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ABSTRACT

An aluminium calorimeter was used to determine an absorbed 'dose in water' calibration factor for a thimble ionisation chamber for ^{60}Co gamma radiation. Several distinct steps were involved in the calibration.

An absorbed 'dose in aluminium' calibration factor for the chamber was measured to determine the effect of depth on this factor; this calibration factor was used to transfer experimentally the measured dose in aluminium to dose in a water phantom at depths of 5 cm and 7 cm for a range of field sizes.

(Continued)

A build-up factor (to describe the radiation quality) in the water phantom was calculated as a function of depth and field size. Using these steps, an absorbed dose in water calibration factor for the thimble chamber was measured over a limited range of radiation quality.

Two further experiments were made to test the overall calibration procedure. The dose in water measurements were used to determine the *G*-value for ferric ion production by irradiating ferrous sulphate dosimeters for two or three field sizes at depths of 5 and 7 cm respectively. The measured *G*-values were compared with those obtained by other workers using calorimetry. The long-term stability of the calorimeter was observed over a period of about 14 months, during which time no change was detected in the calorimeter.

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ACCURACY; CALIBRATION STANDARDS; CALORIMETERS; CALORIMETRIC DOSEMETERS; CHEMICAL DOSEMETERS; DOSE RATES; DOSIMETRY; IONIZATION CHAMBERS; RADIATION DOSES; STABILITY

CONTENTS

1. INTRODUCTION

This report describes the results of further measurements of absorbed dose at ^{60}Co energy using the aluminium calorimeter which has been described by Urquhart, Johnson & Badger (1973).

The aims and methods adopted are shown diagrammatically in Figure 1. Measurements of absorbed dose or ionisation chamber current were made in the aluminium calorimeter, in an aluminium phantom and in a water phantom at a constant distance (x_o) from the same ^{60}Co source. Using the calorimeter, the dose rate $\dot{D}_r$ (x_o, d_r, f_o), in the reference material (*i.e.* aluminium), was measured for a range of depths (d_r) from 2.76 to 5.69 cm. The ionisation current I_r (x_o, d_r, f_o) in the aluminium phantom was measured for the same range of d_r using a Baldwin-Farmer thimble chamber and Townsend balance. From these measurements, the absorbed dose in aluminium calibration factor, N_r, for the thimble chamber was obtained. These measurements were made with a fixed field size f_o (7.5 x 7.5 cm at 60 cm).

The same thimble chamber, fitted with an aluminium build-up cap, was irradiated in the water phantom and the current I_r (x_o, d_w, f) was measured for a range of field sizes f(5 x 5 to 25 x 25 cm at 60 cm), at depths (d_w) of 5 and 7 cm respectively. The dose rate in water $\dot{D}_w$ (x_o, d_w, f) at any point in the phantom is given by

$$\dot{D}_w\ (x_o,\ d_w,\ f) = I_r\ (x_o,\ d_w,\ f) \cdot N_r \cdot \left(\frac{\mu_{ew}}{\mu_{er}}\right) \cdot\ p_{Al} \qquad \ldots \quad (1)$$

where

$\left(\frac{\mu_{ew}}{\mu_{er}}\right)$ = the ratio of mass energy absorption coefficient in water and aluminium, and

p_{Al} = a displacement factor (determined experimentally).

Finally, a thimble chamber fitted with a Perspex build-up cap was irradiated in the water phantom for a range of depths and field sizes, and the absorbed dose in water calibration factor (N_w) was calculated. A thimble chamber calibrated in this way could be used to transfer the dose standard to other centres using ^{60}Co sources.

To test the calibration, the calibrated thimble chamber was used to measure the *G*-value for ferric ion production in ferrous sulphate dosimeters. The *G*-value obtained agreed within experimental error with recent determinations made elsewhere.

All accuracies quoted in this report are at the 2σ confidence level, and values of energy absorption coefficients were obtained from the tabulations of

Evans (1968).

2. CALIBRATION RESULTS

The dose rate in the calorimeter was measured with four aluminium absorber plates (nominal thickness 0.5, 1, 2 and 3 cm) placed successively against the front face of the calorimeter. The results obtained are shown in Figure 2 where the dose rate at each depth (d_r) is shown relative to the dose rate with no additional absorber (depth d_o).

The same plates were attached in turn to the front of the aluminium phantom and the ionisation current in the thimble chamber, placed in the phantom at depth d_o, was measured in the same way. The depth-current curve obtained was indistinguishable from the depth-dose curve shown in Figure 2.

Details of the measured dose rates and currents, and the calibration factor N_r derived from them, are shown in Table 1; it can be seen that there was no significant change in N_r over the depth range. The last column shows experimentally determined values of the photon build-up factor B; this build-up factor gives an indication of the radiation quality at each depth and is the ratio of total dose to dose from primary radiation only. The significance of B in this context will be discussed in Section 4. The values of current and dose rate at depth d_o, given in Table 1, are mean values from a series of measurements repeated over ten months.

All ionisation currents cited in this report are normalised to the current obtained in a 'beam monitor' reference position. The ionisation currents obtained in the water phantom when the thimble chamber was fitted with either aluminium or Perspex build-up caps are shown graphically in Figure 3.

Table 2 shows specific values of chamber current used to measure the dose rate in water $\dot{D}_w$, and therefore the calibration factor N_w for the thimble chamber with the Perspex build-up caps. The values of current shown in Table 2 are mean values for repeated measurements at the reference field size f_o (7.5 x 7.5 cm).

It is of interest to compare the mean calibration factor $N_w = \underline{5.129 \pm 0.02 \times 10^7}$ J kg^{-1} C^{-1} from Table 2 with calibration factors derived in two other ways.

Firstly the thimble chamber has been calibrated in the UK by the National Physical Laboratory (NPL) for exposure (calibration factor = 5.46 x 10^9 R C^{-1}). When this is multiplied by the roentgen to rad conversion factor (the British Hospital Physicists Association (HPA 1969) recommends a value of 0.95 for ^{60}Co), a value $N_w = \underline{5.19 \times 10^7}$ J kg^{-1} C^{-1} is obtained.

Secondly, the International Commission on Radiation Units and Measurements (ICRU 1969) recommends the use of a thin-walled chamber for the transfer of dose from one medium to another. Using the Baldwin-Farmer chamber without build-up cap, and correcting for the finite wall thickness (using experimental data of Barnard, Axton & Marsh (1959)), a value $N_w = \underline{5.016 \times 10^7}$ J kg^{-1} C^{-1} was obtained. This method requires the use of stopping power ratios rather than ratios of energy absorption coefficients and the systematic errors involved are one to two per cent higher than in the method adopted for the transfer from aluminium to water.

3. MEASUREMENT OF *G*-VALUE FOR FERROUS SULPHATE DOSIMETERS

To test the validity of the dose calibration, the *G*-value for ferric ion production in ferrous sulphate dosimeter solution was determined by irradiating $FeSO_4$ dosimeters at various points in the water phantom, and measuring the dose rate at each point with the calibrated thimble chamber.

The procedure used to make the chemical dosimeter measurements was recommended by R. Matthews of the Isotope Division, AAEC, who supplied the dosimeters and made all the measurements of ferric ion yield rate. Five dosimeters were irradiated in turn at each measurement point for times calculated to give doses of approximately 0.1, 0.15, 0.20, 0.25 and 0.30 J kg^{-1}. The measured optical density O was then plotted against time and a linear least-squares fit made to the five points. The slope of this line was then used to calculate the ferric ion yield rate, $\left(\frac{\dot{O}}{\varepsilon}\right)_{Fe}$, and then the *G*-value, from the equation:

$$G_{Fe} = N_A \cdot \left(\frac{\dot{O}}{\varepsilon}\right)_{Fe} \cdot \frac{1.60210 \times 10^{-17}}{\dot{D}_{Fe}\,(x_o,\, d_w,\, f) \cdot \rho_{Fe}} \cdot k_s \,, \qquad \ldots (2)$$

where G_{Fe} = number of ferric ions produced per 100 eV of absorbed energy;

N_A = Avogadro number (6.02252×10^{23} mol^{-1});

$\left(\frac{\dot{O}}{\varepsilon}\right)_{Fe}$ = ferric ion yield rate (mol ℓ^{-1} s^{-1}),

= the extinction coefficient as measured for a standard solution of ferric ions (2180 ℓ mol^{-1} for a 1-cm cell at a wavelength of 304 nm);

ρ_{Fe} = density of the dosimeter solution (1.024 kg ℓ^{-1});

$\dot{D}_{Fe}\,(x_o,\, d_w,\, f)$ = the dose rate (W kg^{-1}) in the dosimeter as measured by the calibrated thimble chamber; and

k_s = a stem correction factor, 1.0060 ± 0.002 for the dosimeter. This corrects for the air space above

the dosimeter solution during irradiation and was determined experimentally.

The dose rate in the dosimeter solution is given by

$$\dot{D}_{Fe}\ (x_o,\ d_w,\ f) = \dot{D}_w\ (x_o,\ d_w,\ f) \cdot \frac{\mu_{eFe}}{\mu_{ew}} \cdot p_{Fe}$$

where μ_{eFe} = the mass energy absorption coefficient for the dosimeter solution and $\mu_{eFe} / \mu_{ew} = 0.9966$; and

p_{Fe} = a calculated displacement factor (0.9995) for the dosimeter solution.

Details of the *G*-value measurements are shown in Table 3, and a comparison of the mean value 15.20 ± 0.13 (100 eV^{-1}) with recent determinations is made in Table 4. The ICRU (1969) recommends a value of 15.5 ± 0.2. The total systematic error in our value is estimated to be ± 0.23; this is the algebraic sum of systematic errors in dose and current measurements, dose transfer, and ferric ion yield rates, and the overall accuracy is therefore ± 0.3.

If the NPL - HPA thimble chamber calibration had been used, the mean *G*-value would have been 15.0 (100 eV^{-1}), and if the calibration using the thin-walled chamber transfer method had been used, the mean *G*-value would have been 15.5 (100 eV^{-1}).

4. TRANSFER OF CALIBRATION TO OTHER CENTRES

A thimble chamber calibrated against the calorimeter (as described above) could be used to standardise dosimeters at other centres equipped with a ^{60}Co teletherapy unit, provided the radiation quality for each unit is the same as that for the Eldorado 6 therapy unit used for the primary calibration.

One way to compare the radiation qualities from different machines is to consider the photon build-up factor B for each source-collimator system. The scattered to primary radiation ratios from various collimators and sources have been published by the ICRU (1970). Source and collimator build-up factors taken from tables in the ICRU report are compared with the build-up in the aluminium and water phantoms in Figure 4. The build-up in water was calculated from 'tissue:air' ratios determined experimentally by Gupta & Cunningham (1966), and the build-up in aluminium from 'aluminium:air' ratios determined experimentally by the authors of this report.

Collimator build-up produces a relatively small amount of beam softening because of the small scattering angles. Build-up values are also small (less than 1.1), as shown in Figure 4d for collimators of various sizes. Since it has been found that build-up in the aluminium phantom (up to 1.6) has no effect on the calibration (Table 1), it can be assumed that calibration factors measured for one ^{60}Co machine can be applied to other machines having different collimator systems.

Source build-up is more significant in its affect on beam quality because of the contribution of large angle scattering (180^{o}) to the scattered spectrum. However, it can be seen from Figure 5c that source build-up factors are generally small and are within the range 1.05 to 1.25 for all practical source dimensions.

5. LONG-TERM STABILITY AND ABSOLUTE ACCURACY OF THE CALORIMETER

The long-term stability of the calorimeter was tested by making repeated measurements of the dose rate $\dot{D}_r\ (x_o, d_o, f_o)$ over a period of about 14 months. The measurements were made in sets of five and all results are shown in the upper graph of Figure 5.

The standard deviation for a single measurement in a set of five was calculated for each set; the mean for all sets was $\sigma = 0.35 \pm 0.06\%$. The theoretical standard deviation for the means is therefore $0.15 \pm 0.03\%$. This figure represents the short-term precision, since all the measurements in each set were generally made in one day, and the position of the calorimeter and beam settings remained undisturbed between measurements. In general however, the calorimeter was repositioned and the beam settings were re-adjusted between each set of measurements. If there were any errors introduced in this way, or if there were any long-term changes in the calorimeter instrumentation or source output, a larger standard deviation would be obtained when calculated, as though all measurements made over the 14 months' period belonged to the same normal distribution. In fact, the long-term experimental standard deviation for the means was $\pm 0.16\%$; this was not significantly different from the short-term value.

The mean value for $\dot{D}_r\ (x_o, d_o, f_o)$ for all measurements was 23.98 ± 0.02 mW kg^{-1} where the stated accuracy is at the 2 σ level and excludes systematic errors. Overall systematic errors for the calorimeter have been estimated by Urquhart *et al.* (1973) as 0.54 per cent (2 σ level), so the absolute dose rate value is:

$$\dot{D}_r\ (x_o, d_o, f_o) = 23.98 \pm 0.13 \text{ mW kg}^{-1} \quad \text{(on 6.11.1972)}^{*}$$

In contrast to the calorimeter, the Baldwin-Farmer thimble chamber shows quite large long-term changes. The short-term theoretical standard deviation for the mean of five measurements is 0.1 per cent (Figure 5, bottom graph), but the actual long-term standard deviation is six times greater. The slope of a linear least-squares fit is also much larger than for the calorimeter.

The instability in the thimble chamber was largely overcome by normalis-

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* *All measurements quoted in this report which involve source decay are normalised to this reference date, using a half life of 1922 days.*

ing all measurements to the mean value in a fixed 'beam monitor' position on the back of the calorimeter. Current measurements in this position were made concurrently with irradiations of the calorimeter. It is expected that this instability problem will be less with the new NPL secondary standard 'graphite-aluminium' chambers.

6. CONCLUSIONS

The aluminium calorimeter has been shown to have the precision and long-term stability required of a primary standard instrument. It has also been shown that small ionisation chambers can be calibrated to measure absorbed dose directly, rather than by the procedure of exposure calibration and exposure to dose conversion which is widely used at present. It can be expected that, as calorimeters become established as primary absorbed dose standards, the use of exposure as a practical radiation quantity is likely to disappear at photon energies above about 500 keV.

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TABLE 1

'DOSE IN ALUMINIUM' CALIBRATION FACTOR (N_r)

Depth (d_r) in Aluminium (cm)	$\frac{I_r\ (x_o, d_r, f_o)}{I_r\ (x_o, d_o, f_o)}$	$\frac{\dot{D}_r\ (x_o, d_r, f_o)}{\dot{D}_r\ (x_o, d_o, f_o)}$	N_r (J kg^{-1} C^{-1} 10^{-7})	B
2.76 (d_o)	1.0000	1.0000	4.353	1.39
3.24	0.9578	0.9551	4.341	1.44
3.73	0.9124	0.9128	4.355	1.48
4.68	0.8241	0.8208	4.336	1.56
5.69	0.7287	0.7302	4.362	1.63

Mean = 4.349 ± 0.01

$\bar{I}_r\ (x_o^*, d_o^*, f_o^*)$ = 550.91 ± 1.0 pA. $\bar{\dot{D}}_r\ (x_o, d_o, f_o)$ = 23.98 ± 0.02 mW kg^{-1}

(x_o = 57.0 cm, d_o = 2.76 cm in reference material, f_o = 7.5 cm*)

TABLE 2

'DOSE IN WATER' CALIBRATION FACTOR (N_w)

Depth (d_w) (cm)	Field (f) (cm)	$\frac{I_r(x_o, d_w, f)}{I_r(x_o, d_w, f_o)}$	$\dot{D}_r(x_o, d_w, f)$ (mW kg^{-1})	$\dot{D}_w(x_o, d_w, f)$ (mW kg^{-1})	$\frac{I_p(x_o, d_w, f)}{I_p(x_o, d_w, f_o)}$	N_w (J kg^{-1} C^{-1} x 10^{-7})
5	10x10	1.0389	24.74	28.73	1.0401	5.129
	15x15	1.0858	25.86	30.04	1.0910	5.113
	20x20	1.1107	26.45	30.72	1.1155	5.114
	25x25	1.1158	26.57	30.86	1.1203	5.115
7	10x10	1.0476	22.68	26.34	1.0491	5.157
	15x15	1.1083	23.99	27.86	1.1119	5.146
	20x20	1.1380	24.64	28.62	1.1442	5.137
	25x25	1.1452	24.79	28.79	1.1542	5.123

Mean = 5.129 ±0.02

$\bar{I}_r(x_o, d_5^*, f_o)$ = 547.6 ± 1.0 pA. $\bar{I}_p(x_o, d_5, f_o)$ = 538.5 ± 1.0 pA.

$\bar{I}_r(x_o, d_7^*, f_o)$ = 497.8 ± 1.0 pA. $\bar{I}_p(x_o, d_7, f_o)$ = 486.9 ± 1.0 pA.

Displacement Factor = 1.015 ± 0.005. μ_{ew}/μ_{er} = 1.1443 ± 0.002

$\bar{N}_r$ = 4.349 ± 0.01 J kg^{-1} C^{-1} x 10^{-7} (From Table 1)

(d_5 = 5 cm, d_7 = 7 cm in water*)

TABLE 3

MEASUREMENT OF G ($Fe^{++} \rightarrow Fe^{+++}$)

Depth (d_w) (cm)	Field (f) (cm)	I_p (x_o, d_w, f) (pA)	$\dot{D}_w$ (x_o, d_w, f) (mW kg^{-1})	$\dot{D}_{Fe}$ (x_o, d_w, f) (mW kg^{-1})	$\dot{O}_{Fe}$ (x_o, d_w, f) ($min^{-1} \times 10^3$)	G (100 eV^{-1})	B
5	7.5x7.5	538.5	27.62	27.51	5.828	15.35	1.23
	16x16	591.0	30.31	30.19	6.305	15.13	1.31
	25x25	603.1	30.93	30.81	6.472	15.12	1.36
7	10x10	510.8	26.20	26.10	5.422	15.05	1.32
	20x20	557.0	28.57	28.46	6.029	15.35	1.42

Mean = 15.20 ±0.13

Estimated total systematic error = ±0.23

Extinction coefficient (ε) = 2180 mol^{-1} (1-cm cell) at 304 nm.

Displacement factor = $0.9995 \cdot \mu_{eFe}/\mu_{ew}$ = 0.9966

Stem correction (k_s) = 1.0060 ± 0.002

$\overline{N}_w$ = 5.129 ± 0.02 J kg^{-1} C^{-1} x 10^{-7} (From Table 2)

[*The NPL - HPA calibration factor (i.e. NPL 2 MV exposure calibration x HPA C_γ factor) for the thimble chamber is 5.19 x 10^7 J kg^{-1} C^{-1}. The mean G-value using this calibration is 15.02 (100 eV^{-1}).*]

TABLE 4

COMPARISON OF RECENT DETERMINATIONS

OF $G(Fe^{++} \rightarrow Fe^{+++})$ FOR ^{60}Co RADIATION

(taken from Table 3.1 ICRU Report No. 14)

Reference	Method	Temp. (^{o}C)	$G(Fe^{++} \rightarrow Fe^{+++})$ (0.4 mol/H_2SO_4) (100 eV^{-1})
Day & Rasoul (1969)	Ionisation	24 ± 1	15.2 ± 0.3
AAEC (this report)	Calorimetry	22.7 ± 0.5	15.2 ± 0.3 *
Davies *et al.* (1963)	Ionisation	22 ± 2	15.4 ± 0.25
Keene & Law (1963)	Calorimetry	20 ± 1	15.42 ± 0.04
ICRU (1969)	Weighted mean	22.5 ± 2.5	15.5 ± 0.2
Pettersson (1967)	Calorimetry	25	15.57 ± 0.14
Shalek *et al.* (1962)	Ionisation	-	15.9 ± 0.4

** Included for comparison only*

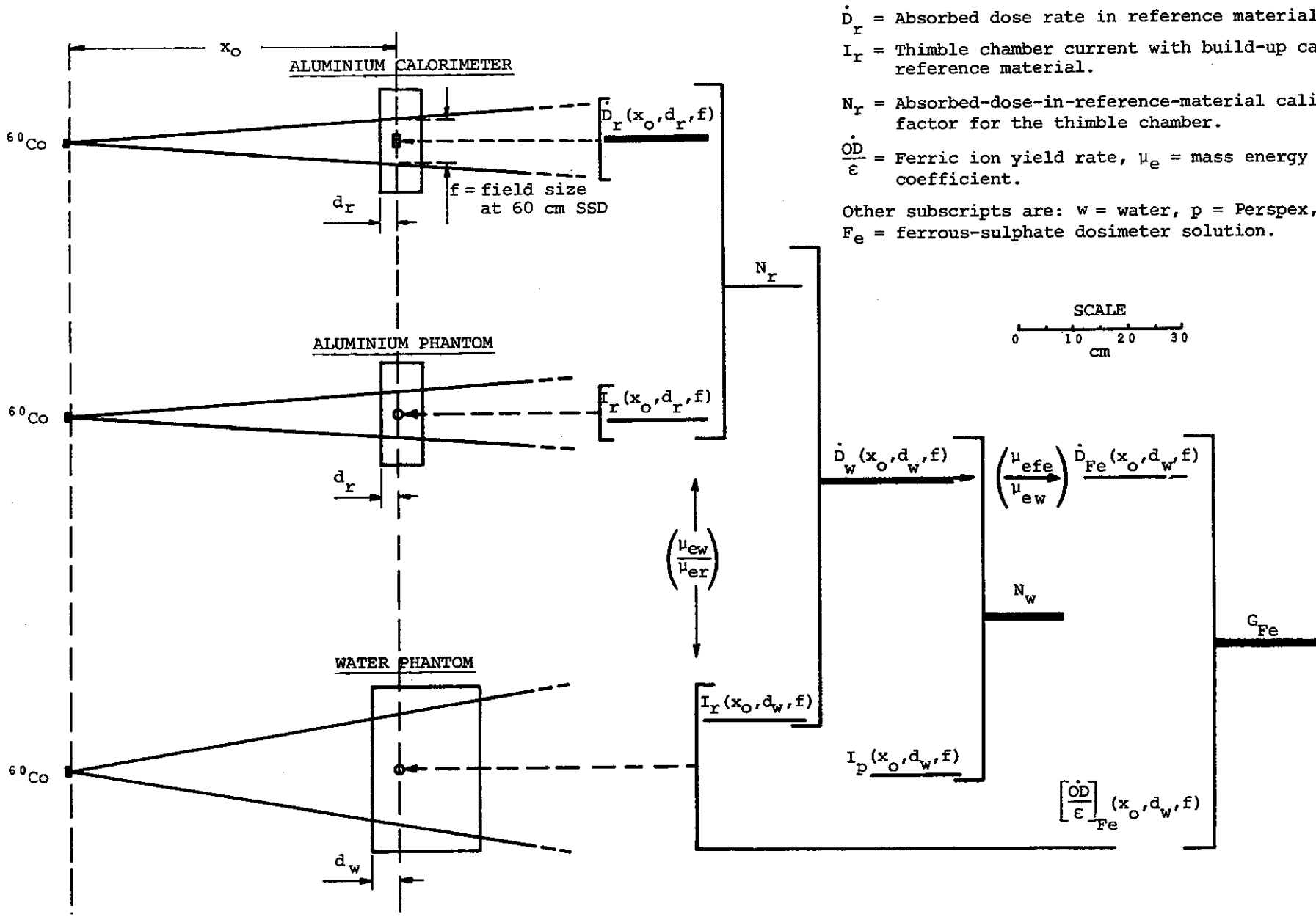

FIGURE 1. CALORIMETRIC CALIBRATION OF A THIMBLE ION CHAMBER AND A FERROUS SULPHATE DOSIMETER FOR ^{60}Co

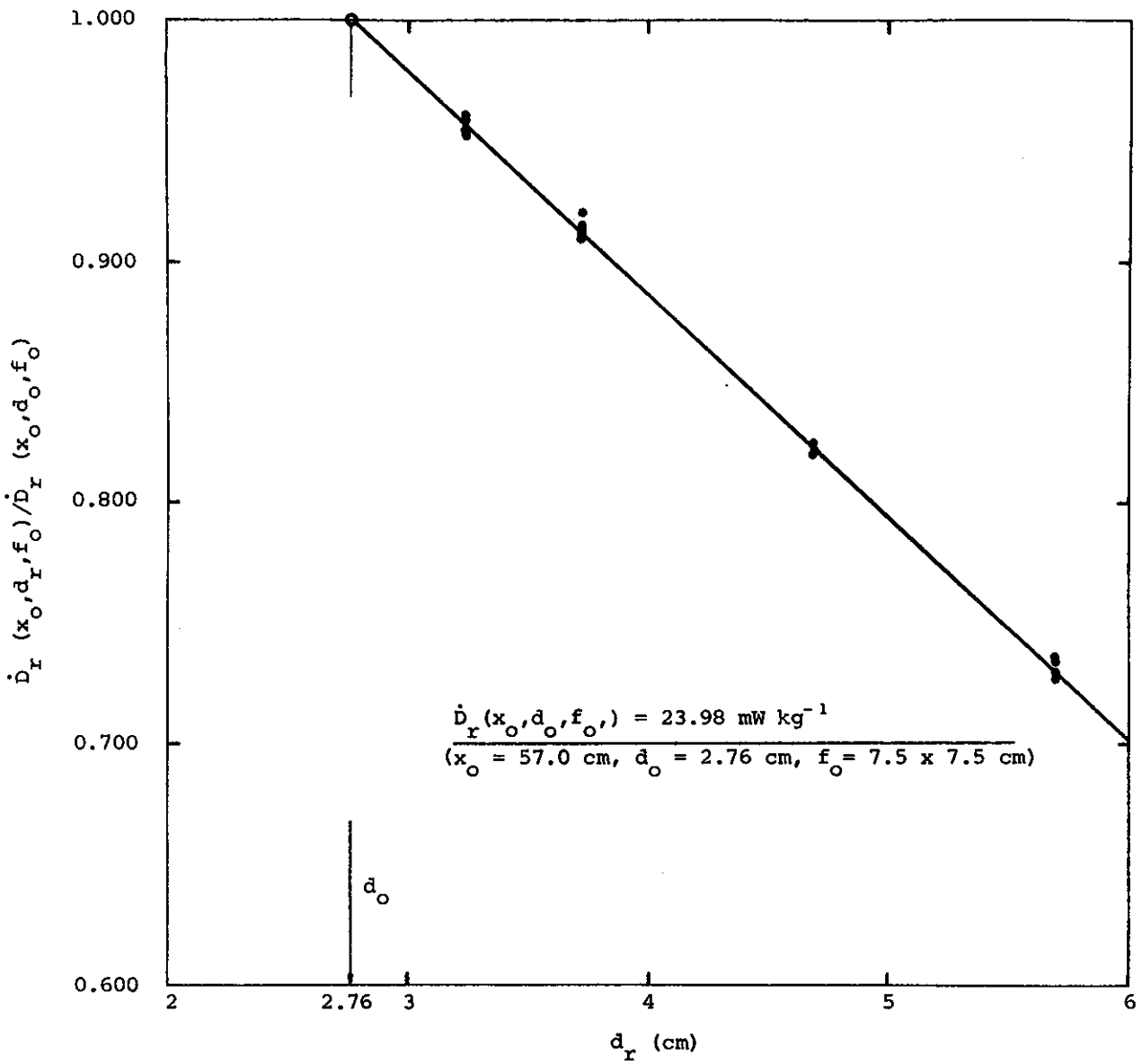

FIGURE 2. MEASURED DEPTH DOSE IN ALUMINIUM

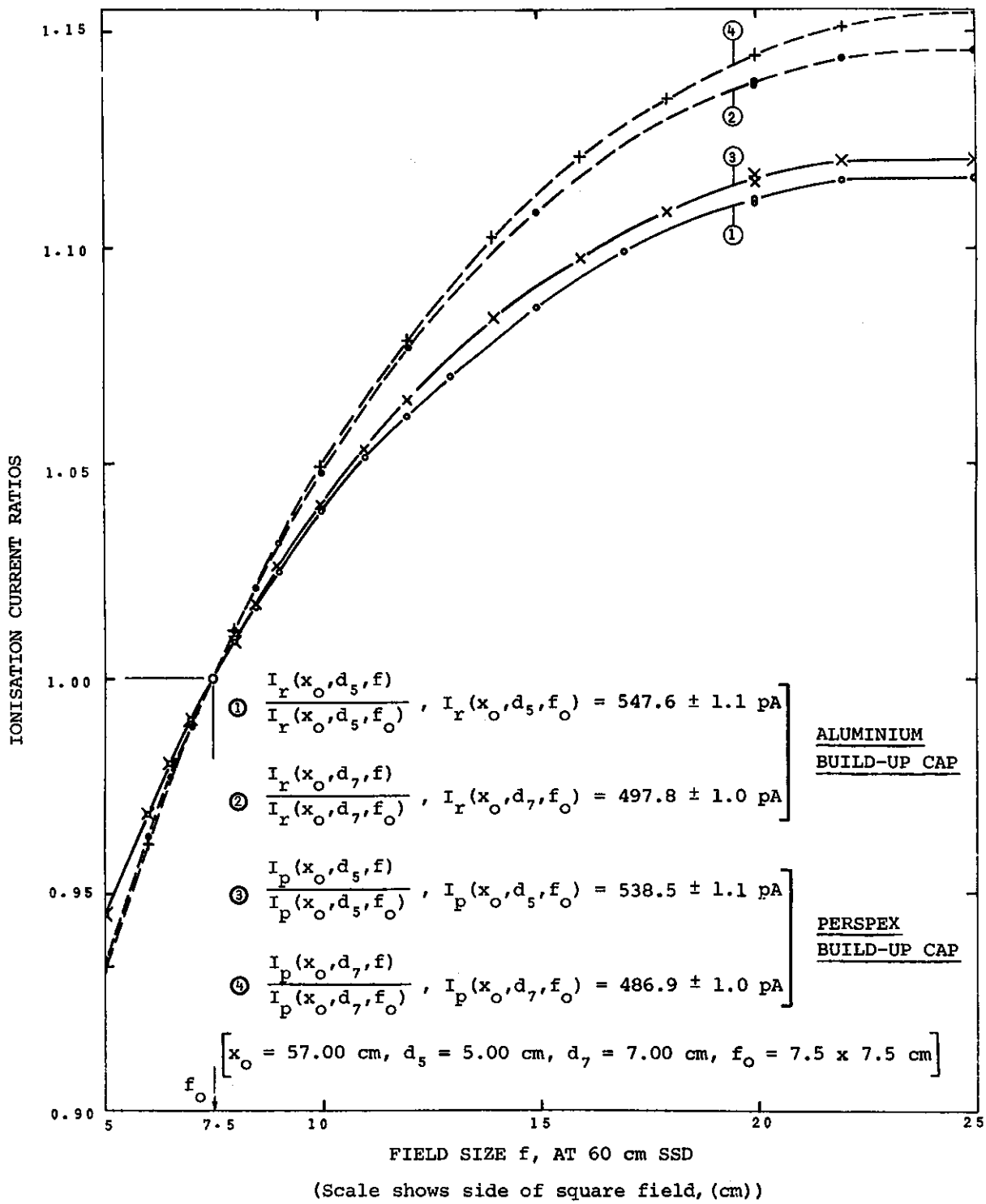

FIGURE 3. EFFECT OF FIELD SIZE ON IONISATION CURRENT IN A THIMBLE CHAMBER AT ^{60}Co ENERGY IN A WATER PHANTOM

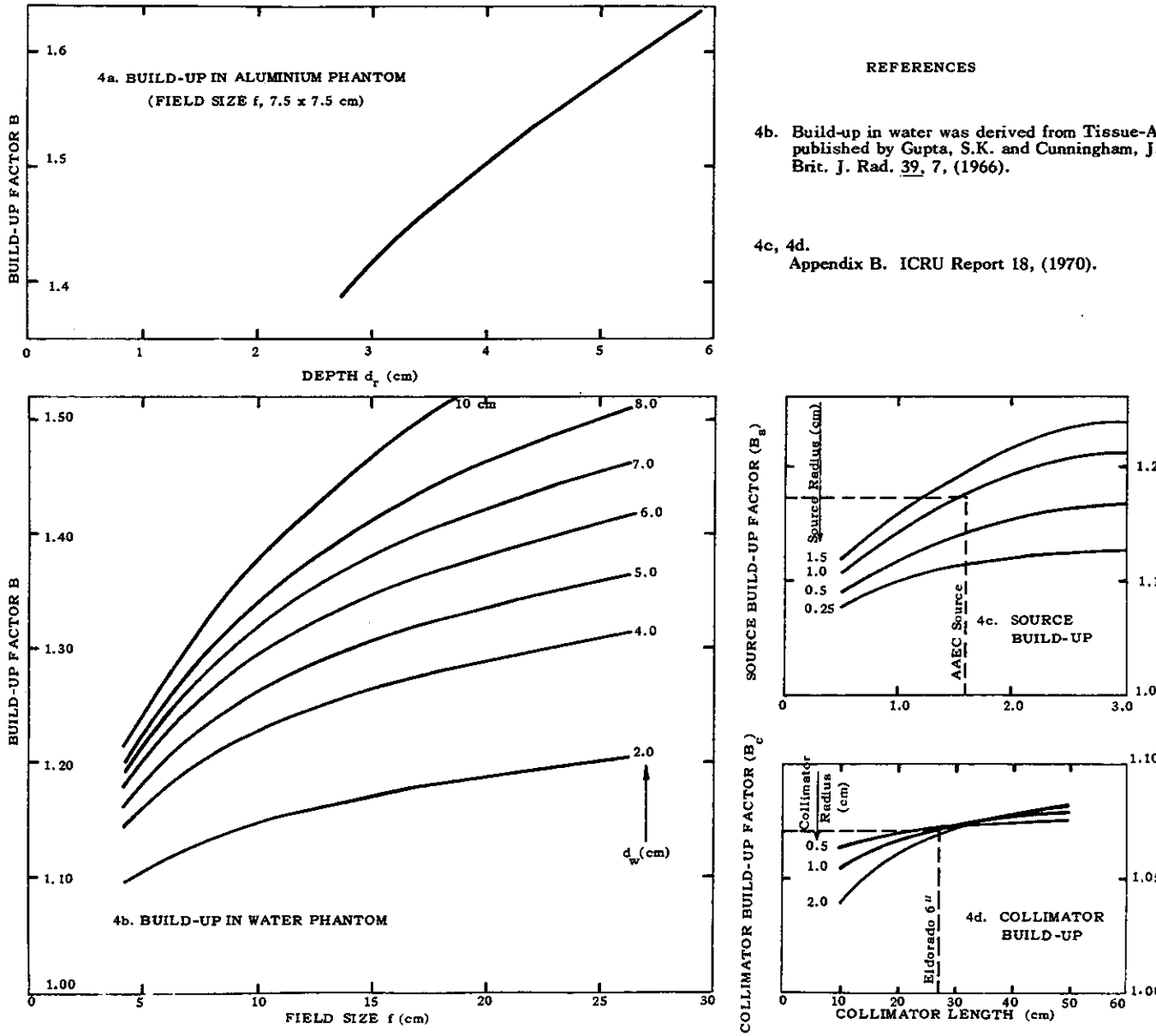

FIGURE 4. COMPARISON OF BUILD-UP FACTORS

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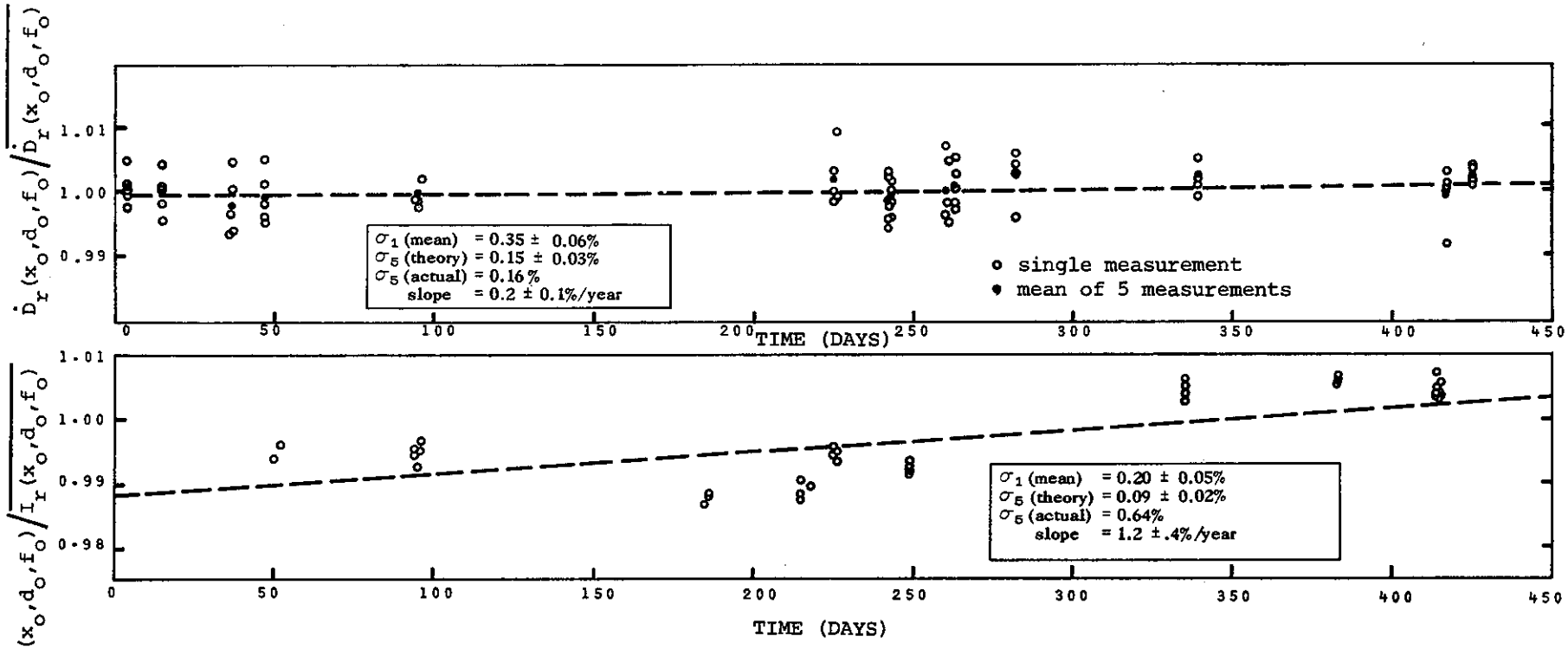
4c, 4d.
Appendix B. ICRU Report 18, (1970).



$\dot{D}_r(x_o,d_o,f_o)$ = dose rate in aluminium calorimeter.

$\overline{\dot{D}_r(x_o,d_o,f_o)}$ = mean of 55 measurements in 10 month period.
= 23.98 ± 0.02 mW. kg^{-1}.

$I_r(x_o,d_o,f_o)$ = thimble chamber current in aluminium phantom.

$\overline{I_r(x_o,d_o,f_o)}$ = current normalised to mean monitor current $\overline{I}_M$.
= 551.0 ± 1.0 pA. [*i.e.* $\overline{I}_M$ x 2.172 where
$\overline{I}_M$ = 253.7 ± 0.5 pA].

FIGURE 5. LONG TERM STABILITY OF CALORIMETER AND THIMBLE CHAMBER