

This also applies if the number displayed fluctuates between several numbers.

Alternatively, instead of deriving the SDOM, the technique of deriving the uncertainty from the observed maximum and minimum readings (as outlined in 2.2.3.1 above) can be employed. As the fluctuation increases the effect of the resolution uncertainty decreases.

2.2.4 Other effects

2.2.4.1 Reading due to background, M_B

The reading is corrected for background and effects such as leakage currents by subtraction of a reading made with the radiation source "off". The uncertainty for the background reading is derived according to the guidance given in section 2.2.3.1 above. It may be necessary to take account of the effect of temporal fluctuation of the background.

2.2.4.2 Field non-uniformity, f_{nu}

This correction may amount to ± 2% for an instrument with a large-volume ionisation chamber calibrated at short source distances. It will be much less for small Geiger-Muller tubes and solid-state detectors.

2.2.4.3 Scatter from the surroundings, f_{room}

These effects are discussed in Sections 2.1.2.8.

2.2.4.4 Scatter from the instrument mount, f_{scim}

The correction will usually be less than ± 2%.

2.2.4.5 Rate (dead time) effects, f_{rate}

Rate effects may arise from the meter having a dead time (for those based on Geiger-Müller tubes) or from saturation phenomena (for ionisation chambers). Compensation may be provided electronically (although the correction is not always perfect) or be incorporated in the scale gradations of an analogue meter. Therefore rate corrections are not made routinely.

If dead time corrections are necessary, the fractional loss for an uncompensated train of pulses may be derived as the product of dead time and effective count rate. (However, dead time is usually rate dependent and it can be difficult to know what value to apply unless the manufacturer gives specific data for the complete unit.) The sensitivity coefficient for deriving the uncertainty in the calibration factor from that in the dead time value is thus the count rate.

It is generally not possible to observe the count rate directly, in which case it has to be derived from the meter reading and a known conversion factor relating reading to count rate.

2.2.4.6 Ambient temperature, pressure and humidity, f_T, f_P, f_H

If the beam monitor is an unsealed ionisation chamber, no corrections for pressure are necessary when the instrument under calibration is also an unsealed ionisation chamber, but a correction for any temperature difference should be applied. Temperature and pressure corrections should be applied to the beam monitor response for the calibration of instruments based on Geiger- Müller tubes or solid-state detectors.

If the beam monitor is not an unsealed ionisation chamber then the response of an unsealed ionisation chamber under calibration should be corrected for ambient conditions. Instruments based on Geiger- Müller tubes need no correction.

2.2.5 Uncertainty budget for the calibration of portable dose rate meter

An example of an uncertainty budget for the calibration of monitor in a beam produced by a ^{137}Cs source at a non-reference position is given in Table 2.2. The monitor is based on a small Geiger-Müller tube and has a linear analogue display with several selectable ranges. It is insensitive to ambient conditions.

A series of ten readings has been made for beam measurements and the mean value and the standard deviation of the mean calculated. The background and its associated uncertainty were calculated from the upper and lower readings obtained over about twenty response times.

2.2.6 Reported result

For the example shown below, the calibration certificate could state:

> *The measured value of the calibration factor for ^{137}Cs at an ambient dose equivalent rate of 30 μSv h^{-1} is:*
>
> $$C_H = 1.03 \pm 8\%$$
>
> *An air kerma to ambient dose equivalent conversion coefficient of 1.20 Sv/Gy [4] has been used.*
>
> *The reported uncertainty is based on a standard uncertainty multiplied by a coverage factor of k = 2, which provides a level of confidence of approximately 95%.*

Table 2.2 Uncertainty budget for calibration of a portable dose rate meter using using a ^{137}Cs beam

Quantity	Value	Uncertainty (δx_i)	Probability distribution	Divisor	$(\partial f/\partial x_i) / y$	c_i / y	u_i (%)	ν_i or ν_{eff}
Ambient dose equ. rate at 3460 mm, H	30.0 µSv/h	0.9 µGy/h	normal	2	$1 / H$	100 / 30	1.50	∞
Mean reading of monitor, M	31.0 µSv/h	0.9 µGy/h	normal	1	$(M - M_B)^{-1}$	100 / 30	3.0	9
Parallax uncertainty	- - -	2%	rectangular	√3	$M / (M - M_B)$	31 / 30	1.2	∞
Mean background reading, M_B	1.0 µSv/h	0.1 µSv/h	normal	2	$(M - M_B)^{-1}$	100 / 30	0.5	19
Parallax uncertainty	- - -	2%	rectangular	√3	$M_B / (M - M_B)$	1 / 30	< 0.01	∞
Conversion coefficient, h	- - -	1%	normal	1	1	1	1.0	∞
Non-uniformity of beam, f_{nu}	1.010	0.004	rectangular	√3	$1 / f_{nu}$	100 / 1.01	0.23	∞
Room scatter, f_{room}	0.970	0.005	rectangular	√3	$1 / f_{room}$	100 / 0.97	0.30	∞
Scatter from mount, f_{scim}	0.990	0.002	rectangular	√3	$1 / f_{scim}$	100 / 0.99	0.12	∞
Distance, r	3.46 m							
position of effective centre		2 mm	rectangular	√3	$2 / r$	200/ 3460	0.07	∞
distance of stand from source		3 mm	rectangular	√3	2 / r	200/ 3460	0.10	∞
Calibration factor, C_H	1.030		normal			$u(C_H)$	3.75	19.1
Expanded uncertainty ($k = 2.09$)	0.080		normal			***U***	7.83	19

$$u_i(y) = (\delta x_i / \text{divisor}) \times (c_i / y)$$

The uncertainty for air kerma rate includes a component for interpolation between measurements at 3 m and 4 m.
The values used for the quantities and their uncertainties are for illustration only and should not be assumed for other situations.
The effective number of degrees of freedom has been calculated using the Welch-Satterthwaite formula (see Appendix A1.3).

3 Calibration of Neutron Area Survey Monitor

A neutron area survey monitor is calibrated by positioning its effective centre at the point of test in a standardised neutron field and measuring its response. Usually the field is produced using a radionuclide neutron source with known emission rate and anisotropy factor. The calibration is normally expressed in terms of ambient dose equivalent rate. This is derived by the application of a conversion factor to the neutron fluence rate at the monitor position.

Neutron monitors are generally based on detectors that produce a pulse for each detected event. The pulse trains are used to produce an analogue or digital display of ambient dose equivalent rate (or ambient dose equivalent), *H*. Some monitors also have a pulse output channel.

3.1 Use of Field Produced Using a Radionuclide Neutron Source

3.1.1 Method

In the following example, the monitor is calibrated using an ^{241}Am-^{9}Be(α,n) neutron source. The neutron fluence rate is calculated from the emission rate of the source, assuming an inverse square relationship with the distance from the source.

The reading, *M*, is given by the expression –

$$M = R_{AmBe} \frac{h_{AmBe} E}{4\pi r^2} f_A f_{aa} f_{sc} + M_B$$

where:
- R_{AmBe} - response for ^{241}Am-Be field in terms of ambient dose equivalent,
- h_{AmBe} - fluence to ambient dose equivalent conversion coefficient for ^{241}Am-Be spectrum
- E - emission rate of source,
- r - distance of effective centre of meter from source,
- f_A - anisotropy factor for source,
- f_{aa} - air attenuation factor, (depends on the distance between source and dosemeter front surface),
- f_{sc} - room scatter factor for dosemeter type and ^{241}Am-Be neutrons,
- M_B - background reading.

Note: A geometrical correction [7] is required for distances less than twice the monitor diameter.

The calibration factor for an ^{241}Am-Be spectrum, C_{AmBe}, is given by

$$C_{AmBe} = \frac{h_{AmBe} E}{4\pi r^2} f_A f_{aa} f_{sc} / (M - M_B)$$

3.1.2 Uncertainty components for calibration of neutron area survey monitor

3.1.2.1 Conversion coefficient, h_{AmBe}

The conversion coefficient h_{AmBe} is evaluated from radiobiological data and applies to an assumed spectrum. The value is published by a recognised authority [8] and as such is widely accepted; it should always be stated in the calibration report or certificate. The conversion coefficient varies with neutron energy and so there is an uncertainty due to that in the assumed spectrum. For ^{241}Am-Be and ^{252}Cf sources the standard uncertainties are quoted as 4% and 1% respectively [7]. This component may be omitted from uncertainty budgets if appropriate, e.g. when comparing values for calibrations using the same ^{241}Am-Be sources. Any such omission of this uncertainty component should be stated on the calibration certificate.

Because the ^{241}Am-Be neutron spectrum depends on the source construction it may differ from the assumed spectrum. This introduces a further uncertainty that is difficult to quantify.

3.1.2.2 Neutron radionuclide source emission rate, *E*

The neutron source emission rate is measured absolutely at a national standards laboratory or by comparison with a source of known emission rate. The uncertainty is a combination of several components and would therefore be a normal distribution. When used for the calibration of a monitor it would be a Type B uncertainty.

The emission rate must be corrected for source decay. The half life of ^{241}Am is 432.2 year with an uncertainty of about 0.15%. The resulting uncertainty in emission rate is negligible (less than 0.1%) for emission rates measured within ten years of source calibration.

3.1.2.3 Distance, *r*

The distance, *r*, is that between the effective centre of the dosemeter and the neutron source. The uncertainty is comprised of two components; -

- distance *d* between centre of the source and the point on the surface of the instrument to which the distance measurement is made,
- position of the effective centre of the instrument relative to the point on its surface to which the distance measurement is made.

The latter is obtained from the manufacturer's specification of the physical dimensions of the device. Both uncertainties are assumed to have rectangular distributions.

3.1.2.4 Neutron radionuclide source anisotropy, f_A

The neutron source anisotropy is obtained in a separate measurement. It would have a Type B uncertainty comprising several components and having a normal distribution.

3.1.2.5 Attenuation correction, f_{aa}

The attenuation correction for the distance between the source and the front face of the monitor is calculated using a published value for the air attenuation coefficient of 0.83 % m^{-1} [7]. This has an uncertainty of less than 10 %, normally distributed. Measurements made at a distance of 1000 mm would require a correction factor of 0.992 ± 0.001.

3.1.2.6 Room scatter correction, f_{sc}

The room scatter component to the response is determined in a separate measurement usually employing the shadow cone technique. Its value depends on room construction, distance from source and type of monitor. The uncertainty is comprised of several components and therefore has a normal distribution.

3.1.2.7 Instrument reading, *M*

As for the photon monitor calibration, the reading may be analogue or digital, and it may be of dose rate or integrated dose. The uncertainties due to the averaging of fluctuating readings, parallax and scale resolution and their derivation are discussed in section 2.2.3.

Rate effects are generally negligible for most calibration and field measurement conditions.

3.1.2.8 Background reading, M_B

Normally the neutron background is low; typically two orders of magnitude less than *D(r)*. The background can have temporal variation due to the storage and movement of neutron sources in the facility. The uncertainties and their derivation are discussed in section 2.2.3

3.1.2.9 Spectral effects

The monitor response per unit of fluence and the fluence-to-ambient dose equivalent coefficient vary significantly with neutron energy, but not necessarily by the same amount or in the same direction. The overall effect on the calibration factor is very difficult to quantify and could lead to small differences between calibrations made using sources with different construction.

Note: Use of the monitor in neutron fields with spectra differing from that of the calibration field will necessitate a correction to the calibration factor. The associated uncertainty can in some cases dominate the uncertainty budget.

3.1.3 Uncertainty budget for calibration of neutron area survey monitor

An example of an uncertainty budget for the calibration of a typical 20 cm diameter area survey monitor placed 1 m from an ^{241}Am-Be source is given in Table 3.1. The emission rate and anisotropy of the source have been measured at the national standards laboratory. The certificate of calibration quotes the associated uncertainties at a confidence level of 95 %.

The room scatter correction has been determined at 1 metre from the source as an additional (12.0 ± 2.0) % of the response to direct neutrons.
Uncertainties in the conversion coefficient and monitor response arising from that in the ^{241}Am-Be spectrum are included. However, as the source is physically small, no corrections are made for spectral effects arising from its construction; and no further uncertainties are included.

The monitor has a digital display that is updated every 2 s. The uncertainty for the reading in the neutron field has been derived from the upper and lower readings obtained over a period of one minute. Effectively, over 25 intervals were sampled and a confidence level was conservatively assumed to be of 95 %. This type of monitor has a sensitivity of about 0.5 event.cm^2 for the ^{241}Am-Be neutron spectrum and the derived uncertainty is typical for a neutron event detection rate of about 9 s^{-1} under these conditions (assumed stochastic).

The background reading ranged between 0.1 and 0.5 μSv h^{-1} over a period of one minute.

3.1.4 Reported result

For the example shown above, the calibration certificate will state:

> *The measured value of the calibration factor for an ^{241}Am-^{9}Be spectrum at an ambient dose equivalent rate of about 30 μSv h^{-1} is:*
>
> *1.03 ± 0.22*
>
> *A value of 391 pSv cm^2 is used for the fluence-to-ambient dose equivalent conversion coefficient [8].*
>
> *The reported uncertainty is based on a standard uncertainty multiplied by a coverage factor of k = 2, which provides a level of confidence of approximately 95%.*
>
> *The uncertainty is dominated by an uncertainty of 18 % due to the instrument reading.*

3.2 Use of Accelerator-produced Neutron Field

3.2.1 Standardisation of field

Because the emission rate can depend on accelerator conditions, a fixed detector is normally used to monitor the field. The monitoring set-up is in turn calibrated using a transfer standard. This situation is similar to that covered in Section 2 because additional uncertainties are introduced including those due to the calibration of the transfer standard and the readings of the transfer standard and the monitor.

3.2.2 Rate effects

As the field intensities can be much higher than those produced using radionuclide sources, attention must be paid to the effect of dead time losses.

Table 3.1 Uncertainty budget for calibration of a portable area survey monitor using an $^{241}Am/^{9}Be$ neutron source

Quantity	Value	Uncertainty (δx_i)	Probability distribution	Divisor	$(\partial f/\partial x_i) / y$	c_i / y	u_i (%)	v_i or v_{eff}
Mean reading of monitor, M	28.0 µSv/h	2.5 µSv/h	normal	1	$(M - M_B)^{-1}$	100 / 27.7	9.0	24
Parallax uncertainty	- - -	2%	rectangular	√3	$M / (M - M_B)$	28 / 27.7	1.2	∞
Mean background reading, M_B	0.3 µSv/h	0.1 µSv/h	normal	2	$(M - M_B)^{-1}$	100 / 27.7	0.2	24
Parallax uncertainty	- - -	2%	rectangular	√3	$M_B / (M - M_B)$	0.3 / 27.7	0.01	∞
Conversion coefficient, h_{AmBe}	391 pSv cm^2	4%	normal	1	1	1	4.0	∞
Emission rate, E	2.205 10^6 s^{-1}	3.3 10^4 s^{-1}	normal	2	$1 / E$	10^{-4} / 2.2	0.75	∞
Distance, r position of effective centre distance of stand from source	1.000 m	 1 mm 2 mm	 rectangular rectangular	 √3 √3	 $2 / r$ $2 / r$	 200/ 1000 200/ 1000	 0.1 0.2	∞
Anisotropy, f_A	1.040	0.008	normal	2	$1 / f_A$	100 / 1.04	0.4	∞
Attenuation correction, f_{aa}	0.992	0.001	normal	2	$1 / f_{aa}$	100 / 0.99	0.05	∞
Room scatter, f_{sc}	1.120	0.020	normal	2	$1 / f_{sc}$	100 / 1.12	0.9	∞
Spectral effects	- - -	2%	normal	1	1	1	2.0	∞
Calibration factor, $C_{Am/Be}$	1.030		normal				10.2	28.5
Expanded uncertainty (k = 2.04)	0.215		normal			***U***	20.8	30

$$u_i(y) = (\delta x_i / \text{divisor}) \times (c_i / y)$$

The values used for the quantities and their uncertainties are for illustration only and should not be assumed for other situations. The effective number of degrees of freedom has been calculated using the Welch-Satterthwaite formula (see Appendix A1.3).

4 Calibration of Surface Contamination Monitors and Radioactive Calibration Sources

This section covers the calibration of large area surface contamination reference sources and the calibration of surface contamination monitors themselves using these reference sources.

4.1 Calibration of Large Area Sources used for Calibrating Surface Contamination Monitors

4.1.1 Method

Surface contamination monitors are calibrated in terms of their response to known rates of radioactive emissions using large-area, planar, sources which have a defined area and whose emission rates have been determined using a calibration instrument. For the highest quality sources, ISO type Class 1 [9], the calibration instrument is a large area, windowless, multi-wire, gas-flow, proportional counter. Emission rates are determined with the electronic threshold set at 590 eV for beta emitters and above electronic noise for alpha emitters. The usual corrections also need to be made for the effects of dead-time and background.

The emission rate of the source, E, is defined by:

$$E \quad = \quad N \,/\, (1 - \tau\, N\,).\; f_{LL} \cdot f_{d} \quad - \quad B \qquad (1)$$

where:
- N - uncorrected source count rate from proportional counter,
- τ - system dead-time,
- f_{LL} - low level threshold factor,
- f_d - positioning factor,
- B - background count rate.

The partial derivatives of (1) are given by:

$$\frac{\partial E}{\partial N} = \frac{1}{(1-\tau N)^2} = \left(\frac{E+B}{N}\right)^2$$

$$\frac{\partial E}{\partial \tau} = \frac{N^2\, f_{LL} f_d}{(1-\tau N)^2} = (E+B)^2$$

$$\frac{\partial E}{\partial f_{LL}} = \frac{N\ f_d}{(1-\tau N)} = E+B$$

$$\frac{\partial E}{\partial f_d} = \frac{N\ f_{LL}}{(1-\tau N)} = E+B$$

$$\frac{\partial E}{\partial B} = 1$$

Under normal conditions, both factors f_{LL} and f_d are assumed to have a value of unity.

If the uncertainties are to be calculated in absolute terms, the uncertainty equation becomes:

$$\sigma_E^{\,2} = \left(\frac{E+B}{N}\right)^4 \sigma_N^{\,2} + (E+B)^4 \sigma_\tau^{\,2} + (E+B)^2 \sigma_{f_{LL}}^{\,2} + (E+B)^2 \sigma_{f_d}^{\,2} + \sigma_B^{\,2}$$

4.1.2 Uncertainty components

The uncertainty components are discussed below. For clarity, measurement results from actual measurements have been used.

In determining the sensitivity coefficients in the example, the values for *N*, *B* and *E* are taken to be 2720.7 s^{-1}, 26 s^{-1} and 2732 s^{-1}, respectively, from the experimental data.

4.1.2.1 Source count rate (uncorrected), *N*

The mean count rate, N, was determined by accumulating a series of consecutive counts. This series of 100 s counts gave 271615, 273109, 272436, 272293, 272004 and 270973 counts, giving a mean count rate of 2720.7 s^{-1} and a standard deviation of the mean of 3.0 s^{-1}. This is a Type A uncertainty with a normal distribution and 5 degrees of freedom. The sensitivity coefficient is $\{(2732 + 26)/2720.7\}^2 = 1.03$.

4.1.2.2 System dead-time, τ

The dead-time, τ, was measured using a double pulse generator as 5.0 μs ± 0.2 μs. This is a Type B uncertainty that is assumed to have a rectangular distribution with infinite degrees of freedom. The sensitivity coefficient is $(2732 + 26)^2 = 7.6 \times 10^6$.

4.1.2.3 Low level threshold factor, f_{LL}

For beta emitters, the low level counting threshold is set at 590 eV using an ^{55}Fe source. Experimental evidence shows that the associated semi-width Type B uncertainty, assumed to have a rectangular distribution, is 0.0025. The sensitivity coefficient is 2732 + 26 = 2758.

4.1.2.4 Positioning factor, f_d

The positioning factor, f_d, is the result of the uncertainty in mounting the source flush with the proportional counter cathode. Experimental results show that the Type B uncertainty (semi-width) arising from this effect is 0.0025. A rectangular distribution is assumed and the sensitivity coefficient is 2758.

4.1.2.5 Background, *B*

The background correction, B, was determined in the same way as the source count rate, i.e. taking a series of 100 s counts, which gave 2513, 2791, 2804, 2313, 2724 and 2536 counts. This yields a mean rate of 26 s^{-1} with a normally-distributed Type A standard uncertainty of 0.8 s^{-1} (standard deviation of the mean). The sensitivity coefficient is unity.

4.1.3 Uncertainty budget

Source of uncertainty	Uncertainty (δx_i)	Probability distribution	Divisor	c_i	$u_i(y)$ (s^{-1})	v_i or v_{eff}
Standard deviation of mean of source count rate, *N*	2.99 s^{-1}	normal	1	1.03	3.08	5
Semi-width of system dead-time, τ	0.2 μs	rectangular	√3	7.6x10^6	0.88	∞
Semi-width of threshold factor, f_{LL}	0.0025	rectangular	√3	2758	3.98	∞
Semi-width of positioning factor, f_d	0.0025	rectangular	√3	2758	3.98	∞
Standard deviation of mean of background, *B*	0.79 s^{-1}	normal	1	1	0.79	n.a.
Combined uncertainty	- - -	normal	- - -	- - -	6.52	100
Expanded uncertainty, (*k*=2)	- - -	normal	- - -	- - -	13.0	100

$$u_i(y) = (\delta x_i / \text{divisor}) \times (c_i / y)$$

4.1.4 Reported result

The calibration certificate could state:

The measured value of the emission rate is:

$$E = 2732 \pm 13 \text{ s}^{-1}$$

The reported uncertainty is based on a standard uncertainty multiplied by a coverage factor of k = 2, which provides a level of confidence of approximately 95%.

4.2 Calibration of Surface Contamination Monitors

4.2.1 Method

Surface contamination monitors are calibrated in terms of their response to known rates of radioactive emissions. In practice this is achieved by using large-area, planar sources that have a defined area and whose emission rates have been determined in a traceable manner [10]. The calibration is normally determined in terms of response/(emission rate per unit area). The source is usually positioned with its active face parallel to and at a distance of 3 mm from the face of the detector For this example, the monitor detector area (50 cm^2) is smaller than the area of the calibration source, which is a 10 cm x 10 cm layer of ^{14}C on a thick aluminium substrate. The monitor is also assumed to have an analogue display and a facility to set the detector voltage.

The calibration factor, C, is defined by:

$$C = \frac{(M - B).A.f_V.f_d.f_u.f_{bs}}{E} \qquad (2)$$

where:
- M - observed monitor reading,
- B - background reading,
- E - emission rate of the calibration source,
- A - area of the active portion of the calibration source
- f_V - plateau voltage factor,
- f_d - source-detector separation factor,
- f_u - source uniformity factor,
- f_{bs} - back-scatter factor.

The partial derivatives of (2) are given by:

$$\frac{\partial C}{\partial M} = (\mathrm{A}/\mathrm{E}) f_V f_d f_u f_{bs} = \frac{C}{(M - B)}$$

$$\frac{\partial C}{\partial B} = -(\mathrm{A}/\mathrm{E}) f_V f_d f_u f_{bs} = \frac{-C}{(M - B)}$$

$$\frac{\partial C}{\partial E} = -(M - B)(A/E^2) f_V f_d f_u f_{bs} = \frac{-C}{E}$$

$$\frac{\partial C}{\partial A} = (M - B)(1/E) f_V f_d f_u f_{bs} = \frac{C}{A}$$

$$\frac{\partial C}{\partial f_V} = (M - B)(A/E) f_d f_u f_{bs} = \frac{C}{f_V}$$

$$\frac{\partial C}{\partial f_d} = (M - B)(A/E) f_V f_u f_{bs} = \frac{C}{f_d}$$

$$\frac{\partial C}{\partial f_u} = (M - B)(A/E) f_V f_d f_{bs} = \frac{C}{f_u}$$

$$\frac{\partial C}{\partial f_{bs}} = (M - B)(A/E) f_V f_d f_u = \frac{C}{f_{bs}}$$

Under normal conditions, the factors f_V, f_d, f_u and f_{bs} are each assumed to have a value of unity.

If the uncertainties are to be calculated in fractional terms, the uncertainty equation becomes:

$$\left(\frac{\sigma_C}{C}\right)^2 = \left(\frac{M}{M - B}\right)^2\left(\frac{\sigma_M}{M}\right)^2 + \left(\frac{B}{M - B}\right)^2\left(\frac{\sigma_B}{B}\right)^2 + \\ + \left(\frac{\sigma_E}{E}\right)^2 + \left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_{f_V}}{f_V}\right)^2 + \left(\frac{\sigma_{f_d}}{f_d}\right)^2 + \left(\frac{\sigma_{f_u}}{f_u}\right)^2 + \left(\frac{\sigma_{f_{bs}}}{f_{bs}}\right)^2$$

If the fractional uncertainties $\left(\frac{\sigma_{x_i}}{x_i}\right)$ are all expressed as percentages, then the combined uncertainty will be a percentage, and this is the way this example will be treated. (It should be noted that this approach produces sensitivity coefficients of unity for the last 6 terms.)

4.2.2 Uncertainty components

4.2.2.1 Monitor reading of source, *M*

Several techniques can be used to determine the mean observed monitor reading, *M*, and its uncertainty. Assume a snap-shot technique is used whereby six successive, but randomly timed, readings are recorded, giving 350, 400, 400, 325, 350, 350 s^{-1}. The mean and standard deviation of the mean become 362.5 $\pm$ 12.5 s^{-1}. This equates to a percentage uncertainty in *M* of 3.45 % and the sensitivity coefficient is 362.5/(362.5 – 32.5), which is equal to 1.10. The distribution is assumed to be normal and the uncertainty of *M* has 5 degrees of freedom.

4.2.2.2 Monitor reading of background, *B*

This may be determined in the same types of ways as those used for the source count rate, M. In this case, an eye-averaging technique was used whereby the highest and lowest count rates were recorded over a given period of time. These count rates were 40 and 25 s^{-1} respectively, giving a mean value of 32.5 s^{-1}. The uncertainty has a rectangular distribution with a semi-width of 7.5 s^{-1}, equating to a percentage uncertainty of 23%. The sensitivity coefficient is 32.5/(362.5 - 32.5), which gives a value of 0.098.

4.2.2.3 Emission rate of calibration source, *E*

The emission rate of the source and its uncertainty were provided on the calibration certificate by the laboratory that calibrated the source using a windowless proportional counter (see section 4.1.4). The statement on the certificate was:

> *The measured value of the emission rate is*
>
> $$E = 2732 \pm 13\ s^{-1}$$
>
> *The reported uncertainty is based on a standard uncertainty multiplied by a coverage factor of k = 2, which provides a level of confidence of approximately 95 %.*

The standard uncertainty on E is therefore 6.5 s^{-1} or 0.24 %. Unless the certificate provides information to the contrary, it is assumed that the uncertainty has a normal distribution and infinite degrees of freedom.

4.2.2.4 Source area, *A*

In the absence of an uncertainty statement by the manufacturer, the only information available is the product drawing which shows the active area dimensions to be 10 cm x 10 cm. On the assumption that the outer bounds of these lengths are 9.9 and 10.1 cm, the uncertainty of the linear dimensions may be taken to be a rectangular distribution with a semi-width of 0.1 cm. The corresponding semi-width uncertainty on the area becomes $(2 \times (10 \times 0.1)^2)^{½}$ cm^2, which equals 1.41 cm^2 or 1.4 %.

4.2.2.5 Plateau voltage factor, f_V

This applies only to those monitors where manual alterations are possible. If the setting is not to be checked and/or adjusted between calibrations, then this has no effect. If, however, the user is allowed to do this, the setting may not be returned to exactly that used during the calibration. In this particular example, the slope of the response curve in this region is taken to be 10% / 50 v. It is assumed that an operator is more likely to set the voltage nearer to the optimum than the extremes and that ± 50 v represents the range at the 100 % confidence level. Accordingly, a triangular distribution is assumed with a semi-width of 50 v equating to a semi-width uncertainty for the voltage factor of 10%.

(It should be noted that changing the plateau voltage without performing a recalibration is not recommended practice).

4.2.2.6 Source-detector separation factor, f_d

This effect arises from the uncertainty in mounting the calibration source exactly 3 mm from the detector face. Experimental evidence has shown that, for the particular ^{14}C source at 3 mm source-detector separation, the change in response was 2.6% / mm. It is assumed that the deviation from the declared 3 mm separation is no greater than 1 mm but that all values are equally probable between 2 and 4 mm, a rectangular distribution. The equivalent semi-width uncertainty of the separation factor is thus 1 mm x 2.6% / mm, equal to 2.6%.

4.2.2.7 Non-uniformity of calibration source, f_u

Large area sources suffer from non-uniformity of the activity distribution. For Class 1 ^{14}C sources, the uniformity shall be better than ± 10% [9]. This is based on comparing 10 cm^2 sections of the source. For a typical monitor with a detector area of 50 cm^2 and a calibration source area of 100 cm^2, a worst case condition could be that the area under the detector has an activity per unit area that is 10% greater than the mean value for the whole source. (The outer area correspondingly will be 10% less than mean value.) Assuming a rectangular distribution, this represents a semi-width uncertainty of 10% for the source non-uniformity factor.

4.2.2.8 Backscatter factor, f_{bs}

Variations in backscatter effects arise from factors such as the nature of the surface on which the calibration source is resting and the proximity to scattering surfaces such as walls. This effect can be quite marked for photon emitters, but for ^{14}C on Class 1 substrates the effect is negligible.

4.2.3 Uncertainty budget

Source of uncertainty	Uncertainty (δx_i)	Probability distribution	Divisor	c_i	$u_i(y)$ (%)	v_i or v_{eff}
Standard deviation of mean of *M*	3.45 %	normal	1	1.10	3.80	5
Standard deviation of mean of *B*	23 %	rectangular	√3	0.098	1.30	∞
Standard uncertainty of calibration source emission rate, *E*	0.24 %	normal	1	1.0	0.24	∞
Semi-width of source area, *A*	1.41 %	rectangular	√3	1.0	0.82	∞
Semi-width of voltage factor, f_V	10 %	triangular	√6	1.0	4.08	∞
Semi-width of source-detector separation factor, f_d	2.6 %	rectangular	√3	1.0	1.50	∞
Semi-width of calibration source non-uniformity factor, f_u	10 %	rectangular	√3	1.0	5.77	∞
Uncertainty of backscatter factor, f_{bs}	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Combined uncertainty	- - -	normal	- - -	- - -	8.27	112
Expanded uncertainty, (k=2)	- - -	normal	- - -	- - -	16.5	112

$$u_i(y) = (\delta x_i / \text{divisor}) \times (c_i / y)$$

4.2.4 Reported result

Using the formula above, the calibration factor in terms of emission rate becomes:

$$C = (362.5 - 32.5)/(2732/100) = 12.1 \quad (counts.s^{-1}) / (s^{-1}.cm^{-2})$$

The calibration certificate could state:

> *The measured value of the calibration factor is:*
>
> $$C = 12.1 \pm 2.0 \quad (counts.s^{-1}) / (s^{-1}.cm^{-2})$$
>
> *The reported uncertainty is based on a standard uncertainty multiplied by a coverage factor of k = 2, which provides a level of confidence of approximately 95%.*

5 References

1 BIPM, IEC, IFCC, ISO, IUPAC, IUPAP and OIML, *Guide to the Expression of Uncertainty in Measurement,* International Organisation for Standardisation, Geneva, Switzerland, First Edition 1993,

Corrected and reprinted as –

BSI PD 6461: Part 3: 1995, *Vocabulary of metrology: Part 3. Guide to the expression of uncertainty in measurement*

2 UKAS publication B 0825, *The Expression of Uncertainty in Radiological Measurements* Edition 1, 1990.

3 UKAS publication M 3003, *The Expression of Uncertainty and Confidence in Measurement,* Edition 1, 1997.

4 ISO 4037: Part 1: 1996, *X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy - Part 1: Radiation characteristics and production methods*

ISO 4037: Part 2: 1997, *X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy - Part 2: Dosimetry for radiation protection over the energy ranges from 8 keV to 1.3 MeV and 4 MeV to 9 MeV*

5 ISO 4037: Part 3: 1997, *X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy - Part 3: Calibration of area and personal dosemeters*

6 Lira, I H and Wöger, W, *The evaluation of standard uncertainty in the presence of limited resolution of indicating device,* Meas. Sci. Technol. **8,** 441-443, 1997.

7 ISO 8529: Part 2: 1998, *Reference neutron radiations: Part 2. Calibration fundamentals related to the basic quantities characterising the radiation field*

8 ISO 8529: Part 3: 1998, *Reference neutron radiations: Part 3. Calibration of area and personal dosimeters and determination of their response as a function of neutron energy and angle of incidence*

9 NPL Measurement Good Practice Guide No.14: 1999, *The Examination, Testing and Calibration of Portable Radiation Protection Instruments.*

10 ISO 8769: 1998, *Reference sources for calibration of surface contamination monitors – Beta-emitters (maximum beta energy greater than 0.15 MeV) and Alpha emitters.*

Appendix 1 Coverage Factors and Use of the *t* Distribution

A1.1 *t*-Distribution

As mentioned in Section 1, the choice of $k = 2$ for coverage factor to give an expanded uncertainty for 95 % confidence level assumes that the Type A uncertainties are based on a large number of observations so that the probability distribution tends to normal. This is often not the case and measurements are sometimes restricted to series of less than ten observations. The choice of $k = 2$ then gives an underestimate of the uncertainty because the probability follows a *t*-distribution.

If the associated Type A standard uncertainties are fairly small compared with the other (Type B) standard uncertainties (these have infinite degrees of freedom), then the use of $k = 2$ would have very little effect on the expanded uncertainty.

On the other hand, if a Type A uncertainty is based on less than ten observations and is, for example, twice the combined Type B uncertainty, then use of $k = 2$ would underestimate the expanded uncertainty by at least 7 %. The coverage factor for a given level of confidence should be derived from the *t*-distribution. The value depends on the effective number of degrees of freedom, v_{eff}, as shown in Table A1.1.

Table A1.1 k-values for 95% confidence level

v_{eff}	2	3	4	5	6	7	8	9	10	12
k	4.30	3.18	2.78	2.57	2.45	2.36	2.31	2.26	2.23	2.18
v_{eff}	14	16	18	20	25	30	35	40	50	∞
k	2.14	2.12	2.10	2.09	2.06	2.04	2.03	2.02	2.01	1.96

A1.2 Degrees of Freedom

The Welch-Satterthwaite expression may be used to derive the effective number of degrees of freedom for a particular uncertainty budget:

$$v_{eff} = \frac{u_c^4(y)}{\sum \{u_i^4(y)/v_i\}}$$

Here, v_i is the number of degrees of freedom for the i^{th} uncertainty component. For a series of n measurements $v_i = n - 1$.

For Type B uncertainties the number of degrees of freedom is usually infinite so that if there is one dominant Type A uncertainty, $u_A(y)$, with v_A degrees of freedom, the expression simplifies to

$$v_{eff} = v_A \{ u_c(y) / u_A(y) \}^4.$$

A1.3 Examples

A1.3.1 Uncertainty budget for calibration of dose rate meter

The budget shown in section 2.2.5 (Table 2.2) has large uncertainty due to the meter reading.

Based on ten observations for reading in beam and twenty for background:

$$u_s(y) = 3.0\ \%$$

$$u_B(y) = 0.5\ \%$$

The combined standard uncertainty:

$$u(y) = 3.62\ \%$$

The effective number of degrees of freedom is

$$v_{eff} = 3.62^4 / \{ (3.0^4 / 9) + (0.5^4 / 19) \}$$

$$= 171 / \{ 9.0 + 0.003 \}$$

$$= 19.1$$

From Table A1.1, the coverage factor for 19 degrees of freedom is 2.09. The expanded uncertainty is therefore $U = 10.3$ % for a confidence level of 95 %.

A1.3.2 Uncertainty budget for calibration of neutron area survey monitor

The budget shown in section 3.1.3 (Table 3.1) has large uncertainty due to the meter reading.

Based on 25 observations for readings in field:

$$u_s(y) = 9.03\ \%$$

The combined standard uncertainty:

$$u(y) = 9.43\ \%$$

The effective number of degrees of freedom is

$$v_{eff} = 9.43^4 / (9.03^4 / 24)$$

$$= 24 \text{ x } (9.4 / 9.0)^4$$

$$= 28.6$$

From Table A1.1, the coverage factor for 28.6 degrees of freedom is 2.04. The expanded uncertainty is therefore $U = 0.199$ for a confidence level of 95 %.

This demonstrates that the effect of assuming a normal distribution instead of a *t*-distribution is negligible for this example where 25 observations have been made.

Changes to March 2003 version

The following changes were made in February 2005

1.1	Expression of uncertainties as percentages indicated
1.4.2	New text relating to above inserted for clarification
1.6	New text relating to above inserted for clarification
2.1.2.7	Clarification
2.2.4.2	The original term "uncertainty" replaced by "correction"
2.2.4.4	The original term "uncertainty" replaced by "correction"
2.2.2.2	Re-written and extended to take into account the uncertainty in kerma-to-dose equivalent conversion coefficient that is due to source spectra not being truly monoenergetic
Table 2.2	New component relating to above inserted into uncertainty budget
3.1.2.1	Expanded to include ^{252}Cf sources. Uncertainty in fluence-to-ambient dose equivalent conversion coefficient due to non-monoenergetic spectra increased
3.1.2.9	Minor changes
3.1.4	Revised value of expanded uncertainty from Table 3.1 inserted (see below)
Table 3.1	Uncertainty in conversion coefficient increased
References	Previous reference [5] moved into reference [4] New reference [5]
References	"Additional Reading" withdrawn