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# A multi-laboratory testing of calibration methods for environmental dose rate meters

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# A MULTI-LABORATORY TESTING OF CALIBRATION METHODS FOR ENVIRONMENTAL DOSE RATE METERS

Lars Bøtter-Jensen and Sven P. Nielsen

Abstract. Calibration experiments were carried out at Risø National Laboratory 28-30 August 1985 with the aim of testing calibration methods for instruments used for background gamma radiation monitoring.

Two calibration methods using certified gamma sources were tested: 1) A shadow-shield calibration method, and 2) A free-field calibration set-up. The experiments comprised studies of 25 instruments from 11 European laboratories.

(Continued on next page)

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For most of the instruments the two methods gave identical results. The shadow-shield calibration, however, proved to be more accurate. Additional measurements of the natural background and the cosmic component gave useful information on the energy dependency of the detectors.

The calibration experiments were sponsored by CEC under contract No. 1244/1/84.

INIS-Descriptors: BACKGROUND RADIATION; CALIBRATION; DOSE RATEMETERS; GAMMA RADIATION; INTERLABORATORY COMPARISONS; NATURAL RADIOACTIVITY; RADIATION MONITORS; TESTING

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## 1. INTRODUCTION

The calibration of environmental gamma monitors is encumbered with several problems. Due to the requirement of high sensitivity, the detectors are usually large, making it difficult to obtain proper radiation geometry in a calibration set-up. Different detector types such as ionisation chambers, scintillators, GM-, and proportional counters show varying energy responses that may cause severe errors if corrections are not applied.

Gamma calibration fields covering a range of low intensities should be established in order to measure the linearity of detector response over a wide range. The natural background and scatter contributions from surrounding materials become significant when high instrument accuracy is demanded.

The Directorate-General, Employment, Social affairs and Education, CEC, Luxembourg supported a pilot study on practical methods for calibrating environmental dose rate meters.
Several of the experiments were carried out at Risø National Laboratory in August 1985[1] and the present report gives a description of the calibration methods and the results from this work.

A total of 21 scientists from 11 different European laboratories participated with 25 instruments.

Two calibration methods that have been used at Risø for several years[2] were tested at low dose rates. One was the "shadow-shield" calibration method where the primary beam intensity from a certified $^{137}$Cs gamma source was determined as the difference between the responses obtained with and without a lead shield placed between the source and detector. The other method used a free field set-up where the detector responses from $^{226}$Ra, $^{137}$Cs, and $^{60}$Co gamma sources were determined as the differences between the readings with and without the sources present. The gamma rays scattered from the ground and air were considered in addition to the unscattered gamma rays from the primary beam.

Since most instruments were calibrated in units of roentgens, all radiation intensities in this report are reported in microroentgens per hour (μR/h); these can be converted to air kerma rates in units of microgray per hour (μG/h) by multiplication with 0.0087.

## 2. INSTRUMENTS

The dose rate meters used were high-pressure ionisation chambers, plastic scintillators, Geiger-Müller counters, and proportional counters.

The instruments are listed in Table 1, showing code numbers for identification of the results, manufacturers, and types of detector.

Table 1. Instruments used in the Risø calibration experiments. The code numbers refer to the reported results.

| Instrument Code No. | Detector | Manufacturer | Type |
|---|---|---|---|
| 1 | High-pressure ionisation chamber | Reuter & Stokes | RSS-111 |
| 2 | " | " | " |
| 3 | " | " | " |
| 4 | " | " | " |
| 5 | " | " | " |
| 6 | " | " | " |
| 7 | " | " | " |
| 8 | " | Centronic | IG5/A8.5N11.5 |
| 9 | Atmospheric-pressure ionisation chamber | Seibersdorf | LS10-120 |
| 10 | " | " | LS120-08 |
| 11 | Plastic scintillator | Münchener Apparatebau | MAB604.1 |
| 12 | " | " | " |
| 13 | " | " | " |
| 14 | " | " | " |
| 15 | " | Halle | H 7907 |
| 16 | " | " | H 7201/10 |
| 17 | " | Studsvik | 2414 |
| 18 | " | Befic | 6134A |
| 19 | GM counter | Mini Instruments | MC70 |
| 20 | " | BNL | " |
| 21 | " | " | " |
| 22 | " | Mini Instruments | " |
| 23 | " | " | MC71 |
| 24 | " | Berthold | BZ120 |
| 25 | Proportional counter | " | LB6123 |

## 3. MEASURING PROGRAMME

The measuring programme was divided into 4 parts:

1) Shadow-shield calibration measurements of a certified $^{137}Cs$ source.

2) Free-field calibration measurements of certified $^{137}Cs$, $^{60}Co$, and $^{226}Ra$ sources.

3) Measurement of a typical Danish background radiation level.

4) Measurement of the cosmic component at sea.

The shadow-shield experiments were arranged in a cellar facility with floor dimensions of 6 metres by 12 metres and with a height to the ceiling of 2.3 metres. Four individual set-ups arranged on wooden benches with a common source position allowed four measurements to be carried out simultaneously. Measurements were taken at source-to-detector distances of 3, 4, and 5 metres to obtain different dose rates with the same source. (See Figs. 1 and 2). The source and detectors were placed 1.15 m above the floor.

The free-field experiments were arranged on a flat grass field with the sources and the instruments placed 1 metre above the ground. The instruments were positioned in circles around the source to obtain source-to-detector distances of 3, 5, and 10 metres. (See Fig. 3)

The background radiation was measured at this field location with the sources removed from the area.

The cosmic component was measured at the nearby Roskilde Fiord. An old steam boat using coal was hired for the occasion. The measurements took place in the middle of the fiord about 3 km from land and at a sea depth of about 4.5 m. These conditions ensured the absence of the terrestrial gamma-ray component.

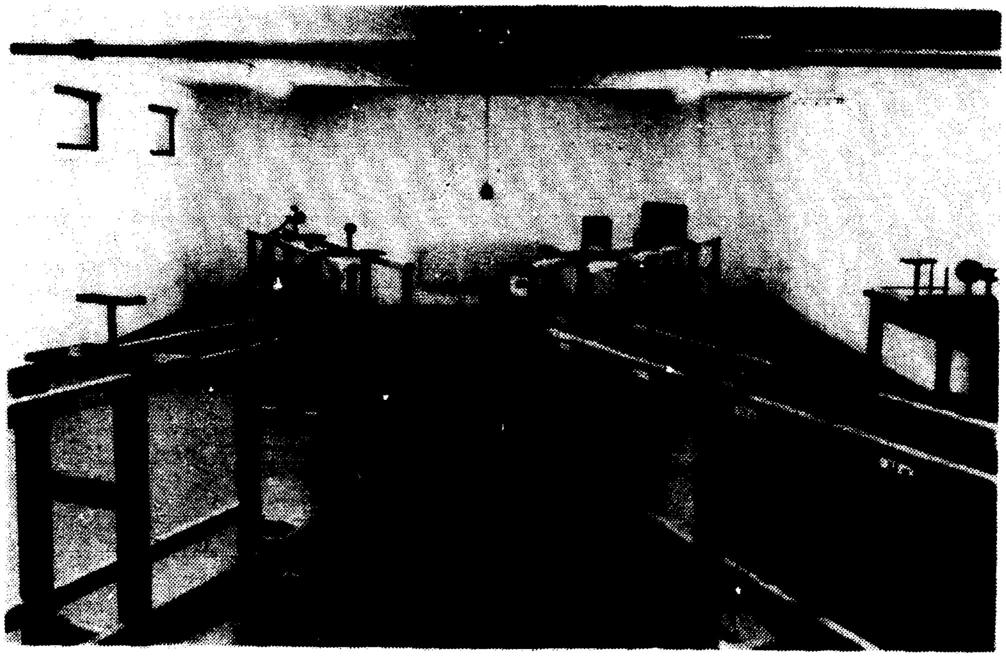

Fig. 1. The shadow-shield calibration facility.

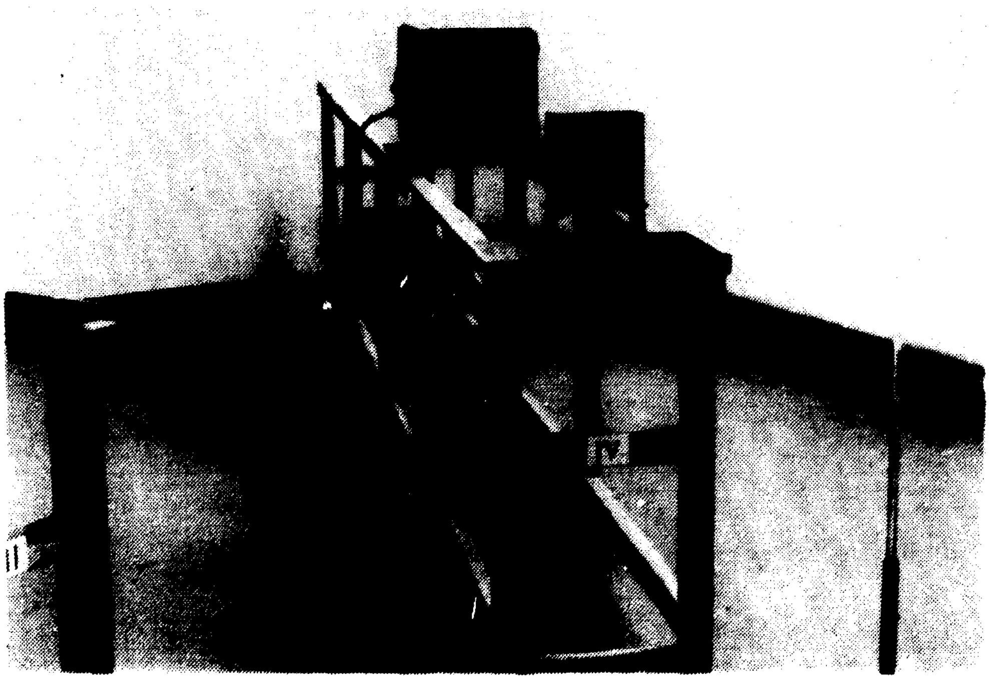

Fig. 2. A shadow-shield calibration set-up for Reuter Stokes RSS-111 high-pressure ionisation chamber.

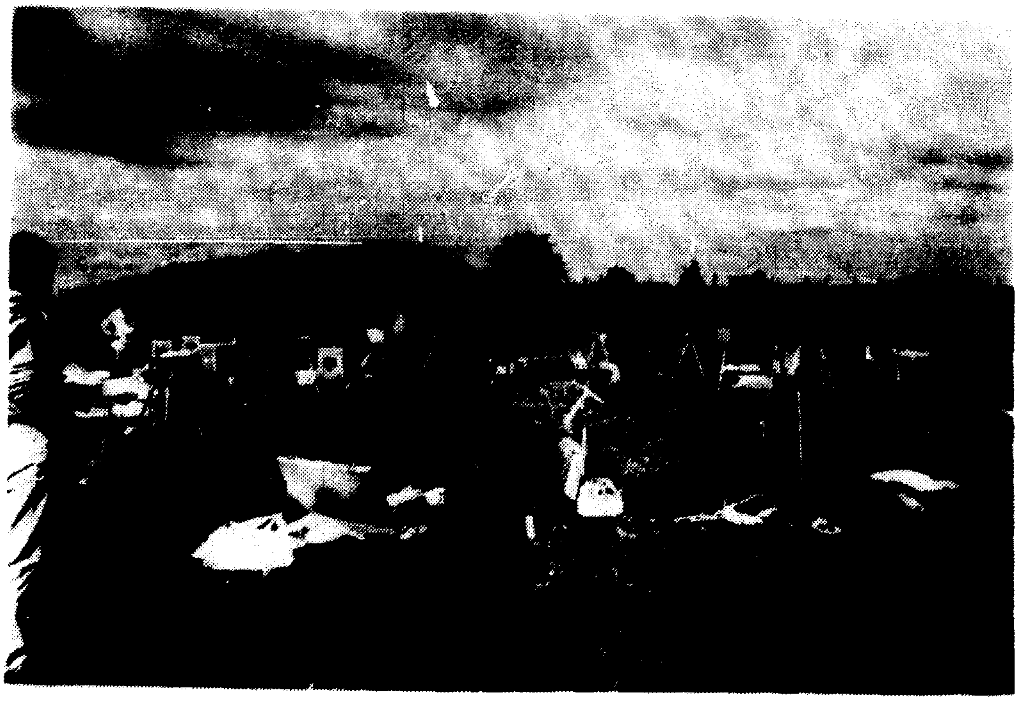

Fig. 3. The free-field calibration set-up.

## 4. CALIBRATION METHODS

Dose rate meters are calibrated by placing them in known radiation fields from certified gamma sources. The present calibration experiments were carried out with $^{226}Ra$, PtIr (nominal activity 1 mg), $^{137}Cs$ (nominal activity 5.4 mCi), and $^{60}Co$ (nominal activity 1.6 mCi) sources produced and certified by the Radiochemical Centre Amersham, U.K. The nominal activity of the $^{226}Ra$ source was certified by weight with an accuracy of ± 1%. The nominal activity for the $^{137}Cs$ and $^{60}Co$ sources were certified in terms of exposure rates measured at 1 metre distance from source. The accuracy of the calibration was ± 5%(3). As a basis, the primary beam intensities from the sources were calculated from the relation:

$$\dot{X}_D = \dot{X}_{100}\left(\frac{100}{D}\right)^2 e^{-\mu(D-100)} K_d$$

where $\dot{X}_{100}$ is the exposure rate at 1 metre distance according to the source certificate (for $^{226}Ra$ using an exposure rate constant of 0.825 $Rm^2\ h^{-1}\ g^{-1}$), $\mu$ the linear attenuation coefficient for the radiation in air, D the distance in cm between detector and source, and $K_d$ the source decay-correction factor.

### 4.1. Shadow shield set-up

The shadow-shield calibration (see Fig. 4) may be carried out indoors. The source-to-detector distance must be sufficiently large to ensure a nearly parallel beam of uniform intensity over the entire detector volume.

The detector response with no shield present is the ambient background (A) plus radiation from the source; the latter comprises primary gamma rays (P) and room scatter (S).

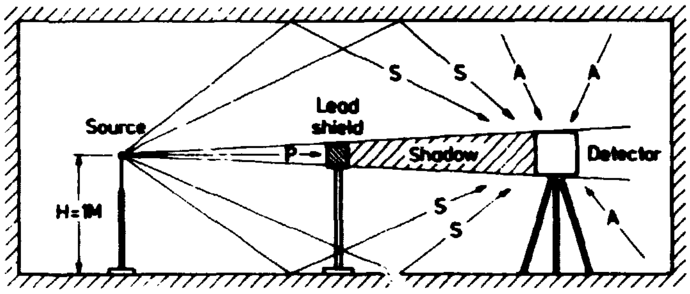


Fig. 4. "Shadow-shield" calibration set-up. (P) primary beam, (A) ambient radiation, (S) room scatter component.

To determine the responses from the components A and S, a lead shield thick enough to absorb the primary gamma rays is placed between the source and detector so as to "shadow shield" the primary beam. The difference between the readings with and without the shield, yields the response from the primary beam.

Dose rates from the $^{137}Cs$ source were measured at three different source-to-detector distances (3, 4, and 5 metres).

The calculated nominal exposure rates on the day of the experiments are shown in Table 2.

Table 2. Nominal exposure rates from the shadow-shield calibration.

| Source: $^{137}Cs$ | |
|---|---|
| Distance | μR/h |
| 3 m | 185.1 |
| 4 m | 103.2 |
| 5 m | 65.4 |

$$\mu \sim 9.28 \times 10^{-5}\ cm^{-1}$$

$$T_{1/2} = 30.02\ y$$

Air temperature = 20°C, air pressure 760 mm Hg

## 4.2. Free-field set-up

The free-field calibration is obtained by arranging a set-up on a flat ground out of doors with source and detector placed at 1 metre above the ground (see Fig. 5).

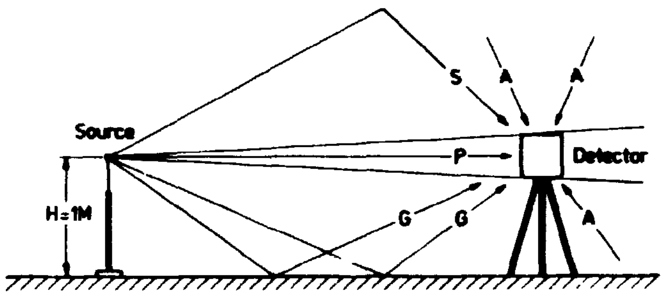


Fig. 5. Free-field calibration set-up. (P) primary beam, (A) ambient radiation, (S) build-up in air, (G) ground albedo.

The radiation components to be considered are the ambient background (A), the primary beam from the source (P), the scattered component from the ground surface (G), and the build-up in air (S). According to the Chilton and Huddleston formula for the differential dose albedo for gamma rays on concrete [4], ground albedo figures for different geometries were calculated for $^{226}Ra$, $^{137}Cs$, and $^{60}Co$ point sources (see Fig. 6). Experience has shown that the difference between concrete and soil in this context is negligible[2]. The air-scattered component at the detector was determined as a function of source-to-detector distance by means of Monte Carlo calculations (see Fig. 7).

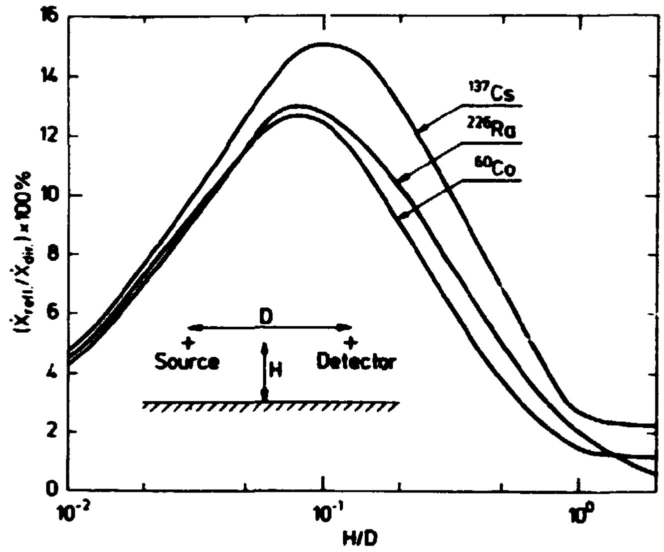


Fig. 6. Reflected dose rate from a flat ground as a percentage of the direct dose rate at different heights and distances for $^{226}Ra$, $^{137}Cs$, and $^{60}Co$ point sources.

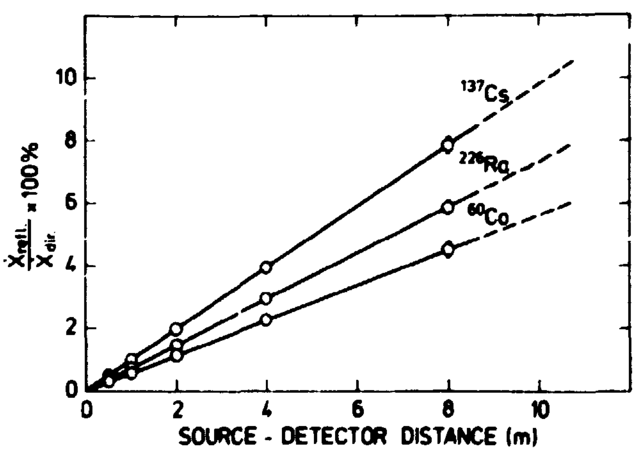


Fig. 7. Build-up in air as a percentage of the direct dose rate from $^{226}Ra$, $^{137}Cs$, and $^{60}Co$ point sources as a function of distance, determined from Monte Carlo calculations.

The nominal values for the calculated exposure rates at 3, 5, and 10 metre distances from the sources 1 metre above ground level are given in Table 3.

Table 3. Nominal exposure rates for the free-field calibrations. (1 m above ground).

| Source | Distance (m) | Decay-corrected exposure rate (μR/h) | Ground albedo (%) | Air build-up (%) | Nominal value (μR/h) |
|---|---|---|---|---|---|
| $^{137}Cs$ | 3 | 185.1 | 9.7 | 3.0 | 208.5 |
| " | 5 | 65.4 | 13.0 | 4.9 | 77.1 |
| " | 10 | 15.6 | 15.0 | 9.7 | 19.5 |
| $^{60}Co$ | 3 | 166.9 | 5.9 | 1.6 | 179.4 |
| " | 5 | 59.3 | 8.8 | 2.8 | 66.2 |
| " | 10 | 14.3 | 12.3 | 5.6 | 16.9 |
| $^{226}Ra$ | 3 | 84.9 | 7.3 | 2.2 | 93.0 |
| " | 5 | 30.1 | 10.3 | 3.7 | 34.3 |
| " | 10 | 7.25 | 12.8 | 7.3 | 8.71 |

| | $^{137}Cs$ | $^{60}Co$ | $^{226}Ra$ |
|---|---|---|---|
| $\mu$ ($cm^{-1}$) | $9.28 \times 10^{-5}$ | $6.8 \times 10^{-5}$ | $7.5 \times 10^{-5}$ (average) |
| $T_{1/2}$ (y) | 30.02 | 5.27 | 1601 |

Air temperature 20°C, air pressure 760 mm Hg

# 5. RESULTS AND DISCUSSION

The results of the measurements are presented in tables and figures in the appendix.

The results of the calibration measurements including their standard deviations are given in Table A1. These results are also shown in histograms. Figure A1 shows the data from the shadow-shield calibration, and Figs. A2, A3 and A4 show the data from the free-field calibration for each of the three sources.

The results of the measurements of the natural background level are given in Table A2 and shown in Fig. A5.

The results of the cosmic-component measurements are given in Table A3 and shown in Fig. A6.

The results of the level of the terrestrial component, obtained as the difference between the two aforementioned measurements, are given in Table A4 and shown in Fig. A7.

## 5.1. Analysis of calibration measurements

The results of the calibration measurements from Table A1 are compared with the nominal values calculated from the source-certificate data. This comparison is shown in Table A5, which lists ratios of measured-to-nominal values of exposure rates for each detector and the two calibration methods. The standard deviations (sd) of the ratios include the sd's of the measurement results and sd's of the nominal data.

The uncertainties of the source data from the certificates are neglected, however, for two reasons. First, because systematic uncertainties are dominant in the uncertainties given by the source manufacturers. These errors are not considered in the present analysis. Secondly, because even the statistical uncertainties from the certificates are irrelevant for the calculations and tests presented in this section.

For the shadow-shield calibration the nominal values, $\dot{X}_{nom}$, are calculated according to

$$\dot{X}_{nom} = \dot{X}_c \exp[-(\mu/\rho)_{att}\ \rho\ (d-1)]/d^2,$$

where $\dot{X}_c$ is the decay-corrected source output from the certificate, $(\mu/\rho)_{att}$ is the mass-attenuation coefficient for air at the mean energy of the unscattered gamma rays from the source, $\rho$ is the air density, and d is the source-to-detector distance in metres.

The uncertainties of these components are assessed on a subjective basis. The uncertainty of $X_c$ is neglected, the sd of $(\mu/\rho)_{att}$ is estimated at 5%, the sd of the air density is estimated at 1%, and the sd of the distance is estimated at 0.5 cm. The uncertainties are combined to give the total sd of the nominal data for each of the distances as shown in Table 4.

Table 4. Relative standard deviations for the nominal data at the shadow-shield calibration measurements.

| Distance | $sd(1/d^2)$ (%) | sd(exp) (%) | sd(tot) (%) |
|---|---|---|---|
| 3 m | 0.33 | 0.09 | 0.34 |
| 4 m | 0.25 | 0.14 | 0.29 |
| 5 m | 0.20 | 0.19 | 0.28 |

For the free-field calibration the nominal data are calculated according to:

$$\dot{X}_{nom} = \dot{X}_c \exp[-(\mu/\rho)_{att}\ \rho\ (d-1)](1+s)/d^2,$$

where s accounts for the scattered gamma rays from the air and the ground and the other symbols have the same meaning as previously. Again the sd of $X_c$ is neglected, the sd of $(\mu/\rho)_{att}$ is estimated at 5%, the sd of $\rho$ is estimated at 1%, the sd of s is estimated at 10%, and the sd of d is estimated at 1 cm. The combination of these uncertainties gives the total sd of the nominal data for each of the sources and each of the distances as shown in Table 5.

Table 5. Relative standard deviations for the nominal data at the free-field calibration measurements.

| Distances | $sd(1/d^2)$ (%) | sd(exp) (%) | sd(1+s) (%) | sd(tot) (%) |
|---|---|---|---|---|
| Cs137, 3 m | 0.67 | 0.09 | 1.13 | 1.32 |
| - 5 m | 0.40 | 0.19 | 1.52 | 1.58 |
| - 10 m | 0.20 | 0.42 | 1.98 | 2.03 |
| Co60, 3 m | 0.67 | 0.07 | 0.70 | 0.98 |
| - 5 m | 0.40 | 0.14 | 1.04 | 1.12 |
| - 10 m | 0.20 | 0.31 | 1.52 | 1.56 |
| Ra226, 3 m | 0.67 | 0.23 | 0.87 | 1.12 |
| - 5 m | 0.40 | 0.38 | 1.23 | 1.35 |
| - 10 m | 0.20 | 0.75 | 1.67 | 1.84 |

For each set of calibration measurements a weighted mean is calculated from the three observations according to:

$$\text{mean}=(\sum x_i/sd_i^2)/\sum(1/sd_i)^2,$$

where the $x_i$'s are the measurement results and the $sd_i$'s the corresponding standard deviations. The standard deviation of the mean is calculated according to:

$$sd(\text{mean})=(\sum(1/sd_i^2)^{-1/2}.$$

It is noted that when all the $sd_i$'s are equal these two expressions yield the well-known formulas for the mean and standard deviation of the mean ($\text{mean}=(\sum x_i)/n$ and $sd(\text{mean})= sd/\sqrt{n}$).

It is, furthermore, tested whether or not the results for the three distances, $x_i$, deviate more (or less) from the mean value than predicted by the standard deviations of the individual results, $sd_i$. For this purpose a test value is calculated:

$$T=\sum[(x_i-\text{mean})/sd_i]^2$$

This test value is chi-square distributed with 2 (=n-1) degrees of freedom, and therefore, the test value is expected to be approximately equal to 2. If the test value is much larger than 2, this indicates that the uncertainties of the measured values are underestimated, and if the test value is much smaller than 2, this indicates that the uncertainties are overestimated.

The statistical tests are carried out at three significance levels: 5%, 1%, and 0.1%. For two degrees of freedom these levels correspond to upper bounds for the test values of 5.99, 9.21, and 13.8, respectively, and to lower bounds for the test values of 0.102, 0.020, and 0.002, respectively.

If for a set of results a T-value of 10.2 is obtained, this value is greater than 9.21 and smaller than 13.8, and the test is thus found significant at the 1% level. This could be due to pure chance, but the probability of that is estimated from the significance level to be less than 1%. Therefore, it might be concluded that the measurement uncertainties from this set of results are underestimated.

The outcome of the tests are indicated in parentheses shown in Table A5 after the mean ratios. Non-significant results are designated by ns. Large deviations are shown by asterisks, * = probably significant (5% level), ** = significant (1% level), and *** = highly significant (0.1% level). Small deviations are shown by plus signs, + = probably significant (5% level), ++ = significant (1% level), and +++ = highly significant (0.1% level).

Where no uncertainties are given by the participants simple arithmetic means are calculated.

The results from Table A5 are shown in Figs. 8, 9, 10 and 11. Figure 8 shows the results from the shadow-shield calibration, and Figs. 9, 10 and 11 show the results from the free-field calibration for each of the three sources. Where not shielded by the circular marks, the error bars give the 95% confidence intervals for the means. Where measurement uncertainties were available a confidence factor of 1.96 from the Normal distribution was used, and where these uncertainties were not available a confidence factor of 4.30 from the Student's-t distribution was used.

Finally, the results of the two calibration methods using the same $^{137}Cs$ source are compared. The mean values from the shadow-shield calibration and from the free-field calibration are compared to see if the difference between the two is statistically significant. A chi-square test like the one mentioned above is used where measurement uncertainties are available and a Students-t test is used elsewhere. The results are shown in Table 6 using the same significance symbols as given previously.

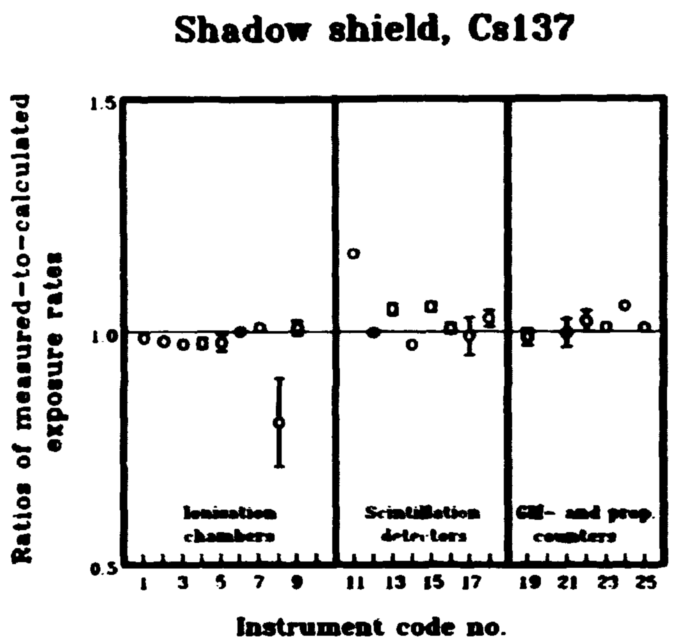


Fig. 8. Mean values of measured-to-calculated exposure rates from $^{137}Cs$ gamma radiation at the shadow-shield calibration measurements. The error bars give 95% confidence intervals.

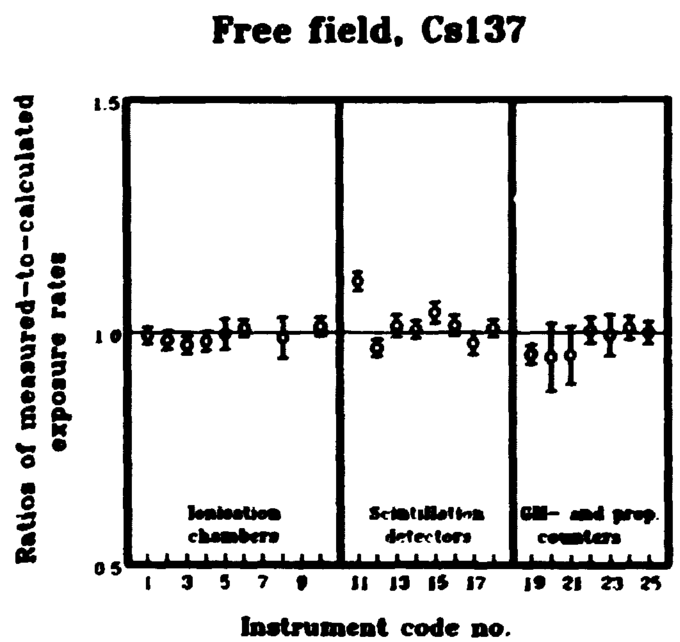


Fig. 9. Mean values of measured-to-calculated exposure rates from $^{137}Cs$ gamma radiation at the free-field calibration measurements. The error bars give 95% confidence intervals.

**Free field, Co60**

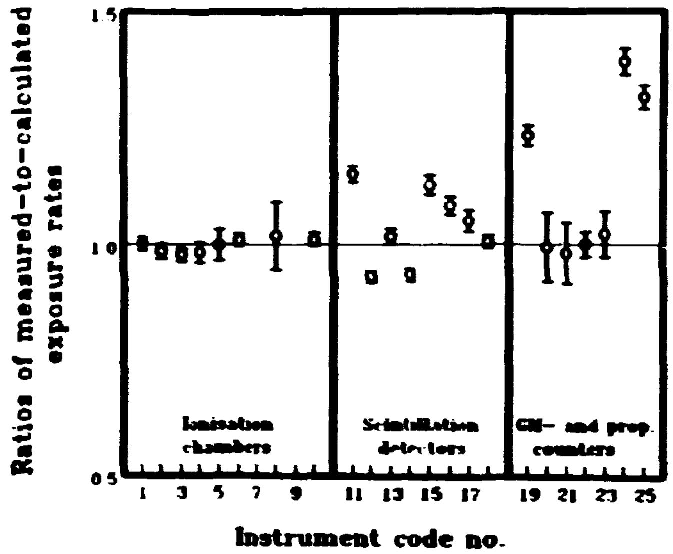


Fig. 10. Mean values of measured-to-calculated exposure rates from $^{60}Co$ gamma radiation at the free-field calibration measurements. The error bars give 95% confidence intervals.

**Free field, Ra226**

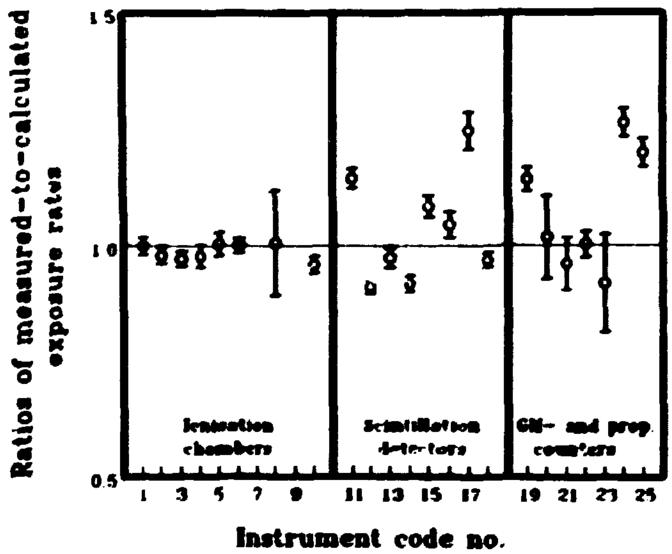


Fig. 11. Mean values of measured-to-calculated exposure rates from $^{226}Ra$ gamma radiation at the free-field calibration measurements. The error bars give 95% confidence intervals.

Table 6. Comparison of measured detector responses obtained with the two calibration methods for $^{137}Cs$ gamma rays.

| Detector | | Significance |
|---|---|---|
| 1. | Ionisation chamber | ns |
| 2. | - | ns |
| 3. | - | ns |
| 4. | - | ns |
| 5. | - | ns |
| 6. | - | ns |
| 8. | - | * |
| 11. | Scintillation detector | *** |
| 12. | - | *** |
| 13. | - | * |
| 14. | - | ** |
| 15. | - | ns |
| 16. | - | ns |
| 17. | - | ns |
| 18. | - | ns |
| 19. | GM counters | * |
| 21. | - | ns |
| 22. | - | ns |
| 23. | - | ns |
| 24. | - | *** |
| 25. | Proportional counter | ns |

## 5.2. Discussion

It is noted from Figs. 8 and 9 and from Table A5 that the results from the shadow-shield calibration method are more precise than those from the free-field calibration method. The results from the former method are also more accurate in the sense that the gamma-ray energies at which the results are obtained, are known well. For the free-field method the scattered gamma-ray component modifies the gamma-ray energy distribution at the detector position, so the average energy is lower and less well-defined.

This may also cause some difficulties when one compares results from detectors that have different responses at low energies.

This low-energy effect causes a trend of the results obtained at the free-field experiments for the three distances. The trend is observed for most of the detectors where the ratios in Table A5 decrease with increasing source-to-detector distance. The effect is less pronounced for the RSS-111 ionisation chambers, which have an energy cut-off of about 50 keV; while the effect is more pronounced for the MAB 604 detectors, which have an energy cut-off of about 10 keV. This effect is also reflected in the comparison of the observed detector responses obtained with the two methods for $^{137}Cs$ gamma rays (Table 6). For the main part of the detectors, however, the two methods give results that agree within a few per cent.

As for gamma-ray energy responses it must be noted that the results for the detectors with code numbers 20, 21, 22, and 23 were derived using different calibration factors for the different gamma-ray sources. For all other detectors the same calibration factors were used for all the sources.

When making a comparison between the merits of the two calibration methods, it should be noted that the dimensions of the shadow shield used for detector number 8 were insufficient for complete shielding of the chamber. Also, the ratios of the observed-to-calculated exposure rates for this instrument would have been higher if the chamber had been adequately shielded. The under-shielding of this chamber, furthermore, causes the standard deviation of the means for all the results at each distance to be higher for the shadow-shield experiments (6-7%) than for the free-field experiments (4-5%), as it is seen in Figs. A1 and A2.

## 6. CONCLUSIONS

The calibration measurements provide a useful means for comparing the two calibration methods. Clearly the shadow-shield calibration method yields the most accurate and reliable results.

This, however, has to be considered in the light of the increased amounts of time and resources required by that method compared to the free-field calibration method, and for most of the instruments the two methods give identical results.

Futhermore, the calibration measurements and the measurements of the natural background and the cosmic component give information on detector responses to gamma rays of different energies. That information is valuable to all laboratories engaged in measurements of environmental dose rates from gamma radiation.

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# APPENDIX

Tables and histograms of
measurement results

<u>Table A1</u>. Results of calibration measurements.

INSTRUMENT NUMBER : 1
INSTRUMENT TYPE : IONISATION CHAMBER, RSS-111
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 246.74 | 64.17 | 182.57 |
| 4 METRES | 149.90 | 48.29 | 101.61 |
| 5 METRES | 102.74 | 37.88 | 64.86 |
| | : SD (uR/h) | | |
| 3 METRES | 0.65 | 0.19 | 0.68 |
| 4 METRES | 0.21 | 0.26 | 0.33 |
| 5 METRES | 0.21 | 0.12 | 0.24 |

INSTRUMENT NUMBER : 1
INSTRUMENT TYPE : IONISATION CHAMBER, RSS-111
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 210.96 | 181.73 | 93.16 |
| 5 METRES | 75.92 | 65.93 | 34.39 |
| 10 METRES | 18.71 | 16.17 | 8.38 |
| | : SD (uR/h) | | |
| 3 METRES | 0.69 | 0.59 | 0.40 |
| 5 METRES | 0.34 | 0.31 | 0.34 |
| 10 METRES | 0.19 | 0.34 | 0.26 |

INSTRUMENT NUMBER : 2
INSTRUMENT TYPE : IONISATION CHAMBER, RSS-111
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 246.50 | 64.80 | 181.70 |
| 4 METRES | 149.40 | 48.80 | 100.60 |
| 5 METRES | 103.20 | 38.90 | 64.30 |
| | : SD (uR/h) | | |
| 3 METRES | 0.40 | 0.40 | 0.60 |
| 4 METRES | 0.50 | 0.20 | 0.50 |
| 5 METRES | 0.40 | 0.30 | 0.50 |

INSTRUMENT NUMBER : 2
INSTRUMENT TYPE : IONISATION CHAMBER, RSS-111
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 207.60 | 178.90 | 91.70 |
| 5 METRES | 75.50 | 65.20 | 33.70 |
| 10 METRES | 18.70 | 16.30 | 8.30 |
| | : SD (uR/h) | | |
| 3 METRES | 1.60 | 1.60 | 0.40 |
| 5 METRES | 0.30 | 0.30 | 0.30 |
| 10 METRES | 0.20 | 0.20 | 0.10 |

Table A1. Continued.

INSTRUMENT NUMBER : 3
INSTRUMENT TYPE : IONISATION CHAMBER, RSS-111
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 245.80 | 65.00 | 180.80 |
| 4 METRES | 149.60 | 48.90 | 100.70 |
| 5 METRES | 102.70 | 39.30 | 63.40 |
| | | : SD (uR/h) | |
| 3 METRES | 0.40 | 0.50 | 0.60 |
| 4 METRES | 0.50 | 0.20 | 0.50 |
| 5 METRES | 0.30 | 0.10 | 0.30 |

INSTRUMENT NUMBER : 3
INSTRUMENT TYPE : IONISATION CHAMBER, RSS-111
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 204.20 | 175.80 | 90.30 |
| 5 METRES | 75.20 | 65.10 | 33.70 |
| 10 METRES | 18.60 | 16.30 | 8.30 |
| | | : SD (uR/h) | |
| 3 METRES | 1.20 | 1.20 | 0.40 |
| 5 METRES | 0.30 | 0.30 | 0.20 |
| 10 METRES | 0.10 | 0.10 | 0.10 |

INSTRUMENT NUMBER : 4
INSTRUMENT TYPE : IONISATION CHAMBER, RSS-111
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 245.42 | 65.41 | 180.01 |
| 4 METRES | 150.71 | 49.90 | 100.81 |
| 5 METRES | 105.30 | 41.01 | 64.29 |
| | | : SD (uR/h) | |
| 3 METRES | 1.18 | 0.45 | 1.26 |
| 4 METRES | 0.86 | 0.51 | 1.00 |
| 5 METRES | 0.68 | 0.46 | 0.82 |

INSTRUMENT NUMBER : 4
INSTRUMENT TYPE : IONISATION CHAMBER, RSS-111
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 204.54 | 176.71 | 90.20 |
| 5 METRES | 75.68 | 64.89 | 34.20 |
| 10 METRES | 18.91 | 16.62 | 8.60 |
| | | : SD (uR/h) | |
| 3 METRES | 1.01 | 1.61 | 0.93 |
| 5 METRES | 0.81 | 1.26 | 0.68 |
| 10 METRES | 0.66 | 0.66 | 0.54 |

Table A1. Continued.

INSTRUMENT NUMBER : 5
INSTRUMENT TYPE : IONISATION CHAMBER, RSS-111
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 4 METRES | 149.02 | 48.17 | 100.85 |
| 5 METRES | 102.87 | 38.92 | 63.95 |
| : SD (uR/h) | | | |
| 4 METRES | 1.04 | 0.40 | 1.11 |
| 5 METRES | 0.77 | 0.47 | 0.90 |

INSTRUMENT NUMBER : 5
INSTRUMENT TYPE : IONISATION CHAMBER, RSS-111
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | | | 93.72 |
| 5 METRES | 77.01 | 66.34 | 34.27 |
| 10 METRES | 19.20 | 16.65 | 8.46 |
| : SD (uR/h) | | | |
| 3 METRES | | | 0.91 |
| 5 METRES | 0.75 | 0.97 | 0.75 |
| 10 METRES | 0.60 | 0.70 | 0.62 |

INSTRUMENT NUMBER : 6
INSTRUMENT TYPE : IONISATION CHAMBER, RSS-111
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 252.74 | 67.14 | 185.60 |
| 4 METRES | 154.44 | 51.16 | 103.28 |
| 5 METRES | 107.72 | 42.26 | 65.46 |
| : SD (uR/h) | | | |
| 3 METRES | 0.10 | 0.05 | 0.11 |
| 4 METRES | 0.09 | 0.05 | 0.10 |
| 5 METRES | 0.08 | 0.05 | 0.09 |

INSTRUMENT NUMBER : 6
INSTRUMENT TYPE : IONISATION CHAMBER, RSS-111
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 212.78 | 183.21 | 94.32 |
| 5 METRES | 78.04 | 66.77 | 34.65 |
| 10 METRES | 19.14 | 16.67 | 8.35 |
| : SD (uR/h) | | | |
| 3 METRES | 0.10 | 0.13 | 0.10 |
| 5 METRES | 0.06 | 0.07 | 0.04 |
| 10 METRES | 0.04 | 0.04 | 0.03 |

Table A1. Continued.

INSTRUMENT NUMBER : 7
INSTRUMENT TYPE : IONISATION CHAMBER, RSS-111
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 254.30 | 67.30 | 187.00 |
| 4 METRES | 155.10 | 51.30 | 103.80 |
| 5 METRES | 108.10 | 41.70 | 66.40 |
| | | : SD (uR/h) | |
| 3 METRES | 0.60 | 0.70 | 0.90 |
| 4 METRES | 0.30 | 0.30 | 0.40 |
| 5 METRES | 0.30 | 0.10 | 0.30 |

INSTRUMENT NUMBER : 8
INSTRUMENT TYPE : IONISATION CHAMBER, Centronics
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. +) |
|---|---|---|---|
| 3 METRES | 192.20 | 51.10 | 141.10 |
| 4 METRES | 117.10 | 31.10 | 86.00 |
| 5 METRES | 78.00 | 24.20 | 53.80 |

INSTRUMENT NUMBER : 8
INSTRUMENT TYPE : IONISATION CHAMBER, Centronics
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 201.80 | 177.54 | 89.58 |
| 5 METRES | 76.86 | 67.62 | 34.37 |
| 10 METRES | 19.50 | 17.70 | 9.18 |

INSTRUMENT NUMBER : 9
INSTRUMENT TYPE : IONISATION CHAMBER, LS10-120
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 249.90 | 63.00 | 186.90 |
| 4 METRES | 152.40 | 48.20 | 104.20 |
| 5 METRES | 105.40 | 39.50 | 65.90 |
| | | : SD (uR/h) | |
| 3 METRES | 1.30 | 0.90 | 1.60 |
| 4 METRES | 1.80 | 1.30 | 2.20 |
| 5 METRES | 1.00 | 1.60 | 1.90 |

+) Inadequate shielding, see discussion in Section 5.2

Table A1. Continued.

INSTRUMENT NUMBER : 10
INSTRUMENT TYPE : IONISATION CHAMBER, LS120-08
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 215.10 | 185.70 | 89.60 |
| 5 METRES | 77.50 | 65.70 | 32.70 |
| 10 METRES | 18.90 | 16.40 | 8.10 |
| | | : SD (uR/h) | |
| 3 METRES | 0.40 | 0.20 | 0.20 |
| 5 METRES | 0.90 | 0.40 | 0.40 |
| 10 METRES | 0.20 | 0.20 | 0.50 |

INSTRUMENT NUMBER : 11
INSTRUMENT TYPE : PLASTIC SCINT., MAB604.1
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 273.46 | 56.97 | 216.49 |
| 4 METRES | 165.01 | 44.44 | 120.58 |
| 5 METRES | 112.40 | 35.82 | 76.59 |
| | | : SD (uR/h) | |
| 3 METRES | 0.97 | 0.34 | 1.03 |
| 4 METRES | 0.10 | 0.07 | 0.12 |
| 5 METRES | 0.68 | 0.34 | 0.76 |

INSTRUMENT NUMBER : 11
INSTRUMENT TYPE : PLASTIC SCINT., MAB604.1
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 237.27 | 210.26 | 105.74 |
| 5 METRES | 85.12 | 75.78 | 39.79 |
| 10 METRES | 20.51 | 18.59 | 10.15 |
| | | : SD (uR/h) | |
| 3 METRES | 0.60 | 1.06 | 0.27 |
| 5 METRES | 0.24 | 0.47 | 0.50 |
| 10 METRES | 0.17 | 0.26 | 0.34 |

INSTRUMENT NUMBER : 12
INSTRUMENT TYPE : PLASTIC SCINT., MAB604.1
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 239.80 | 57.00 | 182.80 |
| 4 METRES | 147.50 | 43.40 | 104.10 |
| 5 METRES | 97.90 | 32.50 | 65.40 |
| | | : SD (uR/h) | |
| 3 METRES | 0.24 | 0.08 | 0.25 |
| 4 METRES | 0.15 | 0.07 | 0.17 |
| 5 METRES | 0.12 | 0.04 | 0.13 |

Table A1. Continued.

INSTRUMENT NUMBER : 12
INSTRUMENT TYPE : PLASTIC SCINT., MAB604.1
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 208.50 | 171.30 | 84.90 |
| 5 METRES | 73.60 | 60.80 | 31.90 |
| 10 METRES | 17.80 | 15.10 | 7.53 |
| | | : SD (uR/h) | |
| 3 METRES | 0.24 | 0.32 | 0.17 |
| 5 METRES | 0.13 | 0.20 | 0.13 |
| 10 METRES | 0.10 | 0.10 | 0.10 |

INSTRUMENT NUMBER : 13
INSTRUMENT TYPE : PLASTIC SCINT., MAB604.1
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 252.00 | 57.70 | 194.30 |
| 4 METRES | 154.50 | 43.90 | 110.60 |
| 5 METRES | 103.70 | 35.90 | 67.80 |
| | | : SD (uR/h) | |
| 3 METRES | 0.75 | 0.85 | 1.13 |
| 4 METRES | 2.50 | 0.35 | 2.52 |
| 5 METRES | 1.00 | 0.25 | 1.03 |

INSTRUMENT NUMBER : 13
INSTRUMENT TYPE : PLASTIC SCINT., MAB604.1
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 208.70 | 179.40 | 89.40 |
| 5 METRES | 79.90 | 69.10 | 34.00 |
| 10 METRES | 19.30 | 17.00 | 8.60 |
| | | : SD (uR/h) | |
| 3 METRES | 2.50 | 1.00 | 0.90 |
| 5 METRES | 0.80 | 0.35 | 0.50 |
| 10 METRES | 0.45 | 0.45 | 0.15 |

INSTRUMENT NUMBER : 14
INSTRUMENT TYPE : PLASTIC SCINT., MAB604.1
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 235.20 | 56.59 | 178.61 |
| 4 METRES | 143.44 | 42.19 | 101.25 |
| 5 METRES | 98.18 | 33.75 | 64.43 |
| | | : SD (uR/h) | |
| 3 METRES | 0.96 | 0.54 | 1.10 |
| 4 METRES | 0.94 | 0.40 | 1.02 |
| 5 METRES | 0.65 | 0.32 | 0.72 |

Table A1. Continued.

INSTRUMENT NUMBER : 14
INSTRUMENT TYPE : PLASTIC SCINT., MAB604.1
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 205.98 | 165.44 | 85.12 |
| 5 METRES | 79.04 | 63.20 | 31.50 |
| 10 METRES | 19.95 | 15.78 | 8.18 |
| | : SD (uR/h) | | |
| 3 METRES | 0.40 | 0.48 | 0.41 |
| 5 METRES | 0.35 | 0.32 | 0.22 |
| 10 METRES | 0.28 | 0.27 | 0.33 |

INSTRUMENT NUMBER : 15
INSTRUMENT TYPE : PLASTIC SCINT., H7907
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 254.90 | 60.37 | 194.53 |
| 4 METRES | 155.93 | 46.64 | 109.29 |
| 5 METRES | 108.13 | 38.64 | 69.49 |
| | : SD (uR/h) | | |
| 3 METRES | 0.88 | 0.30 | 0.93 |
| 4 METRES | 0.96 | 1.09 | 1.45 |
| 5 METRES | 0.86 | 0.32 | 0.92 |

INSTRUMENT NUMBER : 15
INSTRUMENT TYPE : PLASTIC SCINT., H7907
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 217.38 | 200.01 | 101.73 |
| 5 METRES | 80.21 | 75.87 | 36.86 |
| 10 METRES | | | |
| | : SD (uR/h) | | |
| 3 METRES | 1.05 | 1.55 | 1.03 |
| 5 METRES | 0.62 | 0.69 | 0.30 |
| 10 METRES | | | |

INSTRUMENT NUMBER : 16
INSTRUMENT TYPE : PLASTIC SCINT., H7201/10
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 241.96 | 55.87 | 186.08 |
| 4 METRES | 147.41 | 44.07 | 103.34 |
| 5 METRES | 103.96 | 37.07 | 66.49 |
| | : SD (uR/h) | | |
| 3 METRES | 1.19 | 0.80 | 1.40 |
| 4 METRES | 0.98 | 0.79 | 1.26 |
| 5 METRES | 0.57 | 0.45 | 0.73 |

Table A1. Continued.

INSTRUMENT NUMBER : 16
INSTRUMENT TYPE : PLASTIC SCINT., H7201/10
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 211.47 | 193.25 | 97.03 |
| 5 METRES | 78.44 | 72.25 | 35.93 |
| 10 METRES | 19.45 | 18.44 | 9.08 |
| | : SD (uR/h) | | |
| 3 METRES | 1.38 | 1.45 | 1.38 |
| 5 METRES | 0.68 | 0.65 | 0.62 |
| 10 METRES | 0.55 | 0.39 | 0.37 |

INSTRUMENT NUMBER : 17
INSTRUMENT TYPE : PLASTIC SCINT., GAMMAM. 2414
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 225.00 | 55.00 | 170.00 |
| 4 METRES | 148.00 | 48.00 | 100.00 |
| 5 METRES | 106.00 | 35.00 | 71.00 |
| | : SD (uR/h) | | |
| 3 METRES | 8.00 | 1.30 | 8.00 |
| 5 METRES | 3.00 | 1.00 | 3.00 |
| 10 METRES | 2.00 | 1.30 | 2.50 |

INSTRUMENT NUMBER : 17
INSTRUMENT TYPE : PLASTIC SCINT., GAMMAM. 2414
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 204.00 | 189.00 | 114.00 |
| 5 METRES | 74.00 | 69.00 | 44.00 |
| 10 METRES | 21.00 | 19.00 | 11.00 |
| | : SD (uR/h) | | |
| 3 METRES | 2.00 | 2.00 | 2.00 |
| 5 METRES | 1.00 | 1.00 | 1.00 |
| 10 METRES | 1.00 | 1.00 | 1.00 |

INSTRUMENT NUMBER : 18
INSTRUMENT TYPE : PLASTIC SCINT., SCINTOM. 6134A
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 239.30 | 51.70 | 187.60 |
| 4 METRES | 145.20 | 39.40 | 105.80 |
| 5 METRES | 100.20 | 32.40 | 67.80 |
| | : SD (uR/h) | | |
| 3 METRES | 8.00 | 0.50 | 6.00 |
| 4 METRES | 3.00 | 0.30 | 2.00 |
| 5 METRES | 1.50 | 0.20 | 1.00 |

<u>Tabel A1.</u> **Continued.**

INSTRUMENT NUMBER : 18
INSTRUMENT TYPE : PLASTIC SCINT., SCINTOM. 6134A
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 208.50 | 182.80 | 91.50 |
| 5 METRES | 78.90 | 66.80 | 33.20 |
| 10 METRES | 19.50 | 16.40 | 8.10 |
| | : SD (uR/h) | | |
| 3 METRES | 0.20 | 0.20 | 0.20 |
| 5 METRES | 0.15 | 0.20 | 0.20 |
| 10 METRES | 0.20 | 0.10 | 0.05 |

INSTRUMENT NUMBER : 19
INSTRUMENT TYPE : GM COUNTER, MC70
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 237.90 | 55.20 | 182.80 |
| 4 METRES | 146.00 | 42.50 | 103.40 |
| 5 METRES | 99.40 | 36.70 | 62.70 |
| | : SD (uR/h) | | |
| 3 METRES | 1.80 | 0.80 | 2.00 |
| 4 METRES | 1.40 | 0.70 | 1.60 |
| 5 METRES | 1.60 | 1.00 | 1.90 |

INSTRUMENT NUMBER : 19
INSTRUMENT TYPE : GM COUNTER, MC70
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 198.80 | 219.00 | 105.70 |
| 5 METRES | 74.20 | 83.20 | 39.80 |
| 10 METRES | 18.00 | 21.00 | 9.90 |
| | : SD (uR/h) | | |
| 3 METRES | 1.30 | 1.50 | 1.00 |
| 5 METRES | 0.90 | 0.90 | 0.70 |
| 10 METRES | 0.40 | 0.40 | 0.30 |

INSTRUMENT NUMBER : 20
INSTRUMENT TYPE : GM COUNTER, MC70, CM S003
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 199.30 | 177.20 | 93.40 |
| 5 METRES | 74.20 | 66.80 | 34.70 |
| 10 METRES | 17.90 | 16.70 | 9.10 |
| | : SD (uR/h) | | |
| 3 METRES | 13.55 | 11.87 | 6.63 |
| 5 METRES | 4.60 | 4.28 | 2.74 |
| 10 METRES | 1.24 | 1.05 | 0.71 |

**Table A1.** Continued.

INSTRUMENT NUMBER : 21
INSTRUMENT TYPE : GM COUNTER, MC70, CM S009
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | DIFF. |
|---|---|
| 3 METRES | 184.56 |
| 4 METRES | 103.43 |
| 5 METRES | 64.54 |
| | : SD (uR/h) |
| 3 METRES | 4.06 |
| 4 METRES | 2.38 |
| 5 METRES | 3.87 |

INSTRUMENT NUMBER : 21
INSTRUMENT TYPE : GM COUNTER, MC70, CM S009
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 198.00 | 177.30 | 93.40 |
| 5 METRES | 74.80 | 65.00 | 33.50 |
| 10 METRES | 17.50 | 16.50 | 7.40 |
| | | : SD (uR/h) | |
| 3 METRES | 14.65 | 12.94 | 6.91 |
| 5 METRES | 2.92 | 2.80 | 1.07 |
| 10 METRES | 1.33 | 1.20 | 0.62 |

INSTRUMENT NUMBER : 22
INSTRUMENT TYPE : GM COUNTER, MC70, MINI6/80
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | DIFF. |
|---|---|
| 3 METRES | 191.88 |
| 4 METRES | 102.86 |
| 5 METRES | 67.19 |
| | : SD (uR/h) |
| 3 METRES | 2.69 |
| 4 METRES | 2.16 |
| 5 METRES | 1.88 |

INSTRUMENT NUMBER : 22
INSTRUMENT TYPE : GM COUNTER, MC70, MINI6/80
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 209.70 | 181.40 | 94.60 |
| 5 METRES | 78.10 | 66.70 | 34.60 |
| 10 METRES | 19.30 | 16.50 | 8.50 |
| | | : SD (uR/h) | |
| 3 METRES | 3.56 | 3.45 | 2.08 |
| 5 METRES | 1.64 | 1.40 | 0.55 |
| 10 METRES | 0.33 | 0.40 | 0.22 |

**Table A1.** Continued.

INSTRUMENT NUMBER : 23
INSTRUMENT TYPE : GM COUNTER, MC71
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 243.80 | 56.30 | 187.50 |
| 4 METRES | 150.63 | 46.02 | 104.60 |
| 5 METRES | 104.72 | 38.69 | 66.00 |

INSTRUMENT NUMBER : 23
INSTRUMENT TYPE : GM COUNTER, MC71
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 211.60 | 187.60 | 89.30 |
| 5 METRES | 75.90 | 67.00 | 31.60 |
| 10 METRES | 19.18 | 17.10 | 7.63 |

INSTRUMENT NUMBER : 24
INSTRUMENT TYPE : GM COUNTER, BZ120
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 244.80 | 50.30 | 194.50 |
| 4 METRES | 149.60 | 40.70 | 108.90 |
| 5 METRES | 105.30 | 35.20 | 70.10 |
| | | : SD (uR/h) | |
| 3 METRES | 0.85 | 0.49 | 0.98 |
| 4 METRES | 0.70 | 0.57 | 0.90 |
| 5 METRES | 0.47 | 0.37 | 0.60 |

INSTRUMENT NUMBER : 24
INSTRUMENT TYPE : GM COUNTER, BZ120
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 212.50 | 252.70 | 118.50 |
| 5 METRES | 77.30 | 91.20 | 43.00 |
| 10 METRES | 18.60 | 23.50 | 10.50 |
| | | : SD (uR/h) | |
| 3 METRES | 1.51 | 2.86 | 1.26 |
| 5 METRES | 1.38 | 0.97 | 0.70 |
| 10 METRES | 0.81 | 0.74 | 0.60 |

Table A1. Continued.

INSTRUMENT NUMBER : 25
INSTRUMENT TYPE : PROPORTIONAL COUNTER, LB6123
MEASUREMENT : SHADOW SHIELD, RESULTS (uR/h)

| | WO SH. | W SH. | DIFF. |
|---|---|---|---|
| 3 METRES | 247.60 | 60.30 | 187.30 |
| 4 METRES | 151.90 | 48.60 | 103.30 |
| 5 METRES | 107.50 | 40.70 | 66.80 |
| | : SD (uR/h) | | |
| 3 METRES | 0.78 | 0.44 | 0.90 |
| 4 METRES | 0.71 | 0.40 | 0.81 |
| 5 METRES | 0.64 | 0.47 | 0.79 |

INSTRUMENT NUMBER : 25
INSTRUMENT TYPE : PROPORTIONAL COUNTER, LB6123
MEASUREMENT : FREE FIELD, RESULTS (uR/h)

| | CS137 | CO60 | RA226 |
|---|---|---|---|
| 3 METRES | 208.20 | 237.00 | 112.00 |
| 5 METRES | 77.70 | 87.10 | 40.80 |
| 10 METRES | 19.00 | 21.90 | 10.30 |
| | : SD (uR/h) | | |
| 3 METRES | 2.04 | 1.78 | 1.16 |
| 5 METRES | 1.01 | 1.13 | 0.97 |
| 10 METRES | 0.81 | 0.78 | 0.63 |

Table A2. Results of natural-background measurements.

| Instrument no. | Nat.bgr. (uR/h) | sd (uR/h) |
|---|---|---|
| 1 | 7.66 | 0.09 |
| 2 | 7.80 | 0.10 |
| 3 | 7.70 | 0.15 |
| 4 | 7.48 | 0.40 |
| 5 | 7.40 | 0.40 |
| 6 | 7.82 | 0.01 |
| 8 | 5.90 | |
| 10 | 7.80 | 0.40 |
| 11 | 6.26 | 0.15 |
| 12 | 5.54 | 0.19 |
| 13 | 6.00 | 0.10 |
| 14 | 5.19 | 0.07 |
| 15 | 8.02 | 0.20 |
| 16 | 7.54 | 0.49 |
| 17 | 6.00 | 1.00 |
| 18 | 6.63 | 0.03 |
| 19 | 8.60 | 0.15 |
| 20 | 7.50 | 0.47 |
| 21 | 7.70 | 0.56 |
| 22 | 7.10 | 0.11 |
| 23 | 7.10 | |
| 24 | 12.00 | 0.50 |
| 25 | 10.90 | 0.40 |

Table A3. Results of cosmic-component measurements.

| Instrument no. | Cosmic (uR/h) | sd (uR/h) |
|---|---|---|
| 1 | 4.17 | 0.12 |
| 2 | 4.28 | 0.07 |
| 3 | 4.13 | 0.04 |
| 4 | 4.07 | 0.53 |
| 5 | 3.71 | 0.57 |
| 6 | 4.36 | 0.02 |
| 8 | 3.50 | |
| 10 | 3.90 | 0.30 |
| 11 | 2.47 | 0.36 |
| 12 | 1.89 | 0.08 |
| 13 | 2.30 | 0.08 |
| 14 | 1.93 | 0.10 |
| 15 | 4.36 | 0.26 |
| 16 | 3.97 | 0.07 |
| 17 | 2.40 | 0.30 |
| 18 | 3.14 | 0.02 |
| 19 | 4.30 | 0.10 |
| 20 | 3.95 | |
| 21 | 4.04 | |
| 22 | 3.90 | |
| 23 | 3.70 | |
| 24 | 7.75 | 0.39 |
| 25 | 6.77 | 0.34 |

Table A4. Results of the terrestrial component.

| Instrument no. | Terr.comp. (uR/h) |
|---|---|
| 1 | 3.50 |
| 2 | 3.52 |
| 3 | 3.57 |
| 4 | 3.41 |
| 5 | 3.69 |
| 6 | 3.46 |
| 8 | 2.40 |
| 10 | 3.90 |
| 11 | 3.79 |
| 12 | 3.65 |
| 13 | 3.70 |
| 14 | 3.26 |
| 15 | 3.66 |
| 16 | 3.57 |
| 17 | 3.60 |
| 18 | 3.49 |
| 19 | 4.30 |
| 20 | 3.55 |
| 21 | 3.66 |
| 22 | 3.20 |
| 23 | 3.40 |
| 24 | 4.25 |
| 25 | 4.13 |

Table A5. Ratios of measured-to-nominal values of exposure rates for the two calibration methods.

| Detector No., type | Shadow-shield measurements | | Free-field measurements | | | |
|---|---|---|---|---|---|---|
| | Distance (m) | $^{137}Cs$ | Distance (m) | $^{137}Cs$ | $^{60}Co$ | $^{226}Ra$ |
| 1 Ionisation chamber, RSS-111 | 3 | 0.9863±0.0050 | 3 | 1.0118±0.0138 | 1.0130±0.0104 | 1.0017±0.0120 |
| | 4 | 0.9846±0.0043 | 5 | 0.9847±0.0162 | 0.9959±0.0121 | 1.0026±0.0168 |
| | 5 | 0.9917±0.0046 | 10 | 0.9595±0.0218 | 0.9568±0.0251 | 0.9621±0.0347 |
| | Mean | 0.9875±0.0027(ns) | Mean | 0.9927±0.0094(ns) | 1.0014±0.0075(ns) | 0.9991±0.0094(ns) |
| 2 Ionisation chamber, RSS-111 | 3 | 0.9816±0.0047 | 3 | 0.9957±0.0152 | 0.9972±0.0132 | 0.9860±0.0119 |
| | 4 | 0.9748±0.0056 | 5 | 0.9792±0.0160 | 0.9849±0.0119 | 0.9825±0.0159 |
| | 5 | 0.9832±0.0081 | 10 | 0.9590±0.0220 | 0.9645±0.0191 | 0.9529±0.0210 |
| | Mean | 0.9796±0.0033(ns) | Mean | 0.9821±0.0098(ns) | 0.9859±0.0080(ns) | 0.9793±0.0087(ns) |
| 3 Ionisation chamber, RSS-111 | 3 | 0.9768±0.0046 | 3 | 0.9794±0.0142 | 0.9799±0.0116 | 0.9710±0.0117 |
| | 4 | 0.9758±0.0056 | 5 | 0.9754±0.0159 | 0.9834±0.0119 | 0.9825±0.0145 |
| | 5 | 0.9694±0.0053 | 10 | 0.9538±0.0200 | 0.9645±0.0162 | 0.9529±0.0210 |
| | Mean | 0.9742±0.0030(ns) | Mean | 0.9724±0.0093(ns) | 0.9780±0.0074(ns) | 0.9719±0.0083(ns) |

Table A5. contin'ied

| Detector No., type | Shadow-shield measurements | | Free-field measurements | | | |
|---|---|---|---|---|---|---|
| | Distance (m) | $^{137}Cs$ | Distance (m) | $^{137}Cs$ | $^{60}Co$ | $^{226}Ra$ |
| 4 | 3 | 0.9725±0.0076 | 3 | 0.9810±0.0138 | 0.9850±0.0131 | 0.9699±0.0148 |
| Ionisation chamber, RSS-111 | 4 | 0.9768±0.0101 | 5 | 0.9816±0.0187 | 0.9802±0.0220 | 0.9971±0.0240 |
| | 5 | 0.9830±0.0128 | 10 | 0.9697±0.0392 | 0.9834±0.0420 | 0.9874±0.0646 |
| | Mean | 0.9757±0.0055(ns) | Mean | 0.9804±0.0107(+) | 0.9837±0.0109(+) | 0.9777±0.0123(ns) |
| 5 | 3 | | 3 | | | 1.0077±0.0149 |
| Ionisation chamber, RSS-111 | 4 | 0.9772±0.0111 | 5 | 0.9988±0.0185 | 1.0021±0.0185 | 0.9991±0.0257 |
| | 5 | 0.9778±0.0140 | 10 | 0.9846±0.0367 | 0.9852±0.0442 | 0.9713±0.0734 |
| | Mean | 0.9774±0.0087(+) | Mean | 0.9959±0.0165(ns) | 0.9996±0.0171(ns) | 1.0045±0.0127(ns) |
| 6 | 3 | 1.0027±0.0035 | 3 | 1.0205±0.0135 | 1.0212±0.0099 | 1.0142±0.0114 |
| Ionisation chamber, RSS-111 | 4 | 1.0008±0.0031 | 5 | 1.0122±0.0160 | 1.0086±0.0113 | 1.0102±0.0137 |
| | 5 | 1.0009±0.0031 | 10 | 0.9815±0.0200 | 0.9864±0.0156 | 0.9587±0.0180 |
| | Mean | 1.0014±0.0018(ns) | Mean | 1.0096±0.0092(ns) | 1.0103±0.0067(ns) | 1.0022±0.0079(*) |
| 7 | 3 | 1.0103±0.0060 | | | | |
| Ionisation chamber, RSS-111 | 4 | 1.0058±0.0049 | | | | |
| | 5 | 1.0153±0.0054 | | | | |
| | Mean | 1.0101±0.0031(ns) | | | | |
| 8 | 3 | 0.7623 | 3 | 0.9679 | 0.9896 | 0.9632 |
| Ionisation chamber, | 4 | 0.8333 | 5 | 0.9969 | 1.0215 | 1.0020 |
| Centronic IG5 | 5 | 0.8226 | 10 | 1.0000 | 1.0473 | 1.0540 |
| | Mean | 0.8061±0.0221 a) | Mean | 0.9883±0.0102 | 1.0195±0.0167 | 1.0064±0.0263 |

a) Inadequate shielding, see discussion in Section 5.2.

Table A5. continued

| Detector No., type | Shadow-shield measurements Distance (m) | $^{137}Cs$ | Free-field measurements Distance (m) | $^{137}Cs$ | $^{60}Co$ | $^{226}Ra$ |
|---|---|---|---|---|---|---|
| 9 Ionisation chamber, LS 10-120 | 3 | 1.0097±0.0093 | | | | |
| | 4 | 1.0097±0.0215 | | | | |
| | 5 | 1.0076±0.0292 | | | | |
| | Mean | 1.0096±0.0082(++) | | | | |
| 10 Ionisation chamber, LS 120-08 | | | 3 | 1.0317±0.0138 | 1.0351±0.0101 | 0.9634±0.0110 |
| | | | 5 | 1.0052±0.0197 | 0.9924±0.0127 | 0.9534±0.0174 |
| | | | 10 | 0.9692±0.0222 | 0.9704±0.0192 | 0.9300±0.0599 |
| | | | Mean | 1.0120±0.0101(ns) | 1.0116±0.0073(**) | 0.9598±0.0092(ns) |
| 11 Scintillation detector, MAB 604.1 | 3 | 1.1696±0.0068 | 3 | 1.1380±0.0153 | 1.1720±0.0128 | 1.1370±0.0131 |
| | 4 | 1.1684±0.0036 | 5 | 1.1040±0.0177 | 1.1447±0.0147 | 1.1601±0.0214 |
| | 5 | 1.1711±0.0121 | 10 | 1.0518±0.0231 | 1.1000±0.0230 | 1.1653±0.0445 |
| | Mean | 1.1688±0.0031(+) | Mean | 1.1091±0.0103(**) | 1.1512±0.0089(*) | 1.1446±0.0108(ns) |
| 12 Scintillation detector, MAB 604.1 | 3 | 0.9876±0.0036 | 3 | 1.0000±0.0133 | 0.9548±0.0094 | 0.9129±0.0104 |
| | 4 | 1.0087±0.0034 | 5 | 0.9546±0.0152 | 0.9184±0.0107 | 0.9300±0.0131 |
| | 5 | 1.0000±0.0034 | 10 | 0.9128±0.0192 | 0.8935±0.0151 | 0.8645±0.0196 |
| | Mean | 0.9993±0.0020(***) | Mean | 0.9660±0.0089(***) | 0.9308±0.0064(**) | 0.9114±0.0075(*) |
| 13 Scintillation detector, MAB 604.1 | 3 | 1.0497±0.0071 | 3 | 1.0010±0.0178 | 1.0000±0.0112 | 0.9613±0.0145 |
| | 4 | 1.0717±0.0246 | 5 | 1.0363±0.0194 | 1.0438±0.0128 | 0.9913±0.0198 |
| | 5 | 1.0367±0.0160 | 10 | 0.9897±0.0306 | 1.0059±0.0309 | 0.9874±0.0250 |
| | Mean | 1.0491±0.0063(ns) | Mean | 1.0129±0.0121(ns) | 1.0180±0.0081(*) | 0.9745±0.0106(ns) |

Table A5. continued

| Detector No., type | Shadow-shield measurements Distance (m) | $^{137}Cs$ | Free-field measurements Distance (m) | $^{137}Cs$ | $^{60}Co$ | $^{226}Ra$ |
|---|---|---|---|---|---|---|
| 14 Scintillation detector, MAB 604.1 | 3 | 0.9649±0.0068 | 3 | 0.9879±0.0132 | 0.9222±0.0093 | 0.9153±0.0112 |
| | 4 | 0.9811±0.0103 | 5 | 1.0252±0.0168 | 0.9547±0.0117 | 0.9184±0.0140 |
| | 5 | 0.9852±0.0113 | 10 | 1.0231±0.0252 | 0.9337±0.0216 | 0.9392±0.0416 |
| | Mean | 0.9729±0.0051(ns) | Mean | 1.0051±0.0096(ns) | 0.9347±0.0069(ns) | 0.9174±0.0085(ns) |
| 15 Scintillation detector, H 7907 | 3 | 1.0509±0.0062 | 3 | 1.0426±0.0147 | 1.1149±0.0138 | 1.0939±0.0165 |
| | 4 | 1.0590±0.0144 | 5 | 1.0403±0.0183 | 1.1461±0.0165 | 1.0746±0.0169 |
| | 5 | 1.0625±0.0144 | 10 | | | |
| | Mean | 1.0536±0.0053(ns) | Mean | 1.0417±0.0115(ns) | 1.1277±0.0106(ns) | 1.0845±0.0118(ns) |
| 16 Scintillation detector, H 7201/10 | 3 | 1.0053±0.0083 | 3 | 1.0142±0.0149 | 1.0772±0.0132 | 1.0433±0.0189 |
| | 4 | 1.0014±0.0125 | 5 | 1.0174±0.0183 | 1.0914±0.0157 | 1.0475±0.0230 |
| | 5 | 1.0167±0.0115 | 10 | 0.9974±0.0347 | 1.0911±0.0287 | 1.0425±0.0466 |
| | Mean | 1.0074±0.0059(ns) | Mean | 1.0137±0.0110(ns) | 1.0840±0.0095(ns) | 1.0448±0.0139(+) |
| 17 Scintillation detector, Gammameter 2414 | 3 | 0.9184±0.0433 | 3 | 0.9784±0.0161 | 1.0535±0.0151 | 1.2258±0.0255 |
| | 4 | 0.9690±0.0292 | 5 | 0.9598±0.0200 | 1.0423±0.0191 | 1.2828±0.0339 |
| | 5 | 1.0856±0.0383 | 10 | 1.0769±0.0557 | 1.1243±0.0617 | 1.2629±0.1171 |
| | Mean | 0.9910±0.0205(**) | Mean | 0.9762±0.0122(ns) | 1.0519±0.0116(ns) | 1.2469±0.0201(ns) |
| 18 Scintillation detector, Scintomat 6134A | 3 | 1.0135±0.0219 | 3 | 1.0000±0.0132 | 1.0190±0.0099 | 0.9839±0.0112 |
| | 4 | 1.0252±0.0149 | 5 | 1.0233±0.0163 | 1.0091±0.0117 | 0.9679±0.0143 |
| | 5 | 1.0367±0.0120 | 10 | 1.0000±0.0227 | 0.9704±0.0163 | 0.9300±0.0180 |
| | Mean | 1.0293±0.0086(ns) | Mean | 1.0077±0.0094(ns) | 1.0069±0.0069(*) | 0.9686±0.0079(*) |

Table A5. continued

| Detector No., type | Shadow-shield measurements: Distance (m) | Shadow-shield measurements: $^{137}Cs$ | Free-field measurements: Distance (m) | Free-field measurements: $^{137}Cs$ | Free-field measurements: $^{60}Co$ | Free-field measurements: $^{226}Ra$ |
|---|---|---|---|---|---|---|
| 19 | 3 | 0.9876±0.0113 | 3 | 0.9535±0.0140 | 1.2207±0.0145 | 1.1366±0.0167 |
| GM counter, | 4 | 1.0019±0.0158 | 5 | 0.9624±0.0192 | 1.2568±0.0196 | 1.1603±0.0257 |
| MC 70 | 5 | 0.9587±0.0292 | 10 | 0.9231±0.0278 | 1.2426±0.0305 | 1.1366±0.0403 |
| | Mean | 0.9894±0.0088(ns) | Mean | 0.9518±0.0105(ns) | 1.2347±0.0109(ns) | 1.1428±0.0132(ns) |
| 20 | | | 3 | 0.9559±0.0662 | 0.9877±0.0669 | 1.0043±0.0722 |
| GM counter, | | | 5 | 0.9624±0.0616 | 1.0091±0.0656 | 1.0117±0.0810 |
| MC 70 | | | 10 | 0.9179±0.0663 | 0.9882±0.0640 | 1.0448±0.0838 |
| | | | Mean | 0.9463±0.0373(ns) | 0.9950±0.0378(+) | 1.0185±0.0453(ns) |
| 21 | 3 | 0.9971±0.0222 | 3 | 0.9496±0.0714 | 0.9883±0.0728 | 1.0043±0.0751 |
| GM counter, | 4 | 1.0022±0.0232 | 5 | 0.9702±0.0409 | 0.9819±0.0437 | 0.9767±0.0339 |
| MC 70 | 5 | 0.9869±0.0592 | 10 | 0.8974±0.0706 | 0.9763±0.0726 | 0.8496±0.0729 |
| | Mean | 0.9987±0.0155(+) | Mean | 0.9515±0.0317(ns) | 0.9821±0.0333(++) | 0.9613±0.0284(ns |
| 22 | 3 | 1.0366±0.0150 | 3 | 1.0058±0.0216 | 1.0111±0.0216 | 1.0172±0.0251 |
| GM counter, | 4 | 0.9967±0.0211 | 5 | 1.0130±0.0266 | 1.0076±0.0240 | 1.0087±0.0210 |
| MC 70 | 5 | 1.0274±0.0289 | 10 | 0.9897±0.0263 | 0.9763±0.0281 | 0.9759±0.0310 |
| | Mean | 1.0239±0.0112(ns) | Mean | 1.0032±0.0141(ns) | 1.0014±0.0139(ns) | 1.0045±0.0143(ns) |
| 23 | 3 | 1.0130 | 3 | 1.0149 | 1.0457 | 0.9602 |
| GM counter, | 4 | 1.0136 | 5 | 0.9844 | 1.0121 | 0.9213 |
| MC 71 | 5 | 1.0092 | 10 | 0.9836 | 1.0118 | 0.8760 |
| | Mean | 1.0119±0.0014 | Mean | 0.9943±0.0103 | 1.0232±0.0113 | 0.9192±0.0243 |

Table A5. continued

| Detector No., type | Shadow-shield measurements | | Free-field measurements | | | |
|---|---|---|---|---|---|---|
| | Distance (m) | $^{137}Cs$ | Distance (m) | $^{137}Cs$ | $^{60}Co$ | $^{226}Ra$ |
| 24 GM counter, BZ 120 | 3 | 1.0508±0.0064 | 3 | 1.0192±0.0153 | 1.4086±0.0210 | 1.2742±0.0197 |
| | 4 | 1.0552±0.0092 | 5 | 1.0026±0.0239 | 1.3776±0.0213 | 1.2536±0.0265 |
| | 5 | 1.0719±0.0097 | 10 | 0.9538±0.0458 | 1.3905±0.0489 | 1.2055±0.0724 |
| | Mean | 1.0567±0.0046(ns) | Mean | 1.0099±0.0124(ns) | 1.3931±0.0143(ns) | 1.2641±0.0154(ns) |
| 25 Proportional counter, LB 6123 | 3 | 1.0119±0.0060 | 3 | 0.9986±0.0164 | 1.3211±0.0162 | 1.2043±0.0184 |
| | 4 | 1.0010±0.0084 | 5 | 1.0078±0.0206 | 1.3157±0.0226 | 1.1895±0.0325 |
| | 5 | 1.0214±0.0124 | 10 | 0.9744±0.0460 | 1.2959±0.0504 | 1.1825±0.0755 |
| | Mean | 1.0100±0.0045(ns) | Mean | 1.0001±0.0124(ns) | 1.3178±0.0127(ns) | 1.1999±0.0156(ns) |

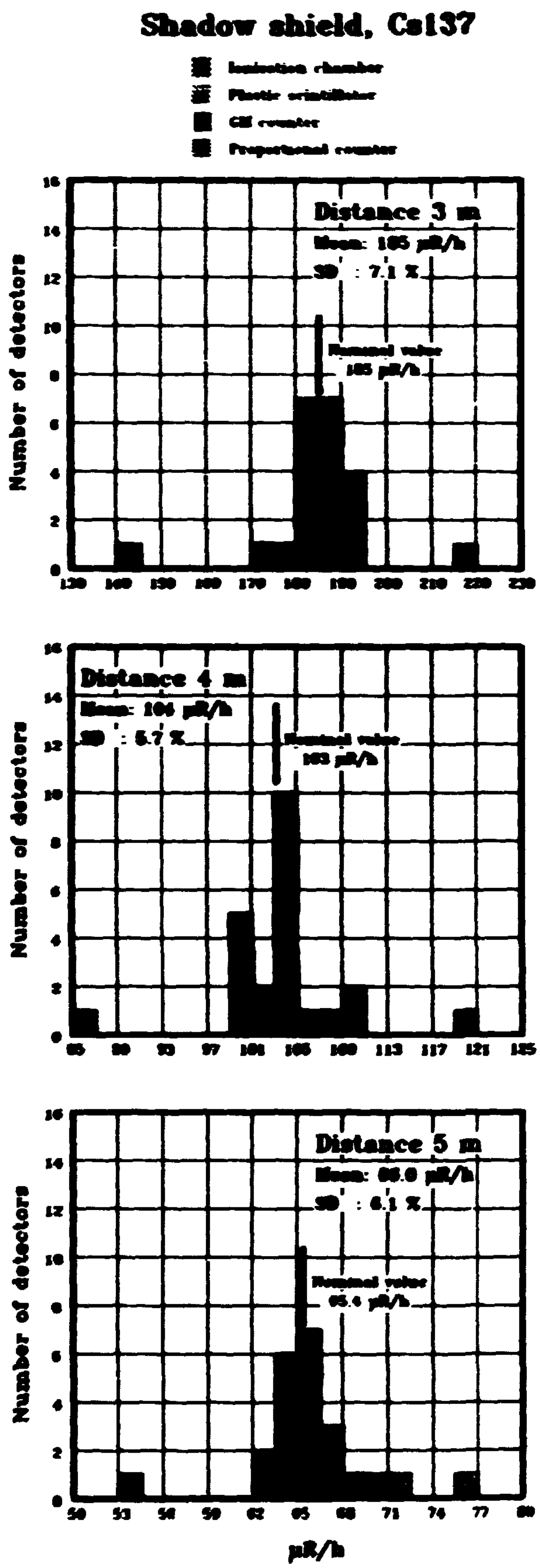


**Fig. A1.** Results of shadow-shield experiments with the $^{137}Cs$ source.

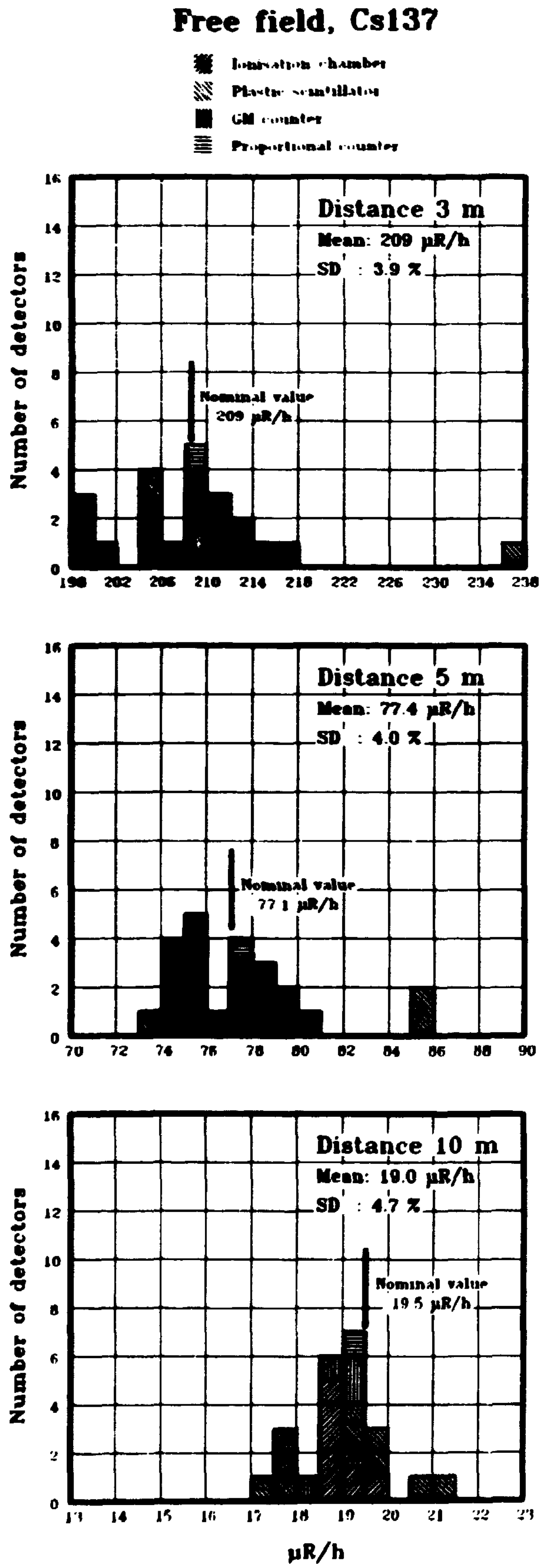


Fig. A2. Results of free-field experiments with the $^{137}Cs$ source.

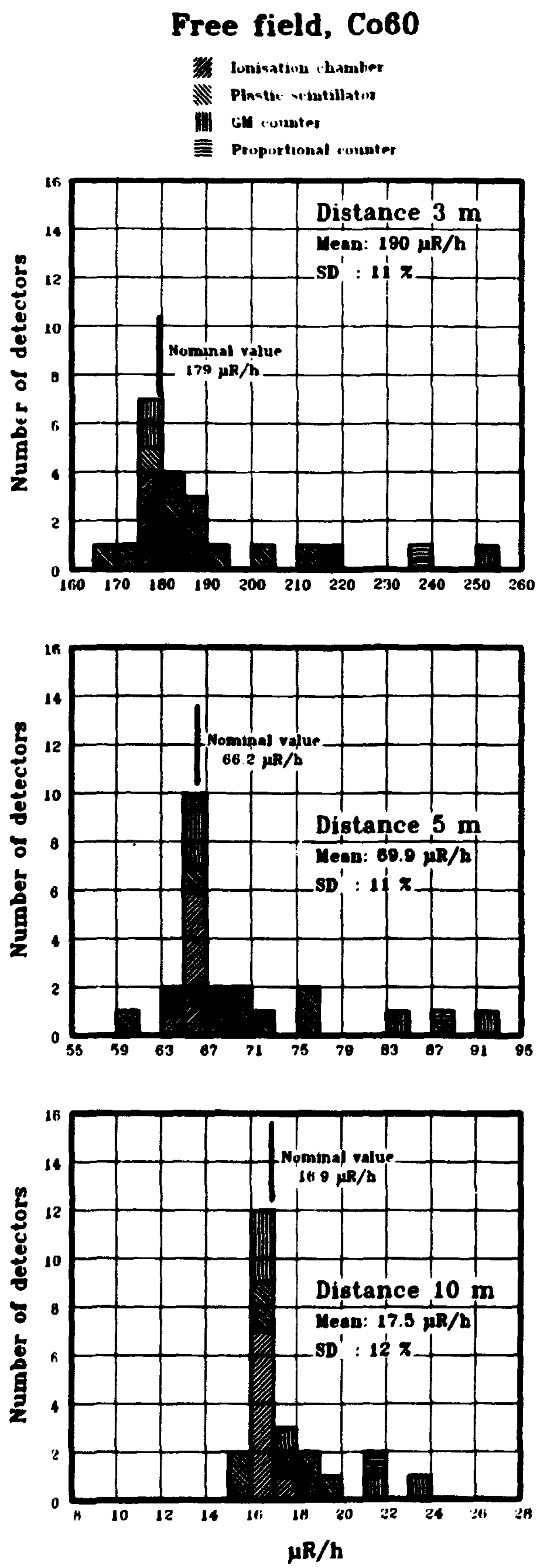


Fig. A3. Results of free-field experiments with the $^{60}Co$ source.

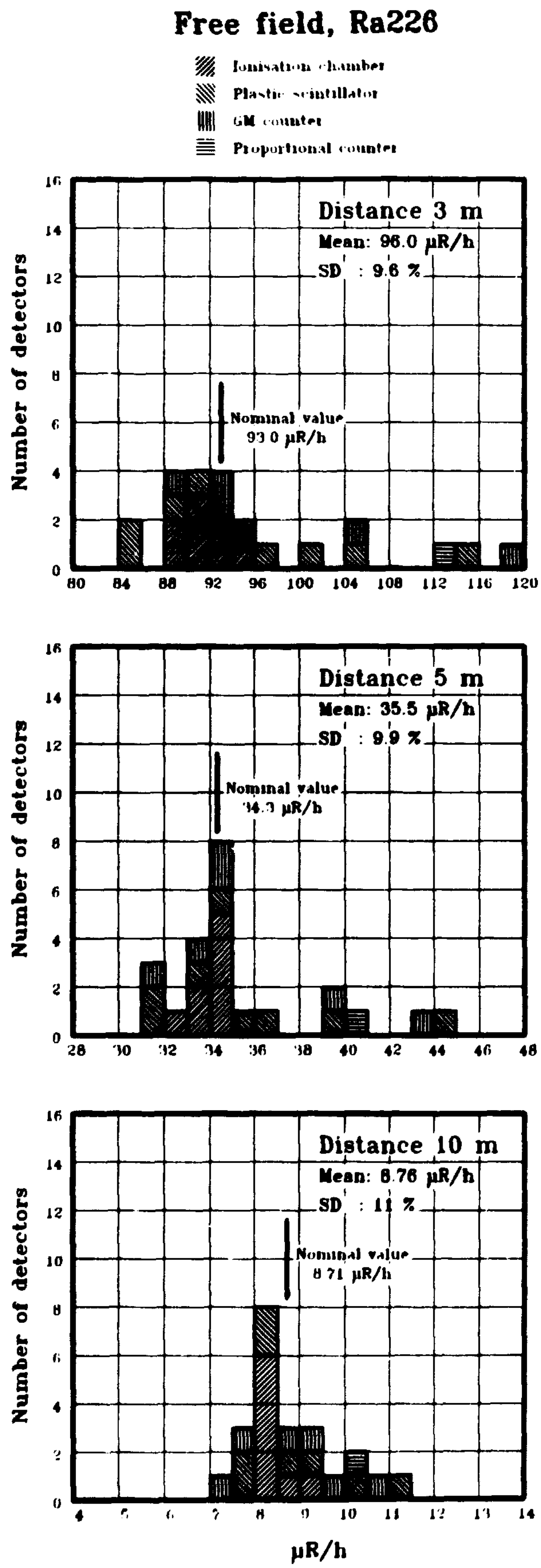


Fig. A4. Results of free-field experiments with the $^{226}Ra$ source.

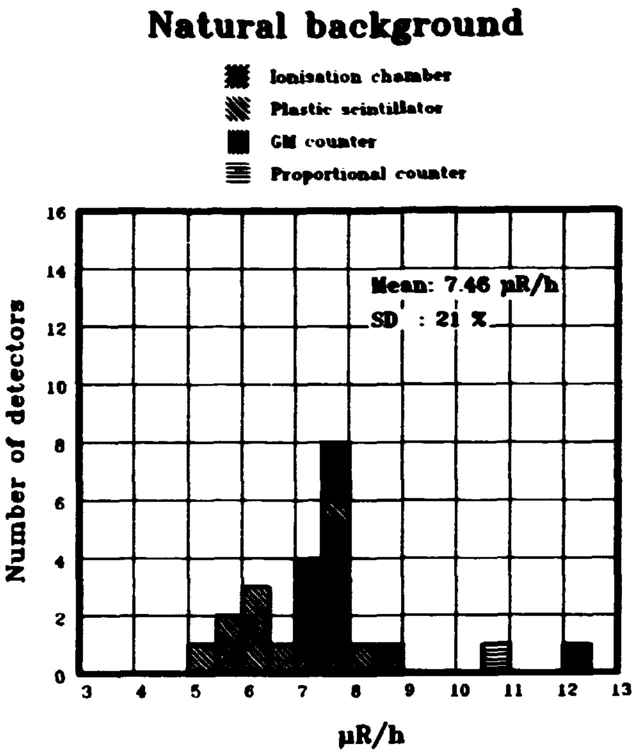


Fig. A5. Natural-background results.

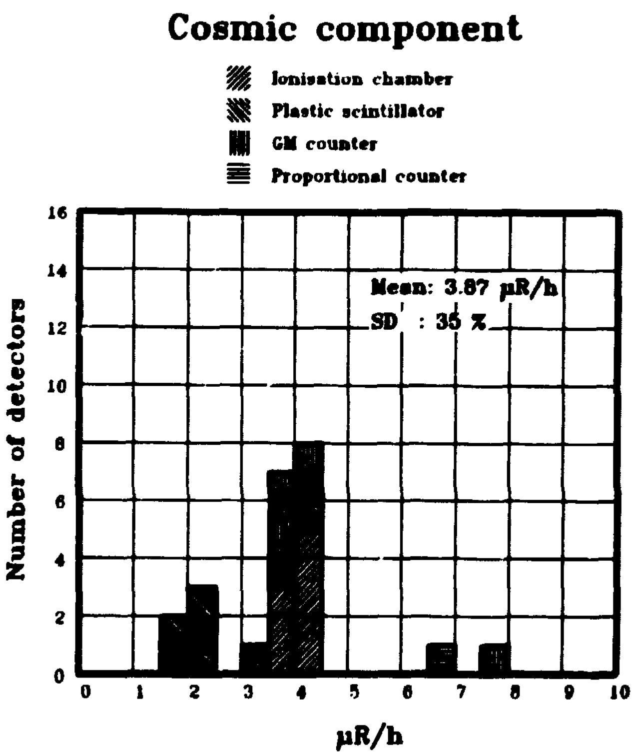


Fig. A6. Cosmic-component results.

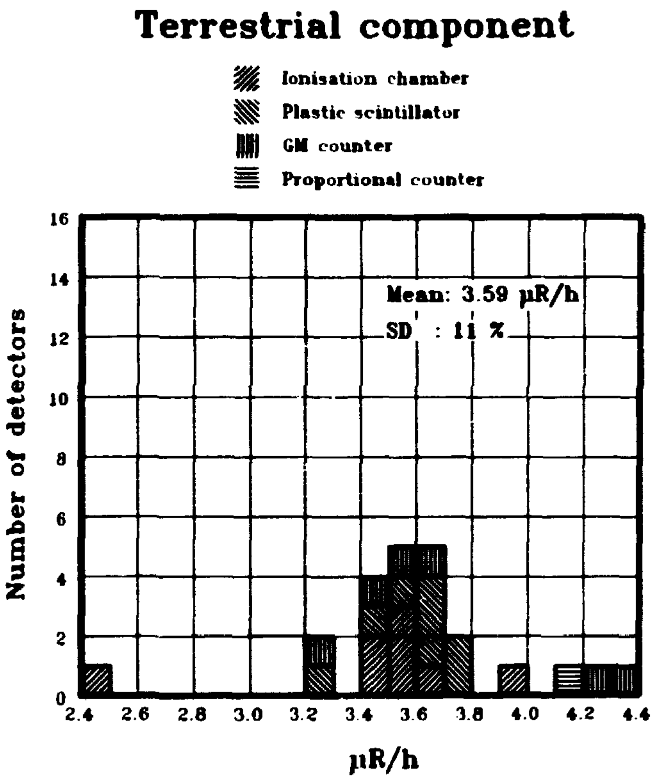


Fig. A7. Terrestrial-component results.

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Title and author(s)

A MULTI-LABORATORY TESTING OF CALIBRATION METHODS FOR ENVIRONMENTAL DOSE RATE METERS

Lars Bøtter-Jensen and Sven P. Nielsen

54 pages + tables + illustrations

Date November 1985

Department or group

Health Physics

Group's own registration number(s)

Abstract

Abstract. Calibration experiments were carried out at Risø National Laboratory 28-30 August 1985 with the aim of testing calibration methods for instruments used for background gamma radiation monitoring.

Two calibration methods using certified gamma sources were tested: 1) A shadow-shield calibration method, and 2) A freefield calibration set-up. The experiments comprised studies of 25 instruments from 11 European laboratories.

For most of the instruments the two methods gave identical results. The shadow-shield calibration, however, proved to be more accurate. Additional measurements of the natural background and the cosmic component gave useful information on the energy dependency of the detectors.

The calibration experiments were sponsored by CEC under contract No. 1244/1/84.

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