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ANSTO

THE AUSTRALIAN COMMONWEALTH STANDARD OF MEASUREMENT FOR ABSORBED RADIATION DOSE

PART 2: ABSORBED DOSE STANDARD FOR GRAPHITE IRRADIATED BY A COBALT-60 TELETHERAPY UNIT

by

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AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION

LUCAS HEIGHTS RESEARCH LABORATORIES

The Australian Commonwealth Standard of Measurement for Absorbed Radiation Dose

Part 2: Absorbed Dose Standard for Graphite Irradiated by a Cobalt-60 Teletherapy Unit

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ABSTRACT

As an agent for the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Australian Nuclear Science and Technology Organisation (ANSTO), is responsible for maintenance of the Australian Commonwealth standard of measurement for absorbed radiation dose. This standard of measurement has an application in radiation therapy dosimetry, which is required for the radiation treatment of cancer patients.

This report is the second in a series documenting the absorbed dose standard for photon beams in the range from 1 to 25 MeV.

Measurements of absorbed dose in graphite irradiated by a beam of cobalt-60 gamma rays from an Atomic Energy of Canada Limited (AECL) El Dorado 6 teletherapy unit are reported. The measurements were performed using a graphite calorimeter, which is the primary standard for absorbed dose. The measurements are used to calibrate a working standard ion chamber in terms of absorbed dose in graphite.

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The following descriptions have been selected from the INIS Thesaurus to describe the subject content of this report for information retrieval purposes. For further details please refer to IAEA-INIS-12 (INIS: Manual for Indexing) and IAEA-INIS-13 (INIS: Thesaurus) published in Vienna by the International Atomic Energy Agency.

AUSTRALIA; CALIBRATION STANDARDS; CALORIMETRIC DOSEMETERS; COBALT 60; DATA COVARIANCES; GRAPHITE; IONIZATION CHAMBERS; RADIATION DOSES; RADIOTHERAPY

EDITORIAL NOTE

The Australian Nuclear Science and Technology Organisation replaced the Australian Atomic Energy Commission on 27 April 1987. Reports issued after April 1987 have the prefix ANSTO with no change of the symbol (E, M, S or C) or numbering sequence.

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1. INTRODUCTION

1.1 Previous Work

This report is a continuation of work performed by D.F. Urquhart [1978], which described the irradiation facility, primary standard, phantoms and working standard. Absent from this report were the calibration figures for the working standard ion chambers.

Unpublished work by Urquhart gave a calibration figure for cobalt-60 gamma rays of 8.86 mGy.division^{-1} in graphite for ion chamber NE2561, serial number 058, using secondary standard exposure meter NE2560, serial number 052. In this present work, performed a decade later, a calibration figure of 8.90 mGy.division^{-1} was obtained for the same instruments. Considering that totally different control systems were used in these two cases, this agreement is gratifying. The modern control system was described by Sherlock [1989].

1.2 Present Work

Reported here are cobalt-60 gamma ray measurements made with the Urquhart graphite microcalorimeter and Nuclear Enterprises system NE2560/ NE2561 secondary standard exposure meter. All measurements, both calorimetric and ionometric, were obtained using automated systems, employing a computer for data collection, storage and analysis.

For the first time, calibration figures for the secondary standard ion chamber are presented. Included are uncertainty estimates in the form suggested by Hohlfeld [1985].

The results given represent the Australian Commonwealth standard of measurement for absorbed radiation dose, at the reference time of 12:01 pm, the first day of November, 1989.

2. CALORIMETRY

2.1 Data Collection Procedure

The graphite microcalorimeter was placed centrally in the radiation beam from the AECL El Dorado 6 cobalt-60 teletherapy unit. The collimators fitted with penumbra trimmers were set to produce a square field of 73 x 73 mm^2 at 1000 mm, with a source-to-surface distance of 998.3 mm. The source-to-absorber distance was 1027.79 mm, which corresponds to a depth in graphite of 29.49 mm (Figure 1).

After vacuum pump-down to less than 1 x 10^{-4} torr, the calorimeter phantom, which is the massive outermost body of the calorimeter, was brought to operating temperature of 27.5°C using the computer program "STARTUP". At this point, the absorber and mantle bridge output voltages come on range for the millivolt inputs of the Keithley model 181 nanovoltmeters; then the data collection program "Co 60V1" is loaded and set running.

This latter program fully automates the calorimeter data collection process. The program stabilises temperature, initiates calibrations and radiation exposures, finally storing the data on disc. Operator intervention is required only when the data storage floppy disc is full. The disc has capacity for 9 pairs of electrical and radiation heating runs. In the present case, 27 runs were performed. The locations of these data are given in Appendix A1.

2.2 Data Analysis Procedure

Reduction of the data to absorbed dose rate was carried out using computer program "ABSORBED DOSE".

The analysis was carried out in a conventional manner, similar to that given by Laughlin and Genna [1966]. Straight lines were least-squares fitted to heating and drift periods and a drift correction factor determined. Electrical power dissipated in the absorber during the calibration runs was computed. The absorbed dose rate was then determined by comparing the electrical and radiation heating rates, which were similar.

Details of the results and correction factors applied are given in Appendix A2.

3. IONOMETRY

3.1 Data Collection Procedure

The absorbed dose working standard is composed of a Nuclear Enterprises graphite ion chamber, model NE2561, serial number 058, and Nuclear Enterprises secondary standard exposure meter, model NE2560, serial number 052.

This working standard is calibrated in terms of absorbed dose per volt output by irradiating the ion chamber in a dummy graphite phantom. The dummy phantom closely resembles the calorimeter, with the centre of the ion chamber residing at the equivalent point to the centre of the calorimeter absorber. In this manner, the ion chamber is exposed to a similar photon and electron energy fluence as the absorber.

The dummy is placed in the same field as the calorimeter, at 1000 mm source-to-surface distance, when the centre of the ion chamber is at a depth of 28.09 mm in graphite (Figure 1(c)).

The NE2560 electrometer is interfaced to an HP86B computer (Hurry [1988], Sherlock [1988]). Computer program "STD 2560 D89" provides for a series of exposures of the ion chamber, under two sets of conditions. The exposures involve moving the radiation source to the exposed position and then back to the stored position.

Very short exposures, circa 20 seconds, and exposures of identical duration (400 seconds) to the calorimeter exposures are performed. These data allow both the ion chamber response and source transit time to be determined. Program "ION RESPONSE" extracts these parameters from the data, determining the mean response in units of volts per second. Further details are given in Appendices A1 and A3.

3.2. Data Analysis Procedure

Program "ION RESPONSE" extracts the ion chamber response and source transit time from the data of Section 3.1. The ion chamber response is determined in units of volts per second. Further details are given in Appendices A1 and A3.

4. STANDARDISATION OF ION CHAMBER

As set out in Appendix A2, the mean absorbed dose rate in graphite at the reference time of 12:01 pm, the first of November, 1989, was determined to be 9.980 $mGy.s^{-1}$ ± 0.25%.

From Appendix A3, the mean ion chamber response in graphite, determined under identical conditions, was 0.0011213 $V.s^{-1}$ ± 0.10%. The range setting on the NE2560 was x10.

The absorbed dose calibration in graphite N_c of ion chamber serial number 058, at the reference depth of 5.000 $g.cm^{-2}$ and field area of 75x75 mm^2, was then given by

$$N_c = 9.980/0.0011213$$
$$= 0.890 \times 10^4 \text{ mGy.V}^{-1} \pm 0.3\%$$

This value of N_c is the standard of measurement for absorbed dose in graphite. The stability of the ion chamber and its electrometer was evaluated using a strontium-90 check source model NE2562, serial number 054. Measurements made on 4-10-89 and 4-12-89 were within 0.1% of the reference value, which was determined in March 1987, at the Australian Radiation Laboratory [Huntley, 1987].

5. TABULATION OF UNCERTAINTIES

In 1985, Dr Klaus Hohlfeld of PTB carried out a survey among members of Comité Consultatif pour les Etalons de Mesure des Rayonnements Ionisants (CCEMRI) Section 1 on the subject of uncertainty estimates for National Standards of Graphite Absorbed Dose Rate by Calorimetry. The survey document included guidelines on uncertainty estimation [BIPM, 1980] and a table of uncertainties. The material included in that survey has been adopted in this report.

The following guidelines are extracted from the survey document:

- "The measured absorbed dose rate $\dot{D}_c^{\circ}$ in graphite at the reference point under reference conditions is given by the expression

$$\dot{D}_c^{\circ} = \frac{P_{el}}{m} \cdot \frac{\alpha_{rad}}{\Delta t_{rad}} \cdot \frac{\Delta t_{el}}{\alpha_{el}} \cdot \prod_{i=1}^{n} K_i$$

where P_{el} is the electrical power during the calibration, m the mass of the absorber/core, α_{rad} and α_{el} are signals proportional to the energies absorbed in the absorber/core during the irradiation time Δt_{rad} and the calibration time Δt_{el} respectively."

- "In the expression given above $\prod_{i=1}^{n} K_i$ is the product of correction factors. An attempt is made to take into account all influences which may contribute to the uncertainty of the measured absorbed dose rate by correction factors."

- "Uncertainties obtained as objective estimates, i.e., obtained from replicate readings by statistical methods, should be listed as Type A, and should preferably be given as one standard deviation along with the number of degrees of freedom."

- "Uncertainties obtained as subjective estimates, i.e., by any other method than statistical, should be listed as Type B, with a brief statement on how the estimate was obtained."

- "Type B uncertainties should be estimated to be like one standard deviation; i.e., they should represent an uncertainty interval that can be treated subsequently as if it were a standard deviation."

- "In some cases it may be appropriate to list the uncertainties for a factor as partly Type A and partly Type B."

- "For both Types A and B, it is seldom justified to use more than one significant figure in expressing the uncertainty estimate, except for numbers between 1 and 2, when two significant figures may be used."

These guidelines have been adopted in the preparation of Table 1. A similar table, applying to the ionometric measurements, is given as Table 2. The combined uncertainty in estimating N_c, the ion chamber absorbed dose calibration in graphite, is given in Table 3.

The result from Table 1, for the uncertainty in calorimetric measurement of graphite absorbed dose, may be compared with that of othe laboratories.

LABORATORY	[+] COMBINED UNCERTAINTY %
ANSTO (Australia)	0.25
National Bureau of Standards (USA, 1985) (NBS)	0.23
Physikalisch-Technische Bundesanstalt (FDR, 1985) (PTB)	0.34
Laboratoire de Métrologie des Rayonnements Ionisants (France, 1985) (LMRI)	0.25
Országos Mérésügi Hivatal (Hungary, 1985) (OMH)	0.25
[+] CCEMRI (I)/85-22	

6. CONCLUSION

The Australian Commonwealth Standard for Absorbed Dose in Graphite for cobalt-60 γ-rays has been established. The standard is maintained as a calibration factor for an ion chamber, in units of $mGy.V^{-1}$, and is denoted by N_c.

The value determined for N_c is 0.890×10^4.

In addition, the uncertainties, both Type A and Type B have been evaluated.

The uncertainty in N_c is 0.3%.

This result compares favourably with a previous unpublished determination by D.F. Urquhart, which gave a value for N_c of 0.886×10^4. Some of the difference is attributable to additional correction factors applied in this report.

7. ACKNOWLEDGEMENTS

This program of measurement has been generously supported by Professor A.O. Langlands and Mr J.F. Drew, of Westmead Hospital, Sydney, and Dr A.J. Leslie, of the Australian Institute of Health.

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APPENDIX A1: COMPUTER RECORDS

A1.1 COMPUTER DATA-COLLECTION PROGRAMS

- "Co 60V1", disc # D600. This program controls and operates the calorimeter. Radiation and calibration runs are performed under full computer control, the results being stored on disc for later analysis.

- "STD2560D89", disc # D600. This program controls and operates the NE2560/NE2561 ion chamber system. The data collected includes long and short exposures, so that both ion chamber response and source transit time may be determined.

A1.2 COMPUTER DATA-ANALYSIS PROGRAMS

- "ABSORBED DOSE", disc # D600. This program loads the calorimeter data produced by "Co 60V1", then converts the raw data to absorbed dose rate. All corrections except decay are included in the analysis. Decay is corrected in "STANDARD 89".

- "STANDARD 89", disc # D600. This program takes the absorbed dose values determined by program "ABSORBED DOSE" and converts them to the reference time of 12:01 pm on 1st November 1989.

- "ION RESPONSE", disc # D600. This program loads the data generated by program "STD 2560 D89" and determines the mean ion chamber response and source transit time correction.

A1.3 COMPUTER DATA STORAGE

- Only raw data are stored. In this way no processing errors are introduced to the archive data.

- The format for retrieving the data is given in the analysis programs. These programs are the subject of a separate technical note.

- The ionisation chamber data are stored on disc # D600 and backed-up on disc # D701.

- The calorimeter data are stored on disc numbers D700, D2011, D2150 with corresponding back-up discs D702, D2015 and D2160.

- The program disc # D600 is backed-up on disc # D701.

APPENDIX A2: ABSORBED DOSE IN GRAPHITE

A2.1 INTRODUCTION

Absolute absorbed dose in graphite was determined for cobalt-60 gamma radiation using the Urquhart graphite microcalorimeter (Urquhart, 1978; Sherlock, 1989). Details of the determination are presented in this Appendix.

A2.2 CALORIMETER SET-UP

The calorimeter was placed centrally in the gamma beam of the El Dorado 6 cobalt-60 teletherapy unit. The square field area set at the depth of the absorber was 75x75 mm^2. The source-to-surface distance, measured to absorbing plate 4c (Figure 1), was set to 998.3 mm. The source-to-centre of absorber distance was 1027.79 mm, with a corresponding depth, including vacuum gaps, for the absorber, of 29.49 mm.

A2.3 CORRECTION FACTORS

A total of 8 correction factors are applied when converting the absorber temperature rises, arising from both radiation and electrical heating, to absorbed dose. These correction factors are detailed here.

A2.3.1 Source Decay k_t

Since the series of 27 experimental runs was spread over a period of some 10 days, a different decay correction for each must be applied. The elapsed time t (hours) between absorbed dose D_{ref} at the reference time of 12:01 pm, the first of November, 1989, and the commencement of each run, was computed using program "STANDARD 89". Then the absorbed dose at the time of the run, D_{run}, was corrected using

$$D_{ref} = D_{run} \exp (.0000150008\ t)$$

which applies for an exact cobalt-60 half-life of 1925.3 days (Nuclear Data Sheets, 1986).

A2.3.2 Source-to-Surface Distance Correction k_z

The reference distance z_o from the source-to-centre of absorber is 1027.8 mm. The choice of 998.3 mm as source-to-surface distance, for an absorber depth of 29.49 mm, then makes the correction factor k_z unity.

[Reference: Urquhart, 1978; AAEC/E455, p11].

A2.3.3 Depth Correction k_d

The reference depth d_o in graphite is 5.000 $g.cm^{-2}$. However, the actual depth of the absorber is 4.9655 $g.cm^{-2}$. This requires a correction k_d of 0.9985.

[Reference: Urquhart, 1978; AAEC/E455, p10].

APPENDIX A2 (Cont)

A2.3.4 Calibration Correction k_c

The power delivered to the absorber during electrical calibration runs is determined in part by measuring the voltage drop across the absorber heater. This voltage measurement includes the leads from the heater to the calibrator, so that a correction k_c is required for power loss in the leads. The value of k_c was determined to be 0.9951.

[Reference: Urquhart, 1978; AAEC/E455, p11].

A2.3.5 Impurity Correction k_i

Impurities in the calorimeter include the thermistor, heater wires and epoxy resin. These impurities affect both the energy absorption coefficients and photon fluence at the absorber. The value of the correction k_i required is 0.9981.

[Reference: Urquhart, 1978; AAEC/E455, p9].

A2.3.6 Axial Dose Gradient Correction k_a

The finite thickness (3 mm) of the absorber introduces a non-linear dose gradient in the absorber. Since the calorimeter measures absorbed dose integrated over the volume of the absorber, a correction k_a is required to yield the absorbed dose at a central point.

With the radial dose gradient assumed to be small, a correction factor k_a of 1.00095 was determined.

[Reference: Urquhart, 1978; AAEC/E455, p9].

A2.3.7 Radial Dose Gradient Correction k_g

There exists a dose gradient across the width (20 mm) of the absorber. This gradient was investigated by moving an ion chamber type 2561 across the beam, with the ion chamber housed in the calorimeter dummy. With no correction for spatial resolution, a dose gradient from centre to absorber edge of 0.25% was observed.

Assuming minimal effect of the axial dose gradient, a radial dose gradient correction factor k_g may be defined as the quotient of absorbed dose at a point in the absorber centre to the absorbed dose integrated over the absorber volume. The factor determined k_g was 1.0012.

APPENDIX A2 (Cont)

A2.3.8 Entrance Foil Attenuation Correction k_m

Mylar entrance foils of total thickness 0.112 mm are required to support the vacuum enclosure. Assuming water equivalence of mylar (polyester), the reduction in photon fluence at the absorber may be approximated using the linear attenuation coefficient of 0.063 cm^{-1}. The correction factor k_m is then 1.0007.

[Reference: British Journal of Radiology, Supplement Number 11, 1972, p53].

A2.4 TABULATION OF RESULTS

With the set-up and correction factors in place, the absorbed dose rate at the reference time and date was determined. The results are summarised in Table 4.

Included in the table is a figure for drift. A drift correction factor may be defined by the quotient of absorbed dose computed with drift correction and absorbed dose computed with no drift correction. Tabulated is the percentage difference between the numerator and denominator of this quotient.

The presence of a drift may indicate departure from quasi-adiabatic operation, so that drifts must be minimised. If the drifts result from a random process, then the expectation value of the arithmetric mean is zero and the degree of control over drifts is indicated by the root mean square value. These values are 0.14% and 0.29% respectively.

A2.5 TYPICAL EXPERIMENTAL OBSERVATIONS

Illustrative plots of the raw data are given in Figures 2 to 6.

A2.6 TRACEABILITY TO PRIMARY STANDARDS

Other than for ionising radiation, the Australian primary standards of measurement are maintained by the Division of Applied Physics, formerly the National Measurement Laboratory of CSIRO. The primary absorbed dose standard is maintained by ANSTO at the Lucas Heights Research Laboratories.

The primary absorbed dose standard, the Urquhart graphite micro-calorimeter, is an absolute standard. The requirement for an absolute standard is that the measure must depend only on other primary absolute standards for determination of the unit. In this case, the units are the volt, ohm and second.

APPENDIX A2 (Cont)

In Australia, absolute primary standards are maintained for the volt and ohm. The determination of the volt depends on the Josephson effect, and the ohm on the quantum Hall effect. Since 1st January 1990, the value of the Josephson constant K_{J-90} has been taken as 483597.9 GHz/V and the von Klitzing constant R_{K-90} as 25812.807 Ω. The calibrations applied in this report are traceable to these values via CSIRO.

The secondary standards maintained at ANSTO are given in Table 2. The second was maintained as a tertiary standard, via the Telecom phone pips.

A2.7 DISCUSSION

In this appendix, considerations leading to a determination of the absorbed dose rate in graphite have been described. Included are geometrical configurations, correction factors and traceability to primary standards.

Not included are the effects of thermistor self-heating and vacuum gaps. In the case of thermistor self-heating, it is assumed that the effect is the same for both radiation and calibration heating, so that the effect cancels out. However, the degree of self-heating is large, so that secondary effects may remain important. Certainly, there are small anomalies present at the start and finish of radiation heating which require further investigations.

Other laboratories have examined the effects of vacuum gaps and obtained corrections as large as 0.2%, depending on the gap size. These estimates are not yet considered sufficiently reliable for adoption by this laboratory.

Also of concern is the departure from quasi-adiabatic operation indicated by the presence of temperature drifts. The error may be expected to be small, yet should still be quantified further. Both this systematic effect and thermistor self-heating will be considered in a further report, with estimates based on a calorimeter simulation computer program.

The Type A uncertainty (statistical) was of order of 0.2%, based on 27 sets of observations. Improvement in this uncertainty is difficult. Most of the noise present in the system is endemic, being Johnson noise generated in the resistors of the Wheatstone bridge.

With the preceding limitations in mind, it is considered that the absorbed dose standard for cobalt-60 gamma rays in graphite is confirmed. The earlier, unpublished figure, determined by Urquhart, is consistent with the present determination.

APPENDIX A3: ION CHAMBER RESPONSE IN GRAPHITE

A3.1 INTRODUCTION

The quantity maintained as the absorbed dose primary standard is in effect an absorbed dose rate in graphite for the El Dorado cobalt-60 teletherapy unit. This figure, while of inherent interest, is of limited application.

Of considerable interest is the absorbed dose in water, as water resembles human soft tissue in its energy absorption characteristics. Conversion from absorbed dose in graphite to absorbed dose in water is possible by application of theory, using a dose transfer instrument.

The device of choice for the dose transfer is an ionisation chamber. By calibrating this device in terms of response to absorbed dose in graphite, it is possible not only to determine absorbed dose in graphite readily but also to determine absorbed dose in other materials, of which water is most useful. Accordingly, Urquhart [1978] constructed a dummy calorimeter phantom for this purpose.

The dummy is a graphite phantom made to the same dimensions as the calorimeter phantom and housed in an aluminium structure which simulates the calorimeter vacuum chamber.

This phantom has been designed to accommodate ionisation chambers, chemical dosimeters and solid state dosimeters, so that they can be irradiated under the same conditions as the calorimeter absorber. These dosimeters can therefore be calibrated, in terms of absorbed dose in carbon, by direct comparison with the primary standard.

The ion chamber is a Nuclear Enterprises model 2561 0.3 cc graphite thimble, serial number 058, connected to a Nuclear Enterprises secondary standard exposure meter model 2560, serial number 052. Calibration of this instrument comprises the secondary or working standard of absorbed dose in graphite.

A3.2 CALORIMETER DUMMY SET-UP

The dummy was placed centrally in the gamma beam of the El Dorado 6 cobalt-60 teletherapy unit. The square field size set at the depth of the ion chamber axis was 75 x 75 mm^2. The source-to-surface distance, measured to absorber plate 5b (Figure 1(c)), was 1000 mm. The source-to-centre of ion chamber distance was 1028.09 mm, giving a depth in graphite of 28.09 mm.

APPENDIX A3 (Cont)

A3.3 CORRECTION FACTORS

Eight correction factors are applied when determining the ion chamber response. These correction factors are detailed as follows:

A3.3.1 Source Decay

As for A1.3.1. Correction to the reference time and date is performed by program "ION RESPONSE".

A3.3.2 Temperature/Pressure Correction $P_{t,p}$

For a barometer calibrated in mm Hg, the correction formula used was

$$P_{t,p} = \frac{760}{p} \frac{(273.15 + T)}{293.15}$$

The reference conditions are 101.325 kPa (760 mm Hg) and 20°C.

A3.3.3 Humidity Correction k_h

This correction was taken from Figure 1 of the Instruction Manual for the NE2560 secondary standard exposure meter. The reference humidity is 50% RH.

A3.3.4 Distance Correction k_z

The reference distance z_o from the source to the centre of the ion chamber is 1027.8 mm. However, the actual distance is 1028.09 mm, requiring a correction k_z of 1.00055.

A3.3.5 Depth Correction k_d

The reference depth in graphite d_o is 5.000 g cm^{-2}. However, the actual depth in the dummy is 5.056 g.cm^{-2}, requiring a depth correction k_d of 1.00181.

A3.3.6 Impurity Correction

There are no added impurities in the dummy. Since the calorimeter and dummy are constructed from the same block of electro-graphite EY927, this correction is unity.

A3.3.7 Gradient Correction

The air cavity of the ionisation chamber thimble displaces graphite. This perturbation means that the chamber response is a function of both radial and axial dose gradients in the dummy. Implied is the need for a correction factor if the chamber response is required in any other than the dose gradients existing at the reference point.

APPENDIX A3 (Cont)

At any other position, the photon energy fluence may also be different, requiring a further correction due to energy dependence of the chamber response.

The requirement for these corrections lies outside the scope of this report. Accordingly, a very narrow interpretation of the chamber response is taken here, i.e. the chamber response is valid ONLY at the reference point. With this restriction, it follows that the chamber response may be interpreted as the chamber calibration in solid graphite. The correction factor is then unity.

A3.3.8 Recombination Correction Factor p_s

The correction for recombination has two components; the "initial recombination" and the "general recombination". Burns and Rosser [1990] explain these features as:

"Initial recombination occurs when positive and negative ions formed in the same secondary-electron path meet and recombine. It is independent of dose rate, ...

General recombination occurs when ions produced in different tracks encounter each other as they are attracted to the two electrodes. The amount of recombination depends on the ion density and therefore on the dose rate, ..."

The correction p_s applied to the ion chamber readings includes only the general recombination. Estimates of p_s were determined by experiment and from the work of Burns and Rosser; the values obtained were 1.0006 ± 0.0002 and 1.00004 respectively. In view of the small size of this correction and the apparent conflict of value, unity was assigned to p_s. Note that the dose rate from the cobalt-60 source was of order 0.01 $Gy.s^{-1}$.

The initial recombination correction, given by Burns and Rosser as 1.0014, was not included in p_s. This means that the polarising voltage on the working standard ion chamber must always be -200V. Thus the calibration of the ion chamber has not been corrected to zero ion recombination.

This usage provides for consistency with the philosophy of the IAEA (1987) protocol for conversion of air kerma to absorbed dose in water. The IAEA protocol determines p_s using the two-voltage method. At zero dose rate, this method yields a value of unity for p_s, i.e. initial recombination is not taken into account.

APPENDIX A3 (Cont)

A3.4 RESULTS

Ion chamber data collected by program "STD 2560 D89" were analysed by program "ION RESPONSE". The set of 60 replicate observations using NE2560/052 and NE2561/058 gave the following results:

- The mean chamber response in the graphite dummy was 0.0011213 $V.s^{-1}$ for a 400 second exposure, including source transit time. The range setting on the NE2560 was x10.

- Standard deviation of the mean chamber response was 0.0000004 $V.s^{-1}$.

- The mean source transit time correction was 3.21 s.

- The standard deviation of the mean source transit time was 0.05 s.

- The mean exposure time as given by the computer clock was 400.065 s with standard deviation of the mean 0.000 s.

A3.5 TRACEABILITY TO PRIMARY STANDARDS

For discussion, refer to Appendix A2, section A2.6.

The secondary standards maintained at ANSTO are given in Tables 5 and 6.

A3.6 DISCUSSION

In this appendix, the considerations leading to a determination of the ion chamber response to cobalt-60 gamma rays in graphite have been described.

The ion chamber system used has been subject to long term stability tests over the last 12 years and has not changed in that time.

The response determined includes the movement of the source during the integrating period. This is the same condition as exposure of the calorimeter, so the results may be compared directly. Since the dose-rate quoted for the calorimeter includes the source transit, it is only valid for a 400 s exposure.

APPENDIX A4: NOTES ON TABLES OF UNCERTAINTIES

A4.1 TABLE 1 - CALORIMETRIC UNCERTAINTIES

The following notes give the origin of the uncertainties quoted in Table 1.

A4.1.1 Note 1: P_α

The electrical calibration P_α is determined as

$$P_\alpha = V_s V_a / R_s$$

where V_a is the voltage drop across the absorber heater and V_s is the voltage drop across the standardised resistor R_s in the calibrator.

Voltage is measured using a Hewlett Packard 3457A digital multimeter as a secondary standard. The DC ranges of the HP3457A have been calibrated at the CSIRO National Measurement Laboratory (Table 5).

Each voltage reading is taken on auto-range with the automatic zero feature of the HP3457A enabled. Since the readings are of order 115 mV, the readings are taken on the 300 mV range. The calibration correction required for the 115 mV reading is $-0.6\ \mu V \pm 0.2\ \mu V$. Since the January 1990 change in the SI volt occurred after calibration of the DMM, a further correction of 8.1 μV per volt is required. Thus a reading of 0.115 V becomes (.115 − .0000006)/1.0000081 V.

The uncertainty in the calibration is given by CSIRO as 1 μV, compared to the Australian maintained standard of electromotive force. Additional uncertainties arise when the voltage source is connected to the DMM input, mainly as a result of thermal effects; these have been minimised (Sherlock [1989]).

However, the additional uncertainties in V_s and V_a remain to be evaluated. Data for these voltages were available in two forms. Multiple readings were available within each calibration run, and 27 runs have been performed.

Thus both a within classes and between classes variation could be assessed. The within classes standard deviation of the mean was of order 3 μV, while for between classes the figure was of order 4 μV, for both V_s and V_a.

APPENDIX A4 (Cont)

Accordingly, a conservative estimate of the uncertainty in determining V_s and V_a is 10 μV.

Uncertainty in the value of the resistor R_s is also small. With a test current of 3 mA, in June 1986, the four terminal resistance of R_s was determined by CSIRO to be 770.058 Ω at 20.0°C. Since the resistor was neither mounted correctly nor provided with a serial number, it could not be treated as a secondary standard, no calibration certificate being issued. Being manganin wound, this Leeds and Northrup resistor has a temperature coefficient less than 5 ppm.C^{-1}. Further, by means of a ballast circuit, the current of order 0.15 mA flowing in the resistor is kept constant, so that no temperature variations occur during a calibration run.

The uncertainty of resistance calibration is ± 100 ppm for a standard 1 kΩ resistor calibrated by CSIRO. An estimate of the uncertainty in R_s of ± 100 ppm is considered appropriate, as the 770 Ω resistor was measured under identical conditions to the 1 kΩ standard. The Type B uncertainty is then given by

$$\text{Type B } \left(\frac{V_s V_a}{R_s}\right) = \left[\left(\frac{10}{114000}\right)^2 + \left(\frac{10}{115000}\right)^2 + \left(\frac{100}{1000000}\right)^2\right]^{\frac{1}{2}} \times 100$$

$$= 0.015\%$$

A4.1.2 Note 2: m

The mass m of the absorber/core was determined by Urquhart [1978] to be 1694.04 mg. This and other measurements imply a weighing accuracy of 0.01 mg. Assuming this to be optimistic, an accuracy of 0.05 mg was considered to be conservative. Then

$$\text{Type B (m)} = 0.05 \times 100/1694.04$$

$$= 0.003\%.$$

A4.1.3 Note 3: α_{rad}

Twenty seven radiation and electrical heating runs were available for estimating Type A uncertainties in α_{rad} and α_{el}. Type A uncertainty is defined as an objective estimate of uncertainty obtained from replicate readings.

APPENDIX A4 (Cont)

In each case, the temperature rise had been corrected for temperature drift and time of exposure before computing the statistical uncertainty. The standard deviation of the mean for α_{rad} was

Type A (α_{rad}; 26) = 0.19%

A4.1.4 Note 4: α_{el}

As per α_{rad}.

Type A (α_{el}; 26) = 0.12%.

A4.1.5 Note 5: Δt_{rad}

The quantity Δt_{rad} is the irradiation time, which has two components of variance. Firstly, the exposure time was determined by a computer clock with a resolution of 1 ms.

This clock was checked against the Telecom time signals over a period of 61140 seconds and was within 0.001% of those signals. This source of variability is negligible.

Secondly, the source transit time varies slightly from exposure to exposure. Thus, although the computer clock gave time-accurate commands to turn the beam on and off, the actual physical transit of the source was variable.

This variability was determined using a set of 60 exposures, which gave a standard deviation of the mean, on 59 d.f., of 0.017%. In order to make this figure compatible with the degrees of freedom for α_{rad} and α_{el}, the Type A error was adjusted to an equivalent 26 d.f. when

Type A (Δt_{rad}; 26) = 0.03%

A4.1.6 Note 6: Δt_{el}

The calibration time period Δt_{el} was under the control of a 1 ms resolution computer clock. At the start of calibration a relay is required to make, which takes 2 ms, and, at the end of a 400 second period, break, which takes 0.2 ms. The resulting variability is negligible in a 400 second heating interval.

APPENDIX A4 (Cont)

A4.1.7 Note 7: K_1

The uncertainty in impurity correction is given by Urquhart [1978] as

Type B (k_i) = 0.05%

A4.1.8 Note 8: K_2

The heat loss (temperature gradients) correction K_2 nominated by Hohlfeld is taken to refer to temperature drift correction. The percentage correction due to drift is given in Table 4 of Appendix 2 for each of 27 runs.

The drift uncertainties were determined by comparing the absorbed dose figure obtained for each run both with and without drift correction. The spread of the corrections was then computed by statistical means to obtain

Type A (K_2; 26) = 0.05%

Note that this uncertainty is a component of the uncertainty in α_{rad} and α_{el}, and should not be included in the quadratic sum of Type A errors.

A4.1.9 Note 9: K_3

The heat defect in graphite for cobalt-60 gamma rays was taken to be negligible [Huntley, 1986].

A4.1.10 Note 10: K_4

The electrical power loss in the leads to the absorber heater was determined by Urquhart [1978]. The uncertainty given was

Type B (K_4) = 0.05%

A4.1.11 Note 11: K_5

Axial non-uniformity is the dose gradient down the central axis of the absorber body. Again, the uncertainty given by Urquhart [1978] was

Type B (K_5) = 0.005%

A4.1.12 Note 12: K_6

Radial non-uniformity results from the lateral dose-gradient across the absorber. The Type A variability in determining this correction factor was made negligible by making multiple high resolution measurements.

APPENDIX A4 (Cont)

However, the limited spatial resolution of the detector used to determine the lateral dose gradient means that a significant systematic uncertainty remains. As the effect is small, no attempt was made to deconvolve the detector response from the correction factor. To be conservative, an uncertainty half the size of the correction was taken. Thus

Type B (K_6) = 0.05%

A4.1.13 Note 13: K_7

The distance correction required by Hohlfeld is taken to refer to setting the source to absorber distance. The uncertainty given by Urquhart [1978] was

Type B (K_7) = 0.05%

A4.1.14 Note 14: K_8

The depth of point of measurement correction required by Hohlfeld is taken to be the amount of graphite overlying the absorber centre, 4.9655 $g.cm^{-2}$, corrected to 5.000 $g.cm^{-2}$. The uncertainty given by Urquhart [1978] was

Type B (K_8) = 0.05%

A4.1.15 Note 15: K_9

The vacuum gaps correction is taken to refer to the change in absorbed dose due to modification of the photon and electron fluences in the vacuum gap. These gaps are of order 250 μm in the Urquhart calorimeter. The effect of the gap has not been evaluated in this laboratory. When reliable estimates become available, they will be applied.

Various Type B uncertainties are quoted for the vacuum gaps correction. These are tabulated below.

LABORATORY	[+] TYPE B UNCERTAINTY (%)
NBS	0.0
PTB	0.05
LMRI	0.1
OMH	0.02

[+] CCEMRI (I)/85-22

APPENDIX A4 (Cont)

With the very small vacuum gap used in the Urquhart calorimeter, it is considered that no correction is required, and no uncertainty figure is applied.

A4.1.16 Note 16: K_{10}

Corrections for homogeneity of graphite are taken to refer to variations in grain density and impurities throughout the bulk of the graphite.

In this standard, the quantity N_c is the ratio of absorbed dose in electro-graphite type EY927 to the ion chamber response measured in graphite from the same block. Thus no correction factor is implied.

A4.1.17 Note 17: K_{11}

The entrance foils used were mylar (polyester). Two were used, each of 0.056 mm thickness. The uncertainty assigned in the correction was

Type B (K_{11}) = 0.005%

A4.1.18 Note 18: K_{12}

No correction was applied for non-infinite phantom geometry. The calorimeter is effectively infinite.

A4.2 TABLE 2 - IONOMETRIC UNCERTAINTIES

The following notes give the origin of the uncertainties quoted in Table 2.

A4.2.1 Note 1: Exposure Meter Reading I

Sixty replicates of the exposure meter reading M were performed. For a 400 s exposure time, the variation was

Type A (M; 59) = 0.04%

A4.2.2 Note 2: Irradiation Time t

The computer determined value of t had negligible Type A uncertainty.

A4.2.3 Note 3: Distance Correction k_z

The distance correction required by Hohlfeld is taken to refer to setting the source-to-absorber distance. The uncertainty given by Urquhart was

Type B (k_z) = 0.05%

APPENDIX A4 (Cont)

A4.2.4 Note 4: Depth of Point of Measurement k_d

The depth of point of measurement correction is taken to represent the amount of graphite overlying the axis of the ion chamber, assuming the air cavity was solid graphite. The uncertainty is

Type B (k_d) = 0.05%

A4.2.5 Note 5: Impurities

No correction applied.

A4.2.6 Note 6: Gradient

No gradient correction applied.

A4.2.7 Note 7: Recombination p_s

The recombination correction for cobalt-60 is close to unity. Measurements using the 2 voltages procedure yielded a correction of 1.0006 with an uncertainty of 0.0002. The uncertainty in the experimental value was assigned to the correction as

Type B (p_s) = 0.02%

A4.2.8 Note 8: Pressure P

The ion chamber reading must be corrected for atmospheric pressure P. The uncertainty given by CSIRO for calibration of the Fortin barometer was 0.1 mm Hg.

In addition, the pressure reading must be corrected for temperature and local value of g, which is 9.79635 $m.s^{-2}$. Uncertainty in this correction is 0.05 mm Hg. Pressure readings are corrected to 0°C and g = 9.80665 $m.s^{-2}$ [British Standard BS 2520: 1983]. Accordingly,

Type B (P) = 0.02%

A4.2.9 Note 9: Temperature T

The ion chamber reading must be corrected for temperature T. The NATA uncertainty given was 0.1°C for the thermometer correction.

Additional uncertainties arise in reading the thermometer and relating this reading to the actual temperature inside the thimble chamber. A total uncertainty was assessed subjectively so that

Type B (T) = 0.05%

APPENDIX A4 (Cont)

A4.2.10 Note 10: Humidity k_h

The presence of gaseous water in the air cavity of the ion chamber lowers the density of air and modifies the energy transfer coefficients. The humidity meter has a manufacturers stated uncertainty of 2%. To be conservative, a 5% uncertainty was assumed and the corresponding variation read from the correction chart of the NE2560 Instruction Manual.

TABLE 1: TABLE OF UNCERTAINTIES IN CALORIMETRIC MEASUREMENT OF GRAPHITE ABSORBED DOSE RATE FOR COBALT-60 RADIATION

Source of Uncertainty			Uncertainty in %[2]		Note (cf: Append A3.1)
Symbol (ANSTO)	Symbol (SURVEY)	Measured Quantity, Physical Data or Correction Factor	Type A, s_i;(n)[1]	Type B, u_i	
		Measured Quantity			
P_α	P_{el}	Electrical calibration power	0	.015	1
	m	Mass of the absorber/core	0	.003	2
	α_{rad}	Temperature rise signal by radiation	.19; 26	-	3
	α_{el}	Temperature rise signal by electrical energy	.12; 26	0	4
	Δt_{rad}	Irradiation time period	.03; 26	0	5
	Δt_{el}	Calibration time period	0	0	6
	-	Others			
		Correction Factors for			
k_i	K_1	Impurities	0	.05	7
	K_2	Heat loss (temp. gradients)	.05; 26	0	8
	K_3	Heat (caloric) defect	-	0	9
k_c	K_4	Electrical power loss in leads	0	.05	10
k_a	K_5	Axial non-uniformity	0	.005	11
k_g	K_6	Radial non-uniformity	0	.05	12
k_z	K_7	Distance	0	.05	13
k_d	K_8	Depth of point of measurement	0	.05	14
	K_9	Vacuum gaps	-	0	15
	K_{10}	Homogeneity of graphite	-	-	16
k_m	K_{11}	Entrance foil attenuation	0	.005	17
	K_{12}	Non-infinite phantom geometry (if applicable)	-	-	18
	K_{13}	Others			
	K_{14}	Others			
Quadratic sum (Root of sum of squares) [not including K_2 - see A4.1.8]			.23	.11	
Combined uncertainty (Quadratic sum)				.25	

1) Number of degrees of freedom.

2) "0" means negligible and "-" means not applicable.

TABLE 2: TABLE OF UNCERTAINTIES IN IONOMETRIC MEASUREMENT OF GRAPHITE ION CHAMBER RESPONSE FOR COBALT-60 RADIATION

Source of Uncertainty		Uncertainty in %[2]		Note (cf: Append A3.2)
Symbol (ANSTO)	Measured Quantity, Physical Data or Correction Factor	Type A, s_i ;(n)[1]	Type B, u_i	
	Measured Quantity			
M	Exposure meter reading	.04; 59	-	1
t	Irradiation time period	0	-	2
	Correction Factors for			
k_z	Distance	-	.05	3
k_d	Depth of point of measurement	-	.05	4
k_i	Impurities	-	-	5
	Gradient	-	-	6
p_s	Recombination	-	.02	7
P	Pressure	-	.02	8
T	Temperature	-	.05	9
k_h	Humidity	-	.03	10
	Decay from reference time	-	0	
Quadratic sum (Root of sum of squares)		.04	.09	
Combined uncertainty (Quadratic sum)		.1		

1) Number of degrees of freedom.

2) "0" means negligible and "-" means not applicable.

TABLE 3: TABLE OF UNCERTAINTIES FOR ABSORBED DOSE CALIBRATION OF ION CHAMBER IN GRAPHITE

Source of Uncertainty		Uncertainty in %[2]	
Symbol	Measured Quantity, Physical Data or Correction Factor	Type A, s_i;(n)[1]	Type B, u_i
-	Calorimetric determination	.23	.11
-	Ionometric determination	.04	.09
Quadratic sum (Root of sum of squares)		.23	.14
Combined uncertainty (Quadratic sum)		.3	

1) Number of degrees of freedom.
2) Insert "0" if negligible or "-" if not applicable.

TABLE 4: ABSORBED DOSE RATES IN GRAPHITE FOR COBALT-60 GAMMA RADIATION (for reference time 12:01 pm, 1st November, 1989. Drift error is also given as a figure of merit for calorimeter temperature stability)

DISC #	D700 Runs 1-9		D2011 Runs 10-18		D2150 Runs 19-27	
File	$mGy.s^{-1}$	Drift %	$mGy.s^{-1}$	Drift %	$mGy.s^{-1}$	Drift %
CoBRUN1 CoERUN1	10.02	+ .19	9.97	- .60	9.82	+ .11
CoBRUN2 CoERUN2	10.04	+ .08	9.98	+ .07	9.86	+ .18
CoBRUN3 CoERUN3	10.09	+ .25	9.89	+ .78	9.93	+ .21
CoBRUN4 CoERUN4	10.11	- .03	9.89	+ .13	10.01	+ .34
CoBRUN5 CoERUN5	10.11	+ .39	10.11	- .12	10.15	+ .33
CoBRUN6 CoERUN6	9.98	+ .14	10.06	+ .13	10.09	+ .16
CoBRUN7 CoERUN7	9.91	- .22	10.12	+ .24	10.00	+ .26
CoBRUN8 CoERUN8	9.93	+ .16	10.14	+ .32	9.86	+ .46
CoBRUN9 CoERUN9	9.66	- .27	9.91	- .01	9.81	+ .21

Mean dose rate	:	9.98 $mGy.s^{-1}$
Standard deviation of the mean	:	.02 $mGy.s^{-1}$
Arithmetic mean drift correction	:	.14%
Root mean square drift correction	:	.29%
Standard deviation of the mean in the drift correction	:	.05%

TABLE 5: SECONDARY STANDARDS FOR THE VOLT AND OHM
(maintained by the Radiation Standards Laboratory, Lucas Height Research Laboratories)

+ REPORT #	DATE OF TEST	DESCRIPTION	MANUFACTURER	SERIAL #	VALUE	UNIT	UNCERTAINTY (at time of calibration)
RS 18390	September 1988	Standard Resistor Type RS1	Croydon Precision Instrument Co	12361	1000.78	ohm	± 100 ppm
RS 18493	September 1988	Digital Multimeter HP 3457A	Hewlett Packard	AO 96562	Range of Values	DC volt	± 5 ppm
RS 18391	Aug-Sept 1988	Standard Cell K231A	Muirhead and Co.	463939	1.017687	volt	± 30 μV
* No Report	June 1986	Unmounted Resistor	Leeds and Northrup	No serial number	770.058	ohm	Not stated

+ Issued by CSIRO, Division of Applied Physics, National Measurement Laboratory, Bradfield Road, West Lindfield, Sydney, NSW

* Not a secondary standard, but calibrated under identical conditions to secondary standard resistor.

TABLE 6: SECONDARY STANDARD FOR ATMOSPHERIC PRESSURE, TERTIARY STANDARD FOR TEMPERATURE AND UN-CALIBRATED HUMIDITY METER

REPORT #	DATE OF TEST	DESCRIPTION	MANUFACTURER	SERIAL #	UNIT	UNCERTAINTY
+ RS 18389	August 1988	Fortin Barometer	A.L. Franklin	520	mm Hg	.10
* 34884/B.5932	May 1979	Thermometer	Dobros	7844	°C	.05
Manufacturers Calibration	Nil	Humidity Meter Series 5500	Jenway Ltd	3190 R	% RH	2% of RH

+ Issued by CSIRO, Division of Applied Physics, National Measurement Laboratory, Bradfield Road, West Lindfield, Sydney, NSW.

* NATA registered laboratory No. 410, Dobbie Instruments Pty Ltd, Sandringham, Victoria

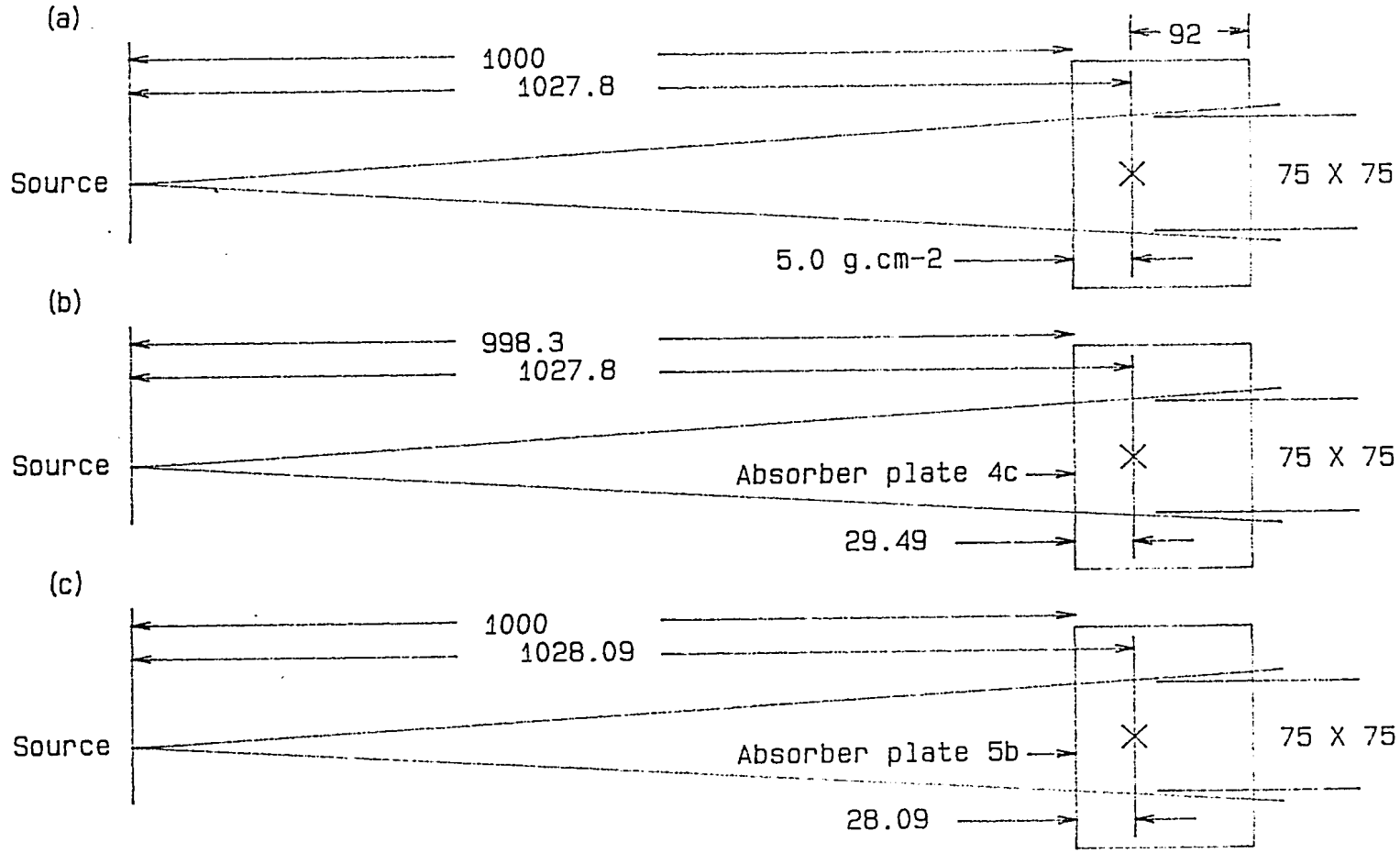

Figure 1 : Reference and experimental geometry for microcalorimeter and calorimeter dummy phantom for cobalt-60 standardisation, November, 1989 Dimensions are mm.

(a) Reference configuration for distance corrections (not to scale)
(b) Experimental set-up for microcalorimeter
(c) Experimental set-up for calorimeter dummy

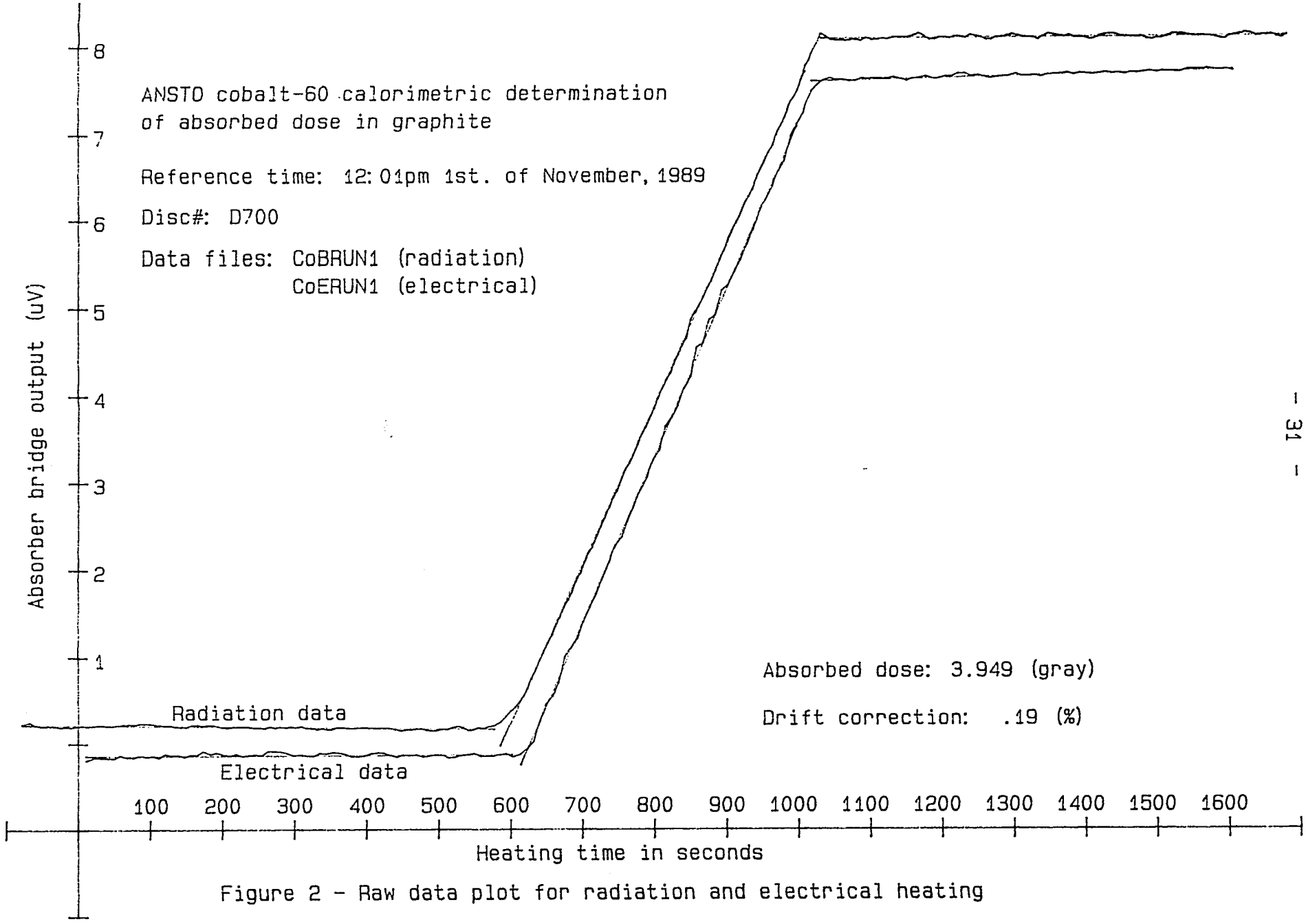

Figure 2 - Raw data plot for radiation and electrical heating

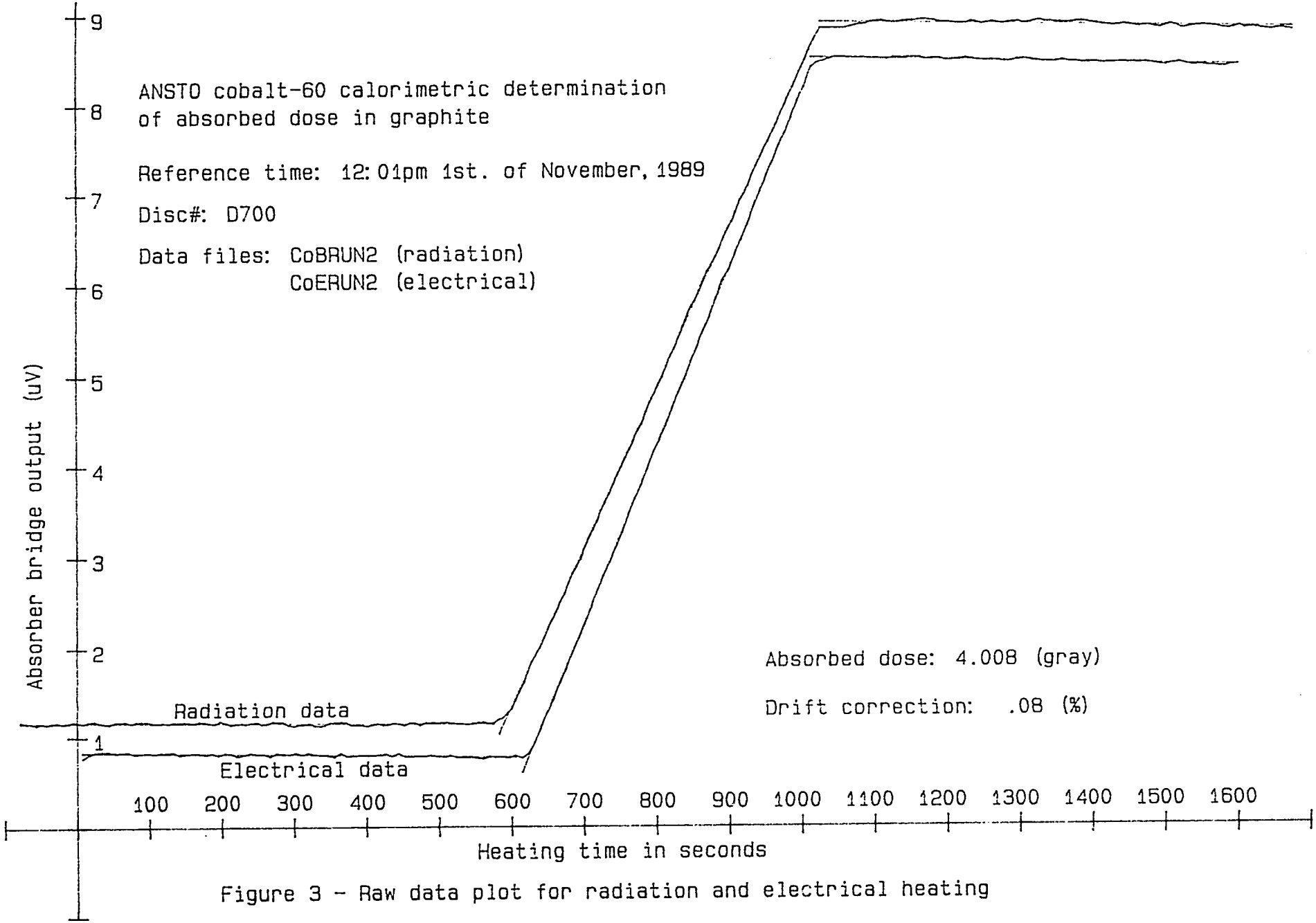

Figure 3 - Raw data plot for radiation and electrical heating

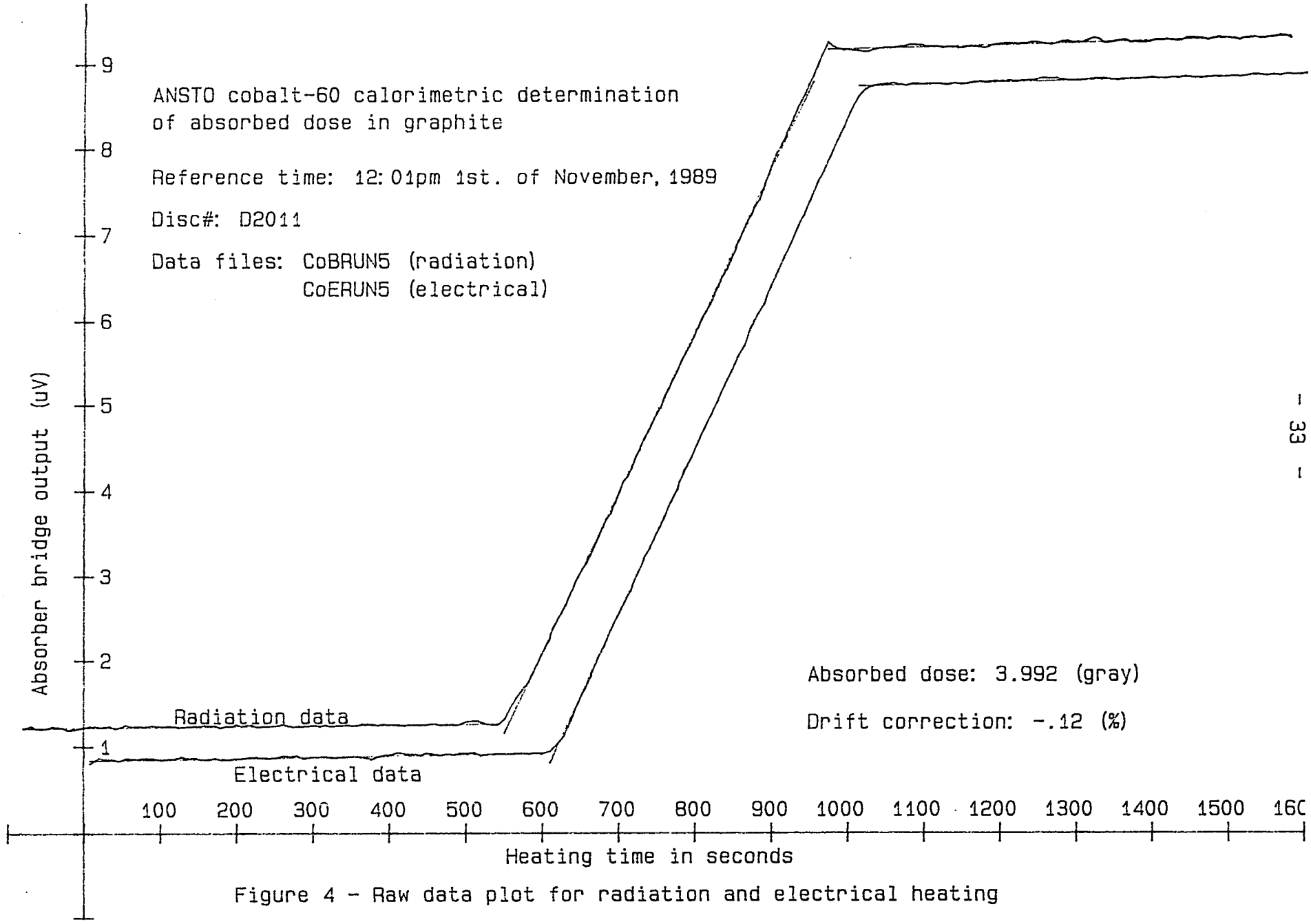

Figure 4 - Raw data plot for radiation and electrical heating

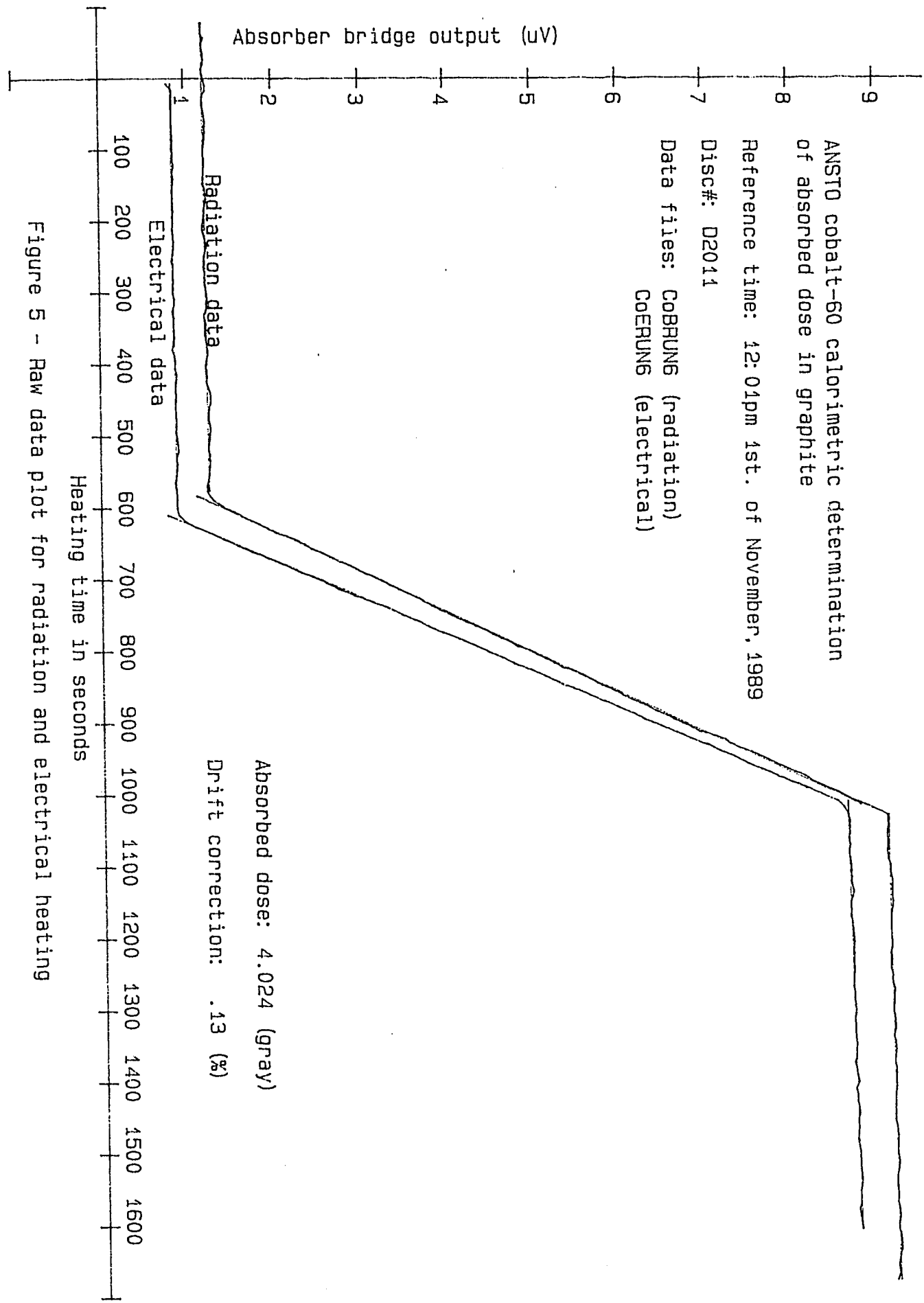

Figure 5 - Raw data plot for radiation and electrical heating

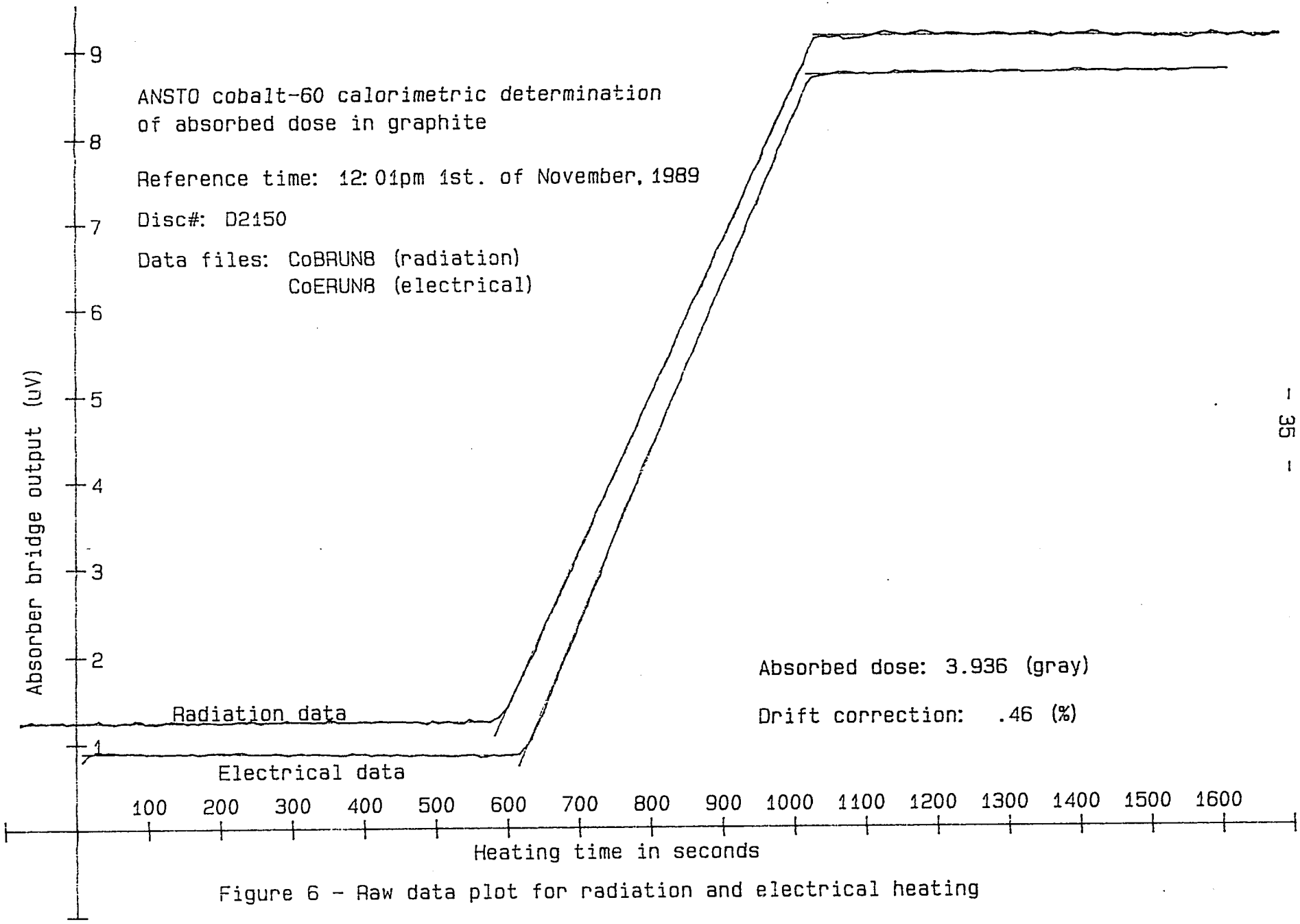

Figure 6 - Raw data plot for radiation and electrical heating