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Second IRMF Intercomparison of Calibrations of Neutron Area Survey Monitors 1998 - 1999

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ABSTRACT

The Ionising Radiations Metrology Forum (IRMF) organised an intercomparison of calibrations of neutron area survey instruments in which five establishments in the UK participated. The exercise involved the circulation of two neutron dose-rate monitors for calibration in the fields produced using ^{252}Cf and ^{241}Am-Be. The instruments used were a Harwell model 0949 and a Studsvik model 2202D.

All results were submitted to the author for analysis. Responses relative to neutron fluence, as stated by the individual participants, were calculated. The results are compared and demonstrate good agreement between establishments.

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CONTENTS

1 INTRODUCTION

One of the main aims of the Ionising Radiations Metrology Forum (IRMF) is to encourage good practice in radiological measurements, including the need for traceability to the appropriate national standards, through the organisation of regular intercomparisons of calibrations of monitoring in areas of ionising radiation metrology. The aim is to hold intercomparisons in each area (neutron, gamma-ray and surface contamination monitoring) at approximately three-year intervals. The main objective of the intercomparisons is to assess the ability of calibration laboratories to perform routine calibrations of instrumentation in pursuance of the Ionising Radiations Regulations 1999 [1].

The first IRMF intercomparison of calibrations of neutron area survey monitors [2] was held in 1995/6. As in that exercise, the present intercomparison involved the circulation of two radiation protection, area survey neutron monitors for participants to calibrate in two neutron fields produced using radionuclide sources and at several dose rates. The participants generally carried out their measurements in the neutron fields and at dose-rates normally used for routine instrument calibrations, employing the same methods to calibrate the two transfer instruments as are routinely used within their organisation.

The calibration quantity for this intercomparison was **neutron fluence**.

The intercomparison was planned by a working party comprising representatives from all participating laboratories (see below). The organisation and coordination of the exercise were funded under the National Measurement System Programme in Ionising Radiation Metrology and were carried out by NPL. All results were reported to the author, who was not involved in any of the calibrations carried out at NPL, for analysis.

Instrumentation matters were referred to and dealt with by Graeme Taylor, NPL.

The measurements started in September 1998 and were thought to be completed in May 1999. The results were analysed by July and circulated in August as sets of normalised values. Further measurements were carried out to investigate some unexpected effects. The schedule is shown in Appendix 1. A workshop to discuss the results was held in early October 1999.

2 PARTICIPANTS

The establishments (and contact persons) participating in the intercomparison were -

AEA Technology, Harwell	R Bosley
Defence Radiological Standards Centre, AWE, Aldermaston	M Chandler
National Physical Laboratory, Teddington	G C Taylor
National Radiological Protection Board, Chilton	T Daniels, D R McClure
*BAE Systems, Barrow-in-Furness	J R Pople, S Marriott

(* Previously VSEL and also Marconi Marine)

The contact persons formed the working party planning the intercomparison.

Prior to the intercomparison it was decided that participants would not be allowed to withdraw results. The participants chose to identify their results in any presentation or report associated with the exercise.

3 PROTOCOL

A comprehensive protocol for the intercomparison, based on that employed in the first IRMF intercomparison [2], was produced by the working party. This provided guidance and included pro forma for reporting various information and the results of measurements to the evaluator. Instructions were given for mounting and operating the instruments correctly. Deviation from the preferred orientation was discouraged unless it was physically impossible to achieve such an orientation in the facility used.

3.1 INFORMATION REPORTED BY PARTICIPANTS

The following pro-forma were provided:

3.1.1 Form IRMF NI.1 Calibration measurement details

This form was used for reporting results obtained using the routine calibration technique. The reported data included -

- source
- distance between source and centre of dose meter
- fluence rate and approximate dose equivalent rate
- monitor responses (pulse and/or dial)
- scatter correction
- calculated fluence rate response.

These details were sufficient to enable the evaluator to calculate the calibration value and check those calculated by the participant. The appropriate uncertainties were also requested.
Temperature, pressure and humidity were also reported.

3.1.2 Form IRMF NI.2 Alternative methods

This form reported essentially the same details as IRMF NI.1 for methods used in addition to the routine calibration technique.

3.1.3 Form IRMF NI.3 Details of neutron sources

Participants were asked to supply information about their sources including -

emission rate
anisotropy factor
air attenuation factor
encapsulation and dimensional details.

3.1.4 Form IRMF NI.4 Details of calibration facilities

Participants were asked to supply the following details of calibration rooms -

approximate dimensions of the exposure room,
source height above floor and distance from walls,
source - instrument separation distance,
wall material.

The dimensions of the calibration rooms, shown in Table 1, varied considerably.

3.1.5 Form IRMF NI.5 Additional details or comments

This form enabled participants to report anything else of relevance.

3.1.6 Form IRMF NI.6 Uncertainties

Participants were asked to supply sample uncertainty budgets.

4 RADIATION FIELDS

Two types of neutron fields, based on ^{252}Cf and ^{241}Am-Be sources, were selected for this intercomparison. The fields used by individual participants are shown in Appendix 1. All five participants reported results based on ^{241}Am-Be fields. Four participants also used ^{252}Cf fields. The ^{252}Cf source used by NRPB was fifteen years old and not used routinely for calibrations. (The ^{252}Cf source of the fifth participant was unavailable at the time because it required re-commissioning.) All participants reported traceability of fluence rates to national standards.

The participants usually possessed only one or two sources of each radionuclide. A range of distance between source and monitor was therefore used to give a range of dose rates. Overall, a range of neutron dose equivalent rates from about 2 to 1200 μSv h^{-1} was covered. The maximum dynamic range for any individual participant was a factor of about 200 between minimum and maximum dose rates.

5 INSTRUMENTATION

Two types of widely-used, neutron dose-equivalent rate monitors, described below, were used as transfer instruments. Both belonged to NPL. The electronics were not deliberately off-set.

5.1 HARWELL MONITOR 0949

The Harwell monitor type 0949 comprises a thermal neutron detector at the centre of a 20 cm diameter spherical polyethylene moderator. It has internal batteries as a power supply for the electronics and can also be powered externally. The monitor has a digital dial indication with several ranges and also an external pulse output.

All five participants reported results for the Harwell 0949 in ^{241}Am-Be fields. Four participants calibrated the Harwell 0949 also in ^{252}Cf fields.

5.2 STUDSVIK MONITOR 2202D

The Studsvik monitor type 2202D comprises a thermal neutron detector at the centre of a cylindrical polyethylene moderator; one end has rounded edges. It has internal batteries as a power supply for the electronics. The monitor has a single, logarithmic range analogue indication and also an external pulse output.

All five participants reported results for the Studsvik 2202D in ^{241}Am-Be fields. Four participants calibrated the Studsvik 2202D using ^{252}Cf fields.

5.3 RECORDED READINGS

Participants were given the choice of whether to report the readings indicated by the dials of the monitors or whether to measure the count rate of the pulse outputs. Two participants chose to report only the pulse rate readings, one reported only the dial readings and two reported both. Subsequently it was found that allowing this choice produced difficulties in comparing the results (see Section 7 below).

5.4 STABILITY CHECKS

In between measurements at the participants' laboratories the instruments were returned to NPL for checks of response to an ^{241}Am-Be source using a fixed geometry. The checks were carried out within one month of the end of the measurements of each participant. Apart from the replacement of some connections, no problems were encountered.

6 MEASUREMENTS AND ANALYSIS

6.1 CALIBRATIONS

6.1.1 Method

The two instruments were circulated together to participating laboratories where they were placed at selected distances from the radionuclide sources and their responses (the count rate of detected events and/or the meter reading per unit fluence or fluence rate) were measured.

The fluence rate was normally determined from the measured value of the source emission rate, the source anisotropy factor and the distance. An attenuation correction, dependent on the distance between source and front face of the monitor was applied for each position.

6.1.2 Formula for response

The reading of a monitor in a neutron field produced by a radionuclide source may be expressed -

$$R(r) = \varepsilon \frac{E}{4\pi r^2} f_g(r)\, f_A\, f_{aa}(d)\, f_{sc}(r) + B(r)$$

where ε is the response (defined as the reading per unit fluence) for source spectrum, E is the emission rate of source and r is the distance between centre of meter and source.

6.1.3 Minor corrections

For a sphere with radius ρ, the geometrical correction, $f_g(r)$ [3], is less than 1% for distance r greater than 4ρ. For the monitors used, the effect was insignificant at distances greater than 40 cm.

The anisotropy of the source, represented by the factor f_A,, can be as high as 4% for physically large ^{241}Am-Be sources, but is closer to 1% for ^{252}Cf sources.

The air attenuation correction, $f_{aa}(d)$, for the distance, d, between the source and the front face of the monitor was calculated using published values of 0.89 % m^{-1} and 1.06 % m^{-1} for the attenuation coefficients for ^{241}Am-Be and ^{252}Cf neutrons respectively.

The background effect, $B(r)$, is generally insignificant.

6.1.3 Room-scatter correction, $f_{sc}(r)$

Participants were asked to report the magnitude of the correction for neutrons scattered from the air, walls, floor and ceiling of the calibration room. The correction was generally expressed in terms of percentage increase of the reading of a monitor relative to the that due to direct neutrons. It was expressed sometimes in terms of a fluence rate or dose equivalent rate.

Although the reading due to the direct component varies according to an inverse square relation with distance (allowing for air-attenuation), the room-scatter component is fairly constant and the air-scatter component varies inversely with distance. Therefore the combined effect of scatter increases with distance relative to the direct component. The room-scatter corrections depended markedly on the room dimensions and structural materials. For comparison between participating laboratories, values are shown in Table 1 for a standard distance from source of one metre.

One participant (NPL) measured the room-scatter component at each distance for each monitor/ source calibration. Another participant (NRPB) assumed that the absolute magnitude of the room-scatter component was constant and used linear regression analysis to fit the data. Other participants used room-scatter corrections that had been derived from previous series of measurements made for the types of monitor used in ^{241}Am-Be and ^{252}Cf. fields.

6.2 ANALYSIS

6.2.1 Calculation of response values

For each monitor/source/distance configuration, participants reported the calculated fluence rate and corresponding monitor reading, using the pro-forma report forms provided with the protocol (see Section 3 above). The participants were asked to calculate the corresponding response values and to derive a weighted mean value for each monitor/source configuration. The pro-forma report forms were sent to the Evaluator for checking and analysis at NPL.

The responses are expressed in terms of fluence (or fluence rate) rather than dose equivalent because the latter is derived from the former simply by using recommended values for the conversion factors for the two radionuclide fields.

6.2.2 Calculation of mean values

For each source/monitor configuration the weighted mean value was calculated for each set of response values obtained over the range of distance used by each participant. The weighting factors were derived as the inverse of the overall random uncertainty for each individual value. The main random (type A) uncertainties were those of statistical origin (recorded events or fluctuation of display) and source-to-detector distance determination. The components due to the source emission rate and anisotropy were excluded.

There were difficulties in including the random component of the room-scatter correction because it was not always known and also because the corrections at different distances were often correlated. However, as the uncertainties were greatest for the greater distances where the statistical uncertainties were largest anyway, this exclusion had little practical effect on the weighted mean values.

Some participants did not calculate mean values; this was done by the Evaluator.

6.3 FURTHER MEASUREMENTS

It became obvious (see Section 7 below) when all the data had been analysed that there were problems with the Studsvik 2202D calibrations when recording the dial reading while simultaneously utilising the pulse output response. Subsequently NRPB investigated this thoroughly and demonstrated that the problems were due to the dial reading changing when the pulse output was loaded with a low impedance such as that of a scaler. A copy of the NRPB report on these investigations is included as an annex to the present report.

It was concluded that the calibrations made by AEA Technology of the Studsvik 2202D in the dial mode of operation could not be compared directly with the results of other participants, but it was agreed not to ask them to repeat these measurements because neither DRaStaC nor NPL had calibrated the Studsvik 2202D in the dial mode of operation. Instead, as only NRPB had performed all their calibrations using the dial response mode, it was agreed to return both monitors to NRPB for the further calibrations to be carried out using the pulsed output mode only. This would enable an intercomparison to be made between all participants of calibrations carried out under the same conditions.

7 RESULTS

7.1 GENERAL

The responses measured by each participant at each individual distance for every source/ monitor configuration are shown in Figures 1, 3, 5 and 7, for the pulse mode of operation. For ease of comparison between the results for the different configurations, the figures are in roughly the same proportions with the upper limit of the ordinate scale being a factor of about 1.25 that of the lower limit. The few data that lie outside these limits have been omitted from the calculation of the mean values.

The corresponding responses for the dial mode of operation are shown in Figures 2, 4, 6 and 8. All values are expressed in terms of reading per unit fluence rate. Figures 2 and 6 (for the Harwell 0949) are in the same proportion with a factor of about 1.5 between the ordinate scale limits; the factor is about 1.77 for Figures 4 and 8 (Studsvik 2202D).

Measurements in accelerator-produced neutron fields with strengths much higher than those obtained using radionuclide sources had previously indicated that the type of monitor used in this intercomparison did not suffer from dose rate effects [2]. In the present exercise, the principal means of varying dose rate was to vary distance between source and monitor, and this produced a change in the room scatter correction that could easily hide any dose rate effect or give the appearance of an effect. It could be assumed therefore that any trend with dose rate in the radionuclide fields used was likely to be due to room scatter effects. As no significant trends were found it was assumed that the room scatter corrections used by all participants were reasonably consistent over the ranges of distance used.

The weighted mean values for the sets of results from each participant are given in Tables 2 and 3. The mean response values for the dial mode of operation are also quoted in terms of the reading per unit ambient dose equivalent because this is the quantity required in practical monitoring. These have been derived using the conversion coefficients based on ICRP 60 [4].

For convenience the mean calibration values of each participant have been normalised to those of AEA Technology (Table 4), who were chosen because only they had carried out calibrations in all eight source/monitor/mode of operation configurations.

7.2 ^{241}Am-Be CALIBRATIONS

7.2.1 Harwell 0949

The responses for all five participants using the monitor in the pulse mode of operation are shown in Figure 1. Nearly all lie in a band of $\pm$ 2.3 % about a mean, with the NRPB values measured at the lower fluence rates (ie. at the greater distances) appearing to be outliers. An NRPB value measured at the greatest distance is very much lower than all other values and lies off-scale. The mean and normalised values shown in Tables 2 and 4 respectively, have a range of 3.0 %, which is well within the estimated uncertainties (see Section 8 below) which vary from around 2 % to 5 %.

The responses for three participants using the dial mode of operation, shown in Figure 2, nearly all lie in a band of $\pm$ 5.5 % about a mean. The reading obtained using switch position (a) was normally used; AEA Technology reported values for ranges (a) and (b). The BAE Systems and NRPB values measured at the greatest distance are off-scale and have large uncertainties; therefore they are not included in the calculation of weighted mean values. The mean and normalised values, given in Tables 3 and 4, have a range of 1 %. This is similar to that for the pulse mode of operation (for the same participants) and well within the estimated uncertainties.

7.2.2 Studsvik 2202D

The results for all five participants for the pulse mode of operation (Figure 3) lie in a band of ± 7.0 % except for the NRPB value for the greatest distance which is off-scale. The scatter is largest at the greater distances (lower count rates) where the random uncertainties are highest. The weighted mean and normalised values (Tables 3 and 4) have a range of 3.5 %, which is within the estimated uncertainties.

The responses (three participants only) for the dial mode of operation (Figure 4) show large (about 10%) variations for each participant. The weighted means of the values for NRPB and BAE Systems are consistent, but in clear disagreement with the AEA Technology mean value which is over 25% lower. This is known to be due to the pulse output being connected to a scaler while the dial reading was being recorded (noted in Section 6.3 above) during the AEA Technology measurements.

7.3 ^{252}Cf CALIBRATIONS

7.3.1 Harwell 0949

The results for the three participants employing the pulse mode of operation (Figure 5) all lie within a band of ± 3.0 %. The mean and normalised values of the participants (Tables 3 and 4) have a range of 2.0 %, which is similar to that achieved with the ^{241}Am-Be fields in 7.2.1 above.

Only two participants reported values for the dial mode (Figure 6). As in 7.2.1 above, the AEA Technology responses were measured using two switch positions. The values are all within a band of ± 4 % except for one value which has been omitted from the derivation of the mean. The means, given in Table 3, agree to within 2.3 %.

7.3.2 Studsvik 2202D

The results for the three participants employing the pulse mode of operation (Figure 7) all lie within a band of ± 5.5 %. The mean and normalised values of the participants have a range of only 1.2 %, which is surprising in view of the relatively large variation. This is much better than that achieved with the ^{241}Am-Be fields in 7.2.2 above, but is probably due in part to the smaller number of participants.

Only two participants reported values for the dial mode (Figure 8). The AEA Technology responses were measured in two sets (with two different sources) on different days. Both sets are internally consistent but differ by about 30%, with the higher set being about 10% lower than the values reported by NRPB. The AEA Technology records showed that the lower values had been obtained while the pulse output was connected to a scaler and the higher set had been obtained with the scaler inadvertently disconnected, on the following day. This 30% difference is a clear demonstration of the effect observed in 7.2.2 above.

8 UNCERTAINTIES

8.1 UNCERTAINTY BUDGETS

Examples of typical uncertainty budgets submitted by four participants are shown in Tables 5, 6, 7 and 8. These are for calibrations carried out at chosen distances and do not apply to the mean values. The fifth participant did not submit an uncertainty budget.

The uncertainties have been treated in accordance with UKAS, 1997 [5]. The expanded uncertainties at 95 % confidence level have been calculated by combining the standard uncertainties of the various components in quadrature and multiplying by a k-factor $(k = 2)$.

8.2 COMPONENTS

8.2.1 Response - statistical

The random uncertainty for the observed response is either calculated from the standard deviation of the number of events observed (taken as the square root) in the pulse counting mode or estimated from the amount of fluctuation of the dial reading.

8.2.2 Neutron source emission rate

The source emission rate used is usually that measured by NPL. The associated uncertainty value of 0.7%, at a confidence level of 95% (k = 2), that used to be quoted have been re-evaluated for routine calibrations. The NPL certificates of calibration currently give a value for the uncertainties of ± 1.0% or greater. This uncertainty is produced by the combination of several components and therefore has a normal distribution.

8.2.3 Neutron source anisotropy

The anisotropy value is normally that measured by NPL. It is around 1% for the ^{252}Cf sources used in this exercise and up to about 4% for ^{241}Am-Be sources. The certificate of calibration gives values for the uncertainties of about 20% of these values (confidence level of 95%). This uncertainty has a normal distribution.

8.2.4 Distance of the effective centre of monitor from neutron source

The uncertainty in the distance between detector and source centre is comprised of three components, namely, those due to -

a) the calibration of the distance measuring device which is assumed to have a rectangular distribution;
b) the accuracy and reproducibility of the reading of the distance d between source and monitor; this would usually be assumed to have a normal distribution;
c) the position of the effective centre of the dosemeter which is assumed to be the physical centre of a spherical detector. The uncertainty is obtained from the manufacturer's specification of physical dimensions of device. It is of the order of ± 1.0 mm and assumed to have a rectangular distribution.

8.2.5 Room- and air-scatter correction

The fractional room- and air-scatter component varies markedly with distance and from one facility to another. The uncertainty is typically around 10% to 20% of the correction (at 95% confidence level) and can be the dominant contribution to the overall uncertainty.

8.2.6 Air attenuation correction

The air attenuation correction is of the order of 1% at one metre. The uncertainty is conservatively assumed to be 10% of the correction.

8.2.7 Half life

The uncertainty due to that in the half life of ^{252}Cf (966.1 $\pm$ 2.9 day) depends on the interval between the calibration of the source and the measurements for the intercomparison; it can be as large as 0.4% . The half life of an individual specific source can vary with time because of the presence of small quantities of other isotopes of californium with significantly different half lives from that of ^{252}Cf.

The uncertainty due to that in the half life of ^{241}Am (1.5785 $\pm$ 0.0024 x 10^5 day) has negligible effect (less than 0.1%) for measurements are made within ten years of calibration of the source.

8.2.8 Dead-time effects

Dead time effects are generally small and the associated uncertainty is also less than 0.1% and considered negligible.

8.2.9 Spectral effects

It should be noted that there could be differences between the spectra of different sources due to differences in the physical properties. The spectra for the ^{241}Am-Be sources used in this intercomparison were assumed to be similar because the encapsulations were not massive for sources of the strengths used. Therefore no uncertainty has been incorporated in the budgets to cover this effect.

8.3 COMMENTS

In the examples chosen, AEA Technology have estimated their uncertainty to be around 1.6%, BAE Systems and NPL have estimated their uncertainties to be around 2.5%, while DRaStaC have estimated a value approaching 5 %. These differences are due mainly to three factors.

First, DRaStaC used a source with an emission rate that had been measured with a calibrated precision long counter whereas BAE Systems and NPL used sources that had been calibrated absolutely using the NPL manganese sulphate bath system. These two values had smaller uncertainties, but were higher than that quoted by AEA Technology. This latter difference reflects a decision to increase some of the uncertainties in the manganese sulphate bath technique at NPL following a recent reappraisal.

Secondly, the room-scatter correction at DRaStaC was greater than those at BAE Systems, and AEA Technology, and had a correspondingly larger uncertainty.

Finally, the statistical uncertainty for the NPL reading was larger than those for the other three participants. However, it does incorporate the air- and room-scatter component subtraction as measured using a shadow cone.

It should be noted that the uncertainties involved in the calibration of monitors in neutron fields produced employing radionuclide sources will generally be much less than those encountered when using the monitors in fields with spectra different to those of the calibration fields.

9 DISCUSSION

The participants' responses obtained employing their routine calibration fields and conditions agree to within ± 3 % for the pulsed mode of operation; this is within the estimated uncertainties.

The agreement is less clear for the dial responses because fewer participants operated the monitors in this mode and also because of the problem with recording the dial readings of the Studsvik 2202D when the pulse output was connected to a scaler. In order to make intercomparisons more meaningful, the protocol should be more specific about which mode of operation to use so that all participants make carry out calibrations under the same conditions. The pulse output mode is the more accurate mode for calibration because of the superior statistics. However, the dial reading mode is the one preferred for field measurements.

The current exercise was similar in scope to the previous intercomparison [2], employing the same models of monitor and the same neutron fields. However, the range of calibrations undertaken was wider, with all participants calibrating both monitors and four participants using both radionuclide fields. There has also been greater emphasis on the derivation and expression of uncertainties.

The sensitivities of the monitors used in this exercise (and of other neutron monitors) vary with neutron energy whether expressed in terms of fluence or in terms of a dose equivalent quantity. There is some evidence of this variation between Am-Be and ^{252}Cf spectra in Table 2 for the calibrations in terms of fluence. Applying the older conversion factors (see [6]) would yield a larger variation, whereas those derived from ICRP60 [4] would have less effect.

10 CONCLUSIONS

The intercomparison has demonstrated that the overall accuracy is very satisfactory and that the calibrating facilities could meet the requirements of the IRRs [1] and the associated codes of practice [7].

The uncertainties that have been given by participating laboratories are adequate for the accuracy required. The participants' approach to the treatment and expression of uncertainty in this area is consistent.

11 ACKNOWLEDGEMENTS

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APPENDIX 1 SCHEDULE OF MEASUREMENTS

	Studsvik 2202D		Harwell 0949	
	^{241}Am-Be	Cf-252	^{241}Am-Be	Cf-252
DRaStaC, Aldermaston	September 98	September 98	September 98	September 98
AEA Technology, Harwell	November 98	November 98	November 98	November 98
NPL, Teddington	January 99	January 99	May 99	May 99
NRPB, Chilton	May 99 October 99	May 99 - - -	March 99 November 99	March 99 - - -
BAE Systems, Barrow-in-Furness	April 99	- - -	April 99	- - -

Table 1 Room dimensions and room scatter corrections

	Dimensions of room Length x width x height (m)	Scatter correction normalised to 1 metre distance			
		Am - Be		Cf-252	
		Harwell 0949	Studsvik 2202D	Harwell 0949	Studsvik 2202D
AEA Technology, Harwell	9.4 x 10 x 6	6	6	6	6
DRaStaC, Aldermaston	9.1 x 5.5 x 4.4	23.5	23.5	19	19
NPL, Teddington	25 x 18 x 18	7.5	6.8	8.0	6.5
NRPB, Rad. Metrology, Chilton	8 x 5 x 2.5 *	10.4	10.4	8.8	6.6
BAE Systems, Barrow in Furness	11.7 x 6.6 x 4.5 **	12	9.8	- - -	- - -

* "PREMADEX" lining over concrete
** Lightweight roof

The room scatter correction is expressed as percentage of direct field

The DRaStaC values for the Studsvik 2202D were assumed to be equal to those measured for the Harwell 0949.

Table 2 Measured responses: pulse output mode of operation

Expressed as detected events per unit neutron fluence (cm^2)

	^{241}Am - Be			Cf-252			Ratio (Cf-252 / ^{241}Am-Be)	
	Harwell 0949 (Figure 1)	Studsvik 2202D (Figure 3)	Ratio	Harwell 0949 (Figure 5)	Studsvik 2202D (Figure 7)	Ratio	Harwell 0949	Studsvik 2202D
DRaStaC, Aldermaston	0.2585	0.398	1.540	0.289	0.416	1.435	1.12	1.045
AEA Technology, Harwell	0.2615	0.4015	1.535	0.295	0.413	1.400	1.13	1.03
BAE Systems, Barrow-in-Furness	0.263	0.388	1.475					
NPL, Teddington	0.262	0.387	1.475	0.290	0.411	1.415	1.11	1.06
NRPB, Chilton	0.2665	0.3905	1.465					

Table 3 Measured responses: dial reading mode of operation

Expressed as: (a) indication per unit neutron fluence rate (μSv h^{-1}/ cm^{-2} s^{-1})
(b) indication per unit ambient dose equivalent rate (μSv h^{-1}/μSv h^{-1})

		^{241}Am - Be			Cf-252			Ratio (Cf-252 / ^{241}Am-Be)	
		Harwell 0949 (Figure 2)	Studsvik 2202D (Figure 4)	Ratio	Harwell 0949 (Figure 6)	Studsvik 2202D (Figure 8)	Ratio	Harwell 0949	Studsvik 2202D
AEA Technology	a)	1.140	0.795	1.44	1.290	0.915	1.41	1.13	1.15
(Harwell)	b)	0.809	0.564		0.931	0.660		1.15	1.17
BAE Systems	a)	1.132	1.032	1.10					
(Barrow-in-Furness)	b)	0.824	0.700						
NRPB Radiation Metrology	a)	1.135	1.040	1.09	1.320	1.032	1.28	1.16	0.99
(Chilton)	b)	0.806	0.738		0.952	0.745		1.18	1.01

Fluence-to-ambient dose equivalent conversion factors: ^{241}Am-Be: 391 pSv cm^2
Ref [4] ^{252}Cf : 385 pSv cm^2

Table 4 **Normalised responses**

	^{241}Am - Be				Cf - 252			
	Harwell 0949		Studsvik 2202D		Harwell 0949		Studsvik 2202D	
	Pulse (Figure 1)	Dial (Figure 2)	Pulse (Figure 3)	Dial (Figure 4)	Pulse (Figure 5)	Dial (Figure 6)	Pulse (Figure 7)	Dial (Figure 8)
DRaStaC	0.990		0.990		0.980		1.007	
AEA Technology	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
BAE Systems	1.005	0.993	0.966	1.300				
NPL	1.002		0.964		0.983		0.995	
NRPB	1.020	0.996	0.973	1.310		1.023		1.13

To aid comparison, all results are normalised to AEA Technology values

Table 5 Uncertainty budget: DRaStaC

Field: Cf-252 Monitor: Harwell 0949 Pulse output response

Symbol	Source of uncertainty	Value	Uncertainty	Probability distribution	Confidence level	u_i ± %
N(r)	Response	2.86×10^4	0.60 %	normal	67 %	0.60
E	Source emission rate	3.7×10^6 s^{-1}	2.8 %	normal	95 %	1.40
t	Period	2400 s	2 s	rectangular	- - -	0.05
f_A	Anisotropy of source	1.01	0.5 %	normal	95 %	0.25
r	Distance:	917 mm				
	calibration uncertainty	----	0.2 mm	rectangular	- - -	0.03
	repeatability	----	2 mm	rectangular	- - -	0.25
	position of effective centre	----	1 mm	rectangular	- - -	0.13
$f_{aa}(d)$	Ancillary data	1.000	0.1 %	normal	95 %	0.05
$f_{sc}(r)$	Room scatter factor	1.168	3.0 %	rectangular	- - -	1.73
$u_c(\varepsilon)$	Combined uncertainty			normal	67 %	2.35
U	Expanded uncertainty ($k = 2$)			normal	95 %	4.7

The response was measured in terms of the number of events *N(r)* recorded in time *t*.

The source emission rate had been measured previously using a calibrated precision long counter.

Table 6 Uncertainty budget: National Physical Laboratory

Field: ^{241}Am - Be Monitor: Studsvik 2202D Pulse output response

Symbol	Source of uncertainty	Value	Uncertainty	Probability distribution	Confidence level	u_i ± %
N(r)	Response - statistics	12,500	0.90 %	normal	67 %	0.90
E	Source emission rate	2×10^6 s^{-1}	1.2 %	normal	95 %	0.60
t	Period	2000 s	0.2 s	rectangular	- - -	0.06
f_A	Anisotropy of source	1.025	0.5 %	normal	95 %	0.25
r	Distance: (combined)	1300 mm	1.3 mm	normal	67 %	0.20
$f_{aa}(d)$	Ancillary data	0.989	0.1 %	normal	95 %	0.05
$f_{sc}(r)$	Room scatter factor *	- - -	- - -	- - -	- - -	- - -
$u_c(\varepsilon)$	Combined uncertainty			normal	67 %	1.13
U	Expanded uncertainty (*k* = 2)			normal	95 %	2.3

* Measured directly using shadow cone - included in statistical uncertainty for response

Table 7 Uncertainty budget: BAE Systems

Field: ^{241}Am - Be Monitor: Harwell 0949 Pulse output response

Symbol	Source of uncertainty	Value	Uncertainty	Probability distribution	Confidence level	u_i ± %
N(r)	Response	3.4 x 10^4	0.54 %	normal	67 %	0.54
E	Source emission rate	10.8 x 10^6 s^{-1}	1.2 %	normal	95 %	0.60
t	Period	900 s	1.2 s	rectangular	- - -	0.07
f_A	Anisotropy of source	1.046	0.7 %	normal	95 %	0.35
r	Distance: calibration uncertainty repeatability position of effective centre	820 mm ---- ---- ----	 2.2 mm 0.5 mm 0.5 mm	 rectangular normal rectangular	 - - - 95 % - - -	 0.31 0.06 0.07
$f_{aa}(r)$	Ancillary data	- - -	0.1 %	normal	95 %	0.05
$f_{sc}(r)$	Room scatter factor	1.088	1.7 %	normal	95 %	0.85
$u_c(\varepsilon)$	Combined uncertainty			normal	67 %	1.27
U	Expanded uncertainty (*k* = 2)			normal	95 %	2.6

Table 8 Uncertainty budget: AEA Technology (Harwell)

Field: ^{241}Am - Be Monitor: Harwell 0949 Pulse output response

Symbol	Source of uncertainty	Value	Uncertainty	Probability distribution	Confidence level	u_i ± %
N(r)	Response	40,000	0.5 %	normal	67 %	0.50
E	Source emission rate	2.3×10^6 s^{-1}	0.7 %	normal	95 %	0.35
t	Period	8000 s	1.0 s	rectangular	- - -	0.01
f_A	Anisotropy of source	1.02	0.5 %	normal	95 %	0.35
r	Distance:	1000 mm				
	calibration uncertainty		0.5 mm	rectangular	- - -	0.06
	repeatability		1.0 mm	normal	95 %	0.10
	position of effective centre		1.0 mm	rectangular	- - -	0.12
$f_{aa}(r)$	Ancillary data	0.989	0.1 %	normal	95 %	0.10
$f_{sc}(r)$	Room scatter factor	1.06	0.7 %	normal	95 %	0.35
$u_c(\varepsilon)$	Combined uncertainty			normal	67 %	0.80
U	Expanded uncertainty ($k = 2$)			normal	95 %	1.6