

# kV X-Ray Dosimetry at NPL

## Brief History

From the early 1900's NPL responded to the requests of British radiotherapists to calibrate the dosimeters they used for standardising the dose delivered to patients. From the beginning, the particular kVs chosen to generate X-ray beams at NPL were intended to match those used in clinical radiotherapy. In 1971 it was decided to derive a new range of X-ray qualities. For many years hospital physicists had been using half-value layer (HVL) to specify the beam qualities for kV energy X-ray beams in terms of HVL in aluminium up to 4 mm Al HVL (about 100 kV), and in terms of copper for the higher energy X-ray beams up to 4 mm Cu HVL (about 300 kV). A total of nineteen X-ray qualities (see Appendix 1) were chosen, at standardised values of HVLs spaced as evenly as possible, so that it would be easy for users to interpolate between them.

Two primary standard parallel plate free-air chambers are maintained by the National Physical Laboratory for the realisation of air kerma (kinetic energy relaxed per unit mass) in terms of the base units, i.e.  $1 \text{ Gy} = 1 \text{ J kg}^{-1}$ . These primary standards are designed to measure X-rays generated between 8 kV and 50 kV and between 40 kV and 300 kV respectively.

In the UK traditionally about 30 secondary standard radiotherapy centres (university and teaching hospitals), send their secondary standards to NPL for calibration against a primary standard every three years. NPL will calibrate any dosimeter that is of secondary standard quality. Regional hospitals calibrate their tertiary standards against the secondary standards held by the secondary centres. Field instruments, used for daily routine measurements, are calibrated in hospitals about once every year against either secondary or tertiary standards.

## Realisation of Air Kerma (from first principles)

Air kerma,  $K$ , is the quantity realised by the **free-air chamber** (FAC) and is defined<sup>1</sup> as "The quotient of  $dE_{tr}$  by  $dm$  where  $dE_{tr}$  is the sum of the initial kinetic energies of all the charged ionising particles liberated by uncharged ionising particles\* in air of mass  $dm$ ",

$$K = \frac{dE_{tr}}{dm} \quad (1)$$

Applying the definition of air kerma to a free-air chamber we obtain Equation 2,

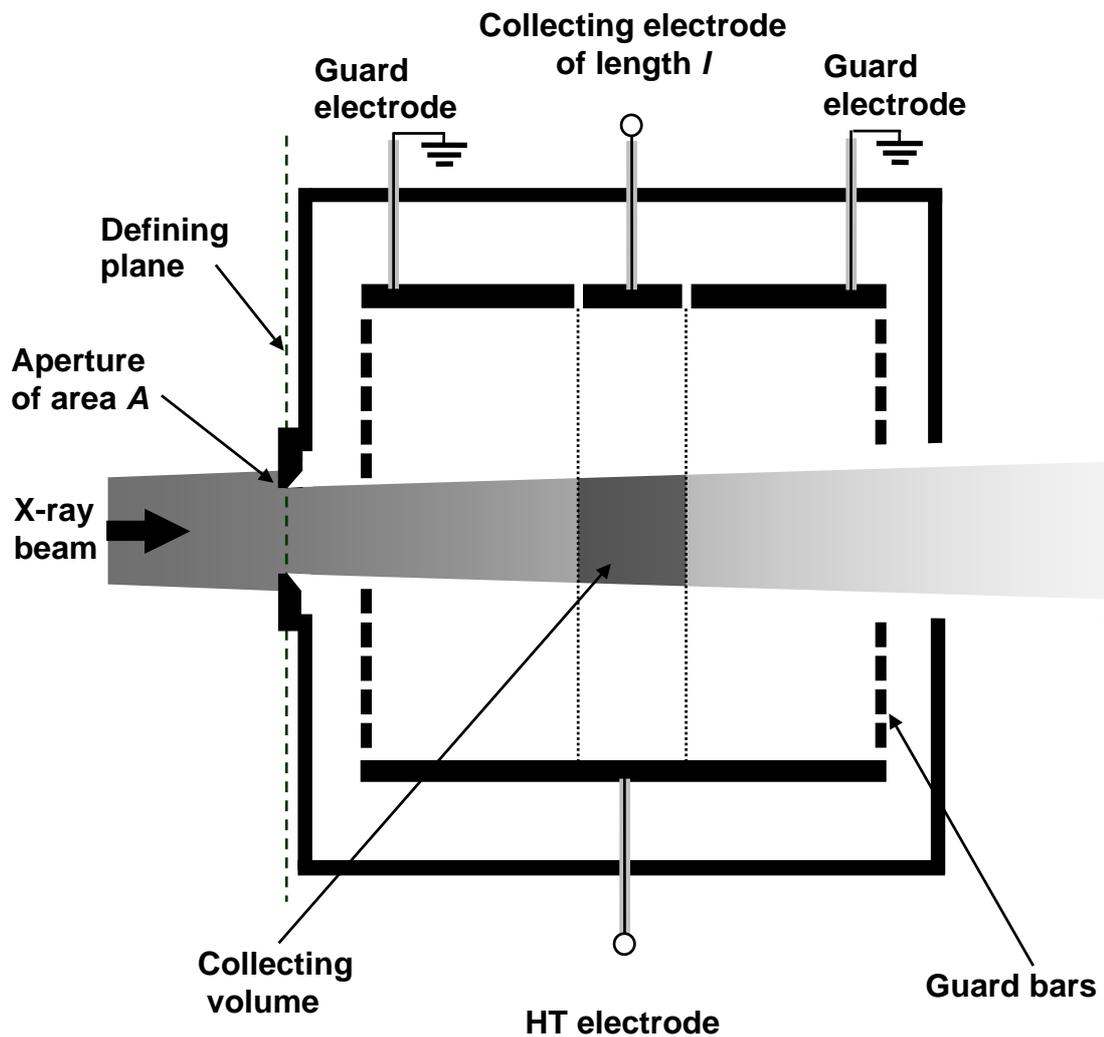
$$K = \frac{Q}{m} \frac{W_{air}}{e} \frac{F}{(1-\bar{g})} \quad (2)$$

\* Air kerma is only defined for photons and neutrons.

where

$Q$  is the measured charge,

$m$  is the mass of air in the collecting volume,  
 $W_{air}/e$  is the energy required to produce an ion pair in dry air<sup>2</sup>  
 (= 33.97 J/C),  
 $F$  is the product of various correction factors (see below) which  
 depend on the design of the free-air chamber and in some  
 cases on the X-ray beam quality and  
 $\bar{g}$  is the fraction of electron energy lost to bremsstrahlung<sup>2</sup>  
 (for kV X-rays generated between 8 kV and 300 kV,  $\bar{g}$  is  
 negligible (=0)).



**Figure 1** Main components of the NPL free-air ionisation chamber  
 (not to scale)

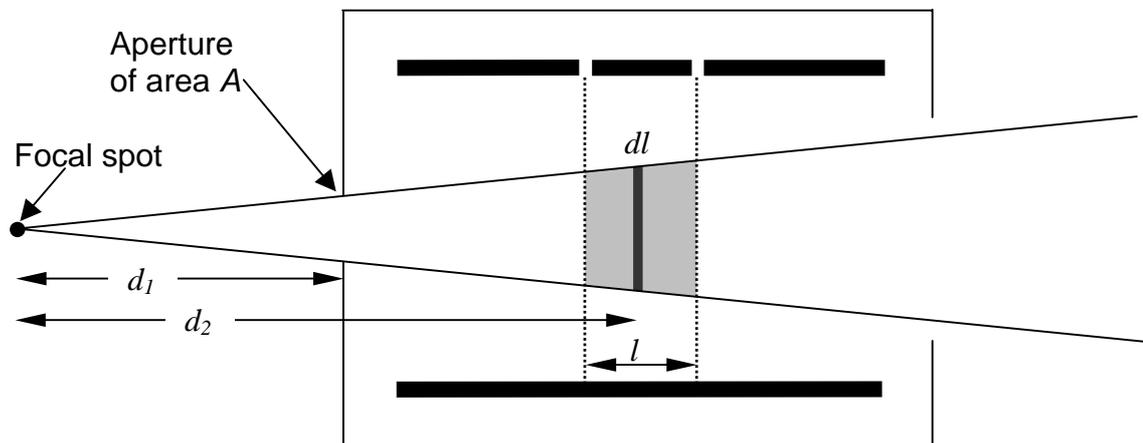
Figure 1 shows a schematic diagram of the NPL free-air chamber. A mono-directional beam of X-rays passes through a defining aperture of accurately known area,  $A$ , enters a metal box and passes out through a hole on the far side of the box without striking anything in the box other than the air it contains.

This fulfils the requirement for the realisation of air kerma, i.e. the X-rays interact only with air.

The separation of the electrodes in the chamber and its other dimensions are such that secondary electrons released in the collecting volume lose all their energy before they can reach the electrodes or chamber walls. This ensures that the electrons are completely stopped by air. A high potential difference (field strength of the order of 100 V/cm) maintained between the high-voltage electrode and the collecting electrode sweeps the ions of one sign produced between the dotted lines (see Figure 1) to the collecting electrode. The effective length,  $l$ , of the collecting electrode is the actual length of the collecting electrode,  $l_{col}$ , plus half the width of the two gaps to the adjacent earthed guard electrodes. A system of guard bars, to which graded electrical potentials are applied, together with the guard electrodes, ensures that the field lines between the collecting electrode and the high voltage electrode are parallel to each other and perpendicular to the surface of the electrodes.

The actual collecting volume (see Figure 1, dark grey area) varies with the distance between the FAC and the focal spot of the X-ray tube. Because of the difficulty of measuring the actual collecting volume, the defining plane of the FAC is moved from the centre of the collecting electrode to the front face aperture. It may not be immediately obvious why this is legitimate. After all, the charge we measure with the FAC is produced in the collecting volume and not at the aperture. However, mathematically it can be shown that the charge collected by a free-air chamber is a measure of the exposure at the defining plane of the aperture provided the air attenuation correction is applied.

We will now derive an expression for the total charge,  $Q$ , produced within the collecting volume.



**Figure 2** Free-air ionisation chamber

Air kerma,  $K$ , is proportional to the charge produced per unit mass ( $Q/m$ ), also called exposure,  $X$  (see Equation 2).

Let aperture area =  $A$ ,

exposure at aperture =  $X_1$ ,

distance from focal spot to aperture =  $d_1$ ,

thickness of infinitesimal volume element within collecting volume =  $dl$  ,  
 cross-sectional area of element  $dl = A_2$  ,  
 exposure at element  $dl = X_2$  ,  
 distance from focal spot to element  $dl$  within collecting volume =  $d_2$  ,  
 charge collected by element  $dl = dQ$  ,  
 charge collected by whole collecting electrode =  $Q$  ,  
 air density =  $\rho$  and  
 air attenuation correction =  $f_{aac}$  .

The charge collected by element  $dl$  is

$$dQ = X_2 \cdot \underbrace{A_2 \cdot \rho \cdot dl}_{\text{mass of air in element } dl} \quad (3)$$

$$A_2 = A \cdot \left( \frac{d_2}{d_1} \right)^2 \quad (4)$$

$A_2$  **increases** with increasing  $d_2$  (inverse square law).

$$X_2 = \frac{X_1}{f_{aac}} \cdot \left( \frac{d_1}{d_2} \right)^2 \quad (5)$$

$X_2$  **decreases** with increasing  $d_2$  (inverse square law).

By combining (3), (4) and (5) we get:

$$dQ = \frac{X_1}{f_{aac}} \cdot \left( \frac{d_1}{d_2} \right)^2 \cdot A \cdot \left( \frac{d_2}{d_1} \right)^2 \cdot \rho \cdot dl \quad (6)$$

The total charge,  $Q$ , produced within the collecting volume can be calculated by integration:

$$\int_0^Q dQ = \int_0^l \frac{X_1}{f_{aac}} \cdot A \cdot \rho \cdot dl \quad (7)$$

From Equation 7 follows:

$$Q = \frac{X_1}{f_{aac}} \cdot A \cdot \rho \cdot l \quad (8)$$

It is interesting to see that the collecting volume of a free-air chamber is defined by the aperture area,  $A$ , and the effective length,  $l$ , of the collecting electrode which can both be measured. The volume then becomes  $Al$ , and the mass of

air within this volume is  $m = A\rho$ , where  $\rho$  is the air density<sup>3,4</sup> at a pressure of 101.325 kPa, a temperature of 20°C and 50% relative humidity.

From Equation 8 we can also see that the charge,  $Q$ , collected by a FAC is a measure of the exposure at the defining plane of the front face aperture,  $X_1$ , corrected for air attenuation ( $f_{aac}$ ).

### The Free-Air Chamber Correction Factors

The total correction factor ( $F$ ) (see Equation 2) is the product of several correction factors, which are listed below.

Some of the ions, which are produced in the collecting volume of the free-air chamber, are lost by ion **recombination** before they reach the collecting electrode and this correction is determined by experiment.

Correction for the **air attenuation** between the aperture and the collecting electrode is necessary because the reference point of the chamber is taken to be the defining plane of the aperture and not the centre of the collector.

A **field distortion** correction is necessary because the electric field inside the free-air chamber is not perfectly perpendicular to the electrodes at all points. This is despite the presence of the guard bars, which only reduce the distortion effect.

Correction for the **front face penetration** is necessary if the front face of the free-air chamber is not thick enough to attenuate the X-ray beam. It is more important with large beam sizes and high energy beams.

An **HT polarity** correction is necessary because the measured charge can depend on the polarity of the HT supply. The potential is negative for routine measurements. A correction of half the difference between measurements with positive and negative polarity is applied.

A correction has to be made for photons which are scattered from the main beam through the chamber and which produce ionisation in the space between the electrodes not defined by the ionisation volume. This was measured by surrounding the X-ray beam through the chamber as closely as possible with a plastic cone of sufficient thickness to stop the secondary electrons produced by interactions in the collecting volume. This allows the **scattered photons** to pass with minimum attenuation and the contribution of these photons to the total ionisation can therefore be measured.

An **ion loss** correction is necessary at higher energies when the plate separation is less than the range of the secondary electrons in air. It has been calculated using Monte Carlo techniques.

A correction for **humidity** is applied in accordance with the recommendation of CCEMRI<sup>5</sup>.

### How a Secondary Standard Ionisation Chamber is Calibrated against the NPL primary standard free-air chamber(s)

A transmission monitor chamber is used to correct all measurements for any variations in X-ray tube output. At the beginning of each measuring cycle

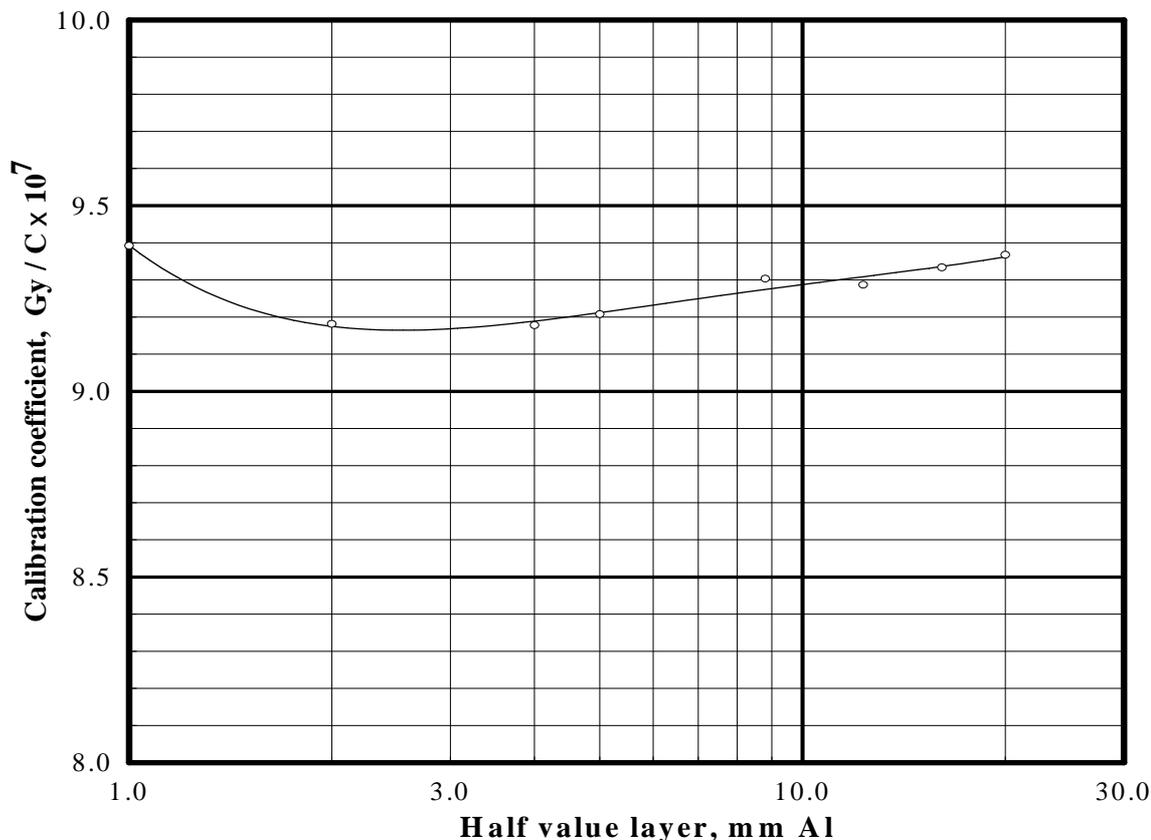
(shutter closed, electrometer unearthed) a pre-exposure leakage current is measured for typically 15 s. Then the shutter opens and the ionisation current is measured for an exposure time of, say, 30 s. The shutter closes, however, the electrometer stays unearthed. Finally, the post-exposure leakage current is measured for another 15 s, after which the electrometer will be earthed before the next measuring cycle starts.

- a) First, the ionisation current is measured using the primary standard FAC.
- b) Next, the secondary standard ionisation chamber is moved into the X-ray beam (same position as the primary standard, i.e the reference plane of the secondary standard is identical with the defining plane of the FAC) and the ionisation current is measured.
- c) Finally, another primary standard measurement will be carried out.
- d) Now the mean ionisation current for the primary standard can be determined and a temperature and pressure correction is applied to the standard to monitor response.
- e) A standard to monitor ratio, corrected for temperature and pressure, is also calculated for the secondary standard.
- f) The calibration coefficient of the secondary standard in terms of Gy/C is the ratio of the primary standard response to the secondary standard response multiplied by the primary standard sensitivity (in terms of Gy/C) for the particular X-ray quality used during the calibration.

A typical calibration curve for a NE 2561 chamber is shown in Figure 3.

## Air kerma calibration coefficient

(corrected to 20 °C, 1013.25 mbar (101.325 kPa) and 50% RH)



**Figure 3** A typical calibration curve for a NE 2561 ionisation chamber

### References

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2. CCEMRI 1985 report of the 8<sup>th</sup> meeting of section I (Rayons X et  $\gamma$ , électrons). *Comité Consultatif pour les Étalons de Mesure des Rayonnements Ionisants, Rapport de la 11<sup>ème</sup> session* (Sèvres: BIPM) R157-166.
3. Giacomo, P; Equation for the determination of the Density of Moist Air (1981). *Metrologia* **18**, 33-40, (1982)
4. Davis, R S; Equation for the determination of the Density of Moist Air (1981/91). *Metrologia* **29**, 67-70, (1992)
5. Correction d'Humidité Report of the 4th meeting of Section I (Rayons X et  $\gamma$ , électrons). *Comité Consultatif pour les Étalons de Mesure des Rayonnements Ionisants, Rapport de la 4<sup>ème</sup> Réunion - 1977* pageR(1)6. Bureau International des Poids et Mesures (BIPM), Sèvres, 1977.

## Appendix 1

### X-ray qualities used for therapy-level exposure and air kerma calibrations at NPL

Quality	Half-value layer	Generating potential	Added filter	Approximate air kerma rate
Reference number	mm Al	kV	mm Al	Gy/min
2.4.1	0.024	8.5	None	0.08
2.4.2	0.036	10	0.025	0.13
2.4.3	0.050	11.5	0.050	0.17
2.4.4	0.070	14	0.11	0.18
2.4.5	0.10	16	0.20	0.18
2.4.6	0.15	20	0.30	0.22
2.4.7	0.25	24	0.45	0.21
2.4.8	0.35	34	0.47	0.39
2.4.9	0.50	41	0.56	0.43
2.4.10	0.70	44	0.74	0.40
2.4.11	1.00	50	1.01	0.33

**Table A1.1** Therapy-level very-low energy X-rays, 0.035-1.0 mm Al HVL.  
Thin-window ionisation chambers (PTW 23344 and PTW 23342)  
Inherent filtration 1 mm Be  
Focus-chamber distance 0.5 m

Quality	Half-value layer		Generating potential	Added filtration	
	mm Al	mm Cu		mm Cu	mm Al
2.2.1	1.0	0.030	50		0.75
2.2.2	2.0	0.062	70		1.6
2.2.3	4.0	0.150	100		3.4
2.2.4	5.0	0.200	105	0.1	1.0

**Table A1.2** Therapy-level low energy X-rays, 1.0-8 mm Al HVL.  
Secondary standard thimble chamber  
Inherent filtration 2.5 mm Be + 4.8 mm Perspex  
Focus-chamber distance 0.75 m

Quality	Half-value layer		Generating potential	Added filtration		
	mm Al	mm Cu		mm Sn	mm Cu	mm Al
(a) Inherent filtration 2.5 mm Be + 4.8 mm Perspex						
2.2.5	8.8	0.50	135		0.27	1.0
(b) Inherent filtration 4 mm Al equivalent + 4.8 mm Perspex						
2.2.6	12.3	1.0	180		0.42	1.0
2.2.7	16.1	2.0	220		1.20	1.0
2.2.8	20.0	4.0	280	1.4	0.25	1.0

**Table A1.3** Therapy-level medium energy X-rays, 0.5-4 mm Cu HVL.  
Secondary standard thimble chamber  
Focus-chamber distance 0.75 m

## Appendix 2

### Definitions

**Primary standard:** An instrument of the highest metrological quality that permits determination of the unit of a quantity from its definition, and the accuracy of which has been verified by comparison with the comparable standards of other institutions participating in the international measurement system. A primary standard is usually a one-off instrument. Our primary standards were designed by the NPL workshop in consultation with the physicists at NPL.

**Secondary standard:** An instrument of secondary standard quality that has been calibrated by comparison with a primary standard.

**Temperature and Pressure correction factor:** The calibration factors reported in the NPL certificate apply when the chamber is used in ambient atmospheric conditions of 20 °C, 1013.25 mbar (101.325 kPa) and 50% relative humidity (standard conditions). For accurate measurements it is therefore necessary to correct for any differences between the air density in the chamber at the time of measurement and that for which the calibration factor applies using:

$$k_{T,P} = \frac{(273.15 + T)}{293.15} \cdot \frac{1013.25}{P}$$

Where:

$T$  is the ambient temperature in °C and

$P$  is the ambient atmospheric pressure in mbar.

**Tertiary standard:** An instrument calibrated by direct comparison with a secondary standard.

**Field instrument:** A measuring instrument used for routine measurements (i.e. for daily QA measurements in a radiotherapy department).

### Standard deviation of the mean (SDOM):

$$SDOM [\%] = \frac{\sigma_{n-1}}{\bar{x} \cdot \sqrt{n}} \cdot 100$$

Where:

$\sigma_{n-1}$  is the standard deviation of  $n$  readings,

$\bar{x}$  is the mean of  $n$  readings and

$n$  is the number of readings.

# MV Photon Dosimetry Practical Session Course Notes

## 1. Introduction

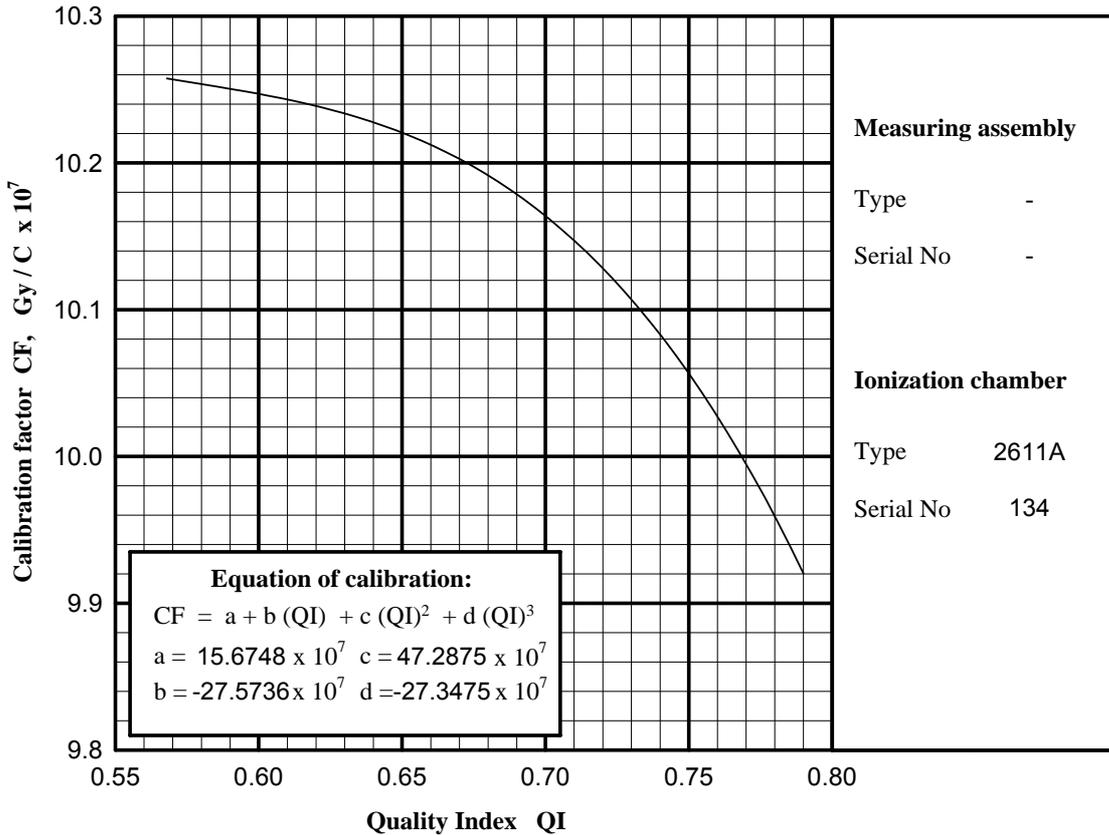
At NPL therapy level dosimeters are calibrated directly in terms of absorbed dose to water and air kerma. Each hospital then follows a UK recommended code of practice for the comparison of the secondary standard dosimeters with the tertiary standards, for MV photons this code is the IPSPM 1990 [1]. For the therapy level photon calibration service, NPL normally accepts dosimeters for calibration for a limited period (approximately 10 weeks) during the spring and autumn of each year. It is recommended that types NE 2561, NE 2611 and Farmer type chambers (graphite walled only for absorbed dose) are calibrated at three yearly intervals.

In 1988 NPL launched a calibration service for secondary standard dosimeters in terms of absorbed dose to water for  $^{60}\text{Co}$   $\gamma$ - rays and seven X-ray qualities between 4 and 19 MV (see Appendix 1). Figure 1 shows a typical calibration curve for a NE 2561 ionisation chamber.

The calibration procedure has four stages:

1. Each year the primary standard graphite calorimeter is used to calibrate at least three type NE 2561/2611 ionisation chambers in a graphite phantom as “reference standards” for a range of radiation qualities.
2. Absorbed dose calibration factors for the reference standards are converted from graphite to water using factors determined by Burns et al 1994 [2] and confirmed by Nutbrown et al 2002 [3].
3. During the calibration period the radiotherapy departments own secondary standard dosimeters are compared with the reference standards in a water phantom for a minimum of four photon qualities including Cobalt 60.
4. The calibration factors for a range of qualities between Co-60 and 19 MV are calculated using empirical  $k_Q$  factors and reported in the form of a graph with an equation to allow the calculation of calibration factors for any beam within the range of  $\text{TPR}_{20/10}$  0.568 to 0.790.

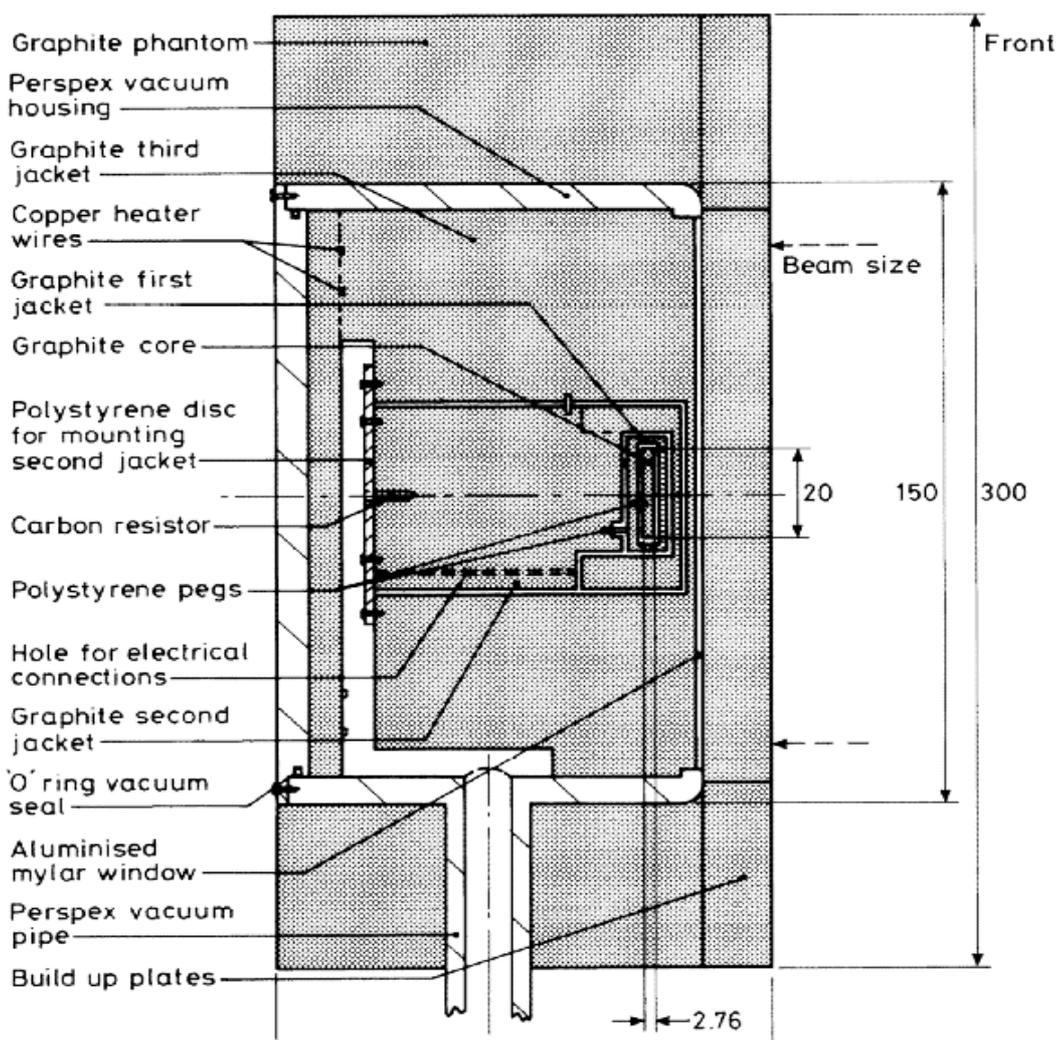
Absorbed dose calibration factors, corrected to 20 °C, 1013.25 mbar (101.325 kPa) and 50% RH



**Figure 1** A typical calibration curve for a NE 2611 ionisation chamber

## 2. Primary standard graphite calorimeter

The National Physical Laboratory (NPL) uses a graphite calorimeter as the UK primary standard of absorbed dose. The advantage of calorimetry over exposure standards is that the radiation energy is absorbed in the calorimetric medium and absorbed dose is directly related to the temperature rise. Ideally the calorimetric medium would be water (as much of the human body is water), however chemical reactions in irradiated water may evolve or absorb heat and so interfere with the measurement of absorbed dose, this is known as the heat defect. Graphite has the advantage of being very similar to water in terms of radiation absorption and scattering properties, but without any of the disadvantages of the heat defect associated with chemical reactions in water. A number of water calorimeters have been developed, including one at NPL, however graphite remains the calorimetric material recommended by the International Commission on Radiation Units and Measurements (ICRU) Report 14 (1969) [4]. The calorimetric measurement of absorbed dose to graphite is then converted to the quantity of interest i.e. absorbed dose to water.



**Figure 2** Schematic diagram of the primary standard graphite micro calorimeter (all dimensions in millimeters).

The NPL primary standard graphite calorimeter is based on a design by Domen and Lamperti (1974) [5] with modifications to the vacuum housing, electrical connector and one of the graphite jackets, as described by Cross (1988) [6]. Figure 2 shows that the micro calorimeter consists of a small disc shaped core of graphite (20 mm diameter, 3 mm thick) where the temperature rise due to the radiation and hence the absorbed dose is measured, surrounded by three graphite jackets and an extensive graphite phantom. The gaps of 1 mm between the core and the jackets are evacuated allowing the calorimeter to be operated adiabatically. The jackets and phantom present a nearly homogeneous graphite medium for the absorption and scattering of the beam and thermally insulate the core. Two thermistors are embedded in the core; one is used as a sensor and the other as a heater for the electrical calibration.

When irradiated the energy absorbed by the core raises the core temperature by  $T_R$ , which is sensed by a thermistor in one arm of an AC bridge circuit, Stoker et al (1991) [7] and DuSautoy (1996) [8].

The calorimeter is calibrated by dissipating a measured quantity of electrical energy  $E_E$  in the core and measuring the corresponding increase in core temperature,  $T_E$ . For a core of mass  $m$ , the absorbed dose to graphite  $D_c$  is given by:

$$D_c = \frac{E_E}{m} \cdot \frac{T_R}{T_E} \quad (1)$$

For a dose of 1 Gy, the energy absorbed raises the temperature of the core by about 1.4 mK.

### **3. Conversion from graphite to water**

#### **3.1 Reference standard ionisation chambers**

Reference standard ionisation chambers are introduced because:

1. Operation of the calorimeter is time-consuming, making it impractical to compare directly each secondary standard with the calorimeter,
2. Conversion from absorbed dose to graphite to that of water is included in the reference chamber calibration factors.
3. The reference chambers have established long-term stability, so their calibration factors provide a check of the consistency of the absorbed dose standard.

#### **3.2 Conversion from graphite to water**

The absorbed dose to graphite measured using the graphite calorimeter is converted to the required absorbed dose to water using factors determined by Burns at al 1994 [2] for all photon energies provided by the high-energy X-ray calibration service. This work determined the factors in two ways:

1. Use of the photon fluence-scaling theorem. This states that if two blocks of different material are irradiated by the same photon beam, and if all dimensions are scaled in the inverse ratio of the electron densities of the two media then, assuming that all photon interactions occur by Compton scatter, the photon attenuation and scatter factors at corresponding scaled points of measurement in the phantom will be identical.
2. Use of cavity ionisation theory to calculate the relation between the calibration factors.

However, subsequent to the completion of this work, it was identified that the NPL high-energy photon beam has much less inherent filtration in the beam than clinical LINACs. In order to match clinical beams more closely calibrations are currently carried out with additional filtration in the path of the beam. The additional filtration is provided by an extra thickness of aluminium where the thickness has been selected in order to match the NPL beam as closely as

possible with a typical clinical beam by matching values of  $TPR_{20/10}$ . Previously determined conversion factors for lightly filtered qualities were used to generate values for heavily filtered qualities by interpolation and extrapolation against  $TPR_{20/10}$ .

More recently work has been carried out by Nutbrown et al 2002 [3] to re-evaluate the conversion factors for all MV photon energies provided by the NPL LINAC using light filtration and for  $^{60}\text{Co}$   $\gamma$ -radiation. The conversion factors have also been evaluated for all mega-voltage photon energies using heavy filtration and compared with the interpolated and extrapolated values that are currently in use. These factors were determined in two ways:

1. Use of the photon fluence-scaling theorem as described previously.
2. Making in-phantom measurements of chamber response at a constant target-chamber distance. Monte Carlo techniques are then used to determine the corresponding dose to the medium in order to determine the chamber calibration factor directly.

The best fit to results determined by Nutbrown et al 2002 [3] agrees with values determined by Burns et al 1994 [2] to within 0.3% ( $1\sigma$  uncertainty). It is found that the conversion factor is not sensitive to beam filtration and so overall the ratio of the calibration factors varies smoothly between 1.130 and 1.142 for  $TPR_{20/10}$  values between 0.565 and 0.763 respectively.

#### 4. Calibration of hospital chambers

Secondary standard ionisation chambers are compared with the reference standard chambers in a 26 cm cubic water phantom with chambers in close-fitting waterproof Perspex sleeves with a wall thickness of 1.5 mm

Throughout the photon calibrations, the axis of the thimble chamber is positioned perpendicular to that of the beam. The effective point of measurement for positioning the chamber is taken to be on the chamber axis: 5 mm from the tip of the graphite cap for type NE 2561 or NE 2611, and 12 mm from the tip of a Farmer type chamber (e.g. NE 2571), always measured without the buildup cap. The chambers are placed with their reference points at the reference depth in water (see Appendix 1) and irradiated with a 10 x 10 cm field at the chamber.

The chambers are irradiated at NPL using two radiation sources:

1.  $^{60}\text{Co}$   $\gamma$ -ray beam

The beam is square in cross-section, 10 x 10 cm at the chamber and gives an absorbed dose rate to water of about 1.0 Gy per minute at a source to chamber distance of 85 cm.

## 2. High energy X-ray beams

The beams produced by the NPL electron linear accelerator are circular in cross-section with a diameter of approximately 11.3 cm, which is equivalent to a 10 x 10 cm field at the chamber and gives an absorbed dose rate to water of about 0.5 Gy per minute at a source distance of 125 cm.

The linear accelerator is operated at 240 pulses per second with a pulse width of approximately 1 microsecond.

The NPL linac is a research machine and does not have as much inherent filtration as a clinical machine. To ensure that the NPL beams match those used in the clinic as closely as possible additional filtration is placed in the beam, the NPL beam filtrations are given in Appendix 1.

### 4.1 Corrections to calibration factors

The absorbed dose to water ( $D_w$ ) can be obtained from an NPL calibration certificate using:

$$D_w = M \cdot N_{W,Q} \cdot k_{T,P} \cdot k_{ion} \cdot k_{charge} \cdot k_{lin} \cdot k_{range} \quad (2)$$

Where:

- M is the uncorrected instrument reading, made in water,
- $N_{W,Q}$  is the absorbed dose to water calibration factor at Quality Q in Gy/C or Gy/instrument reading,
- $k_{T,P}$  is to correct to standard temperature and pressure,
- $k_{ion}$  is the factor to correct to zero ion recombination,
- $k_{charge}$  is the factor to convert the instrument reading, if required, to charge,
- $k_{lin}$  is the scale linearity correction factor for the electrometer,
- $k_{range}$  is the range correction factor for the electrometer.

#### 4.1.1 Temperature and Pressure correction factor

The calibration factors reported in the NPL certificate apply when the chamber is used in ambient atmospheric conditions of 20 °C, 1013.25 mbar (101.325 kPa) and 50% relative humidity (standard conditions). For accurate measurements it is therefore necessary to correct ( $k_{T,P}$ ) for any differences between the air density in the chamber at the time of measurement and that for which the calibration factor applies using:

$$k_{T,P} = \frac{273.15 + T}{293.15} \cdot \frac{1013.25}{P} \quad (3)$$

Where:

- T is the ambient temperature in °C,
- P is the ambient atmospheric pressure in mbar.

However for high-energy photons we are operating in a water phantom therefore special precautions need to be taken:

1. The wall of the waterproof sheath should be sufficiently thin to allow the chamber to achieve thermal equilibrium with the phantom in about 5 minutes; the sheath designed by NPL has a wall thickness of 1.5 mm.
2. The sheath should be vented to allow the air pressure in the chamber to reach ambient air pressure quickly.
3. The temperature of the air in the chamber should be taken as that of the water phantom when in equilibrium; the water temperature should be measured, as it will usually be a degree or so below that of room temperature due to evaporation. Covering the surface of the water with plastic balls or bubble wrap limits the rate of water evaporation and minimises any temperature difference between the room air temperature and that of the water.
4. Water phantoms, particularly with thin windows, should not be left full of water for longer than necessary otherwise the phantom dimensions may temporarily change as water is absorbed by Perspex; similarly, Perspex waterproof sheaths should not be left in water longer than necessary.
5. It is difficult to determine the relative humidity of the air in a chamber, however the correction for any differences between the humidity at the time of measurement and 50% relative humidity for which the calibration factor applies is small (a maximum of 0.1% for a relative humidity between 10 and 90%), and can usually be neglected.

#### **4.1.2 Ion recombination correction**

The secondary standard calibration factors relate to conditions of zero ion recombination so that strictly all subsequent chamber readings should be corrected for ion recombination losses.

The correction for ion recombination is the sum of two components, initial recombination that is independent of dose-rate and general or volume recombination, which is dose-rate dependent. Initial recombination is usually dominant for continuous radiation i.e. from a Cobalt 60 unit, whilst for pulsed radiation from a linear accelerator general recombination is dominant.

For the measurement of pulsed X-ray beams it is recommended that a correction for ion recombination should be made. This can be determined experimentally using the "half voltage" technique; if the chamber reading decreases by  $x\%$  when the polarising voltage is reduced to half its normal value then the recombination correction to be applied to the reading at the normal polarising voltage is  $+x\%$ .

Alternatively for the NE 2561 and NE 2611 chambers, when operated with a polarizing potential of -200 volts the percentage correction for ion recombination

for pulsed radiation ( $k_{ion}$ ) may be calculated from the equation (Burns and Rosser 1990 [9]):

$$k_{ion} = 1.0014 + 0.23p \quad (4)$$

where  $p$  is the dose per pulse in centigrays at the chamber.

The first term in the expression represents the initial component and the second term the general component of the recombination correction.

In continuous radiation beams, as from a  $^{60}\text{Co}$  unit, the recombination correction may be neglected since it is normally small.

#### 4.1.3 Quality-dependent correction factor $k_Q$

The UK primary standard has been used to determine the absorbed dose to water calibration of many chambers of types NE 2561, NE 2611 and NE 2571, and for each quality listed in Appendix 1.

For each chamber, the absorbed dose calibration is expressed as a product:

$$N_{w,Q} = N_{w,Q_0} \cdot k_Q \quad (5)$$

Where:

$N_{w,Q}$  is the absorbed dose to water calibration factor in a photon beam of quality  $Q$ ,

$N_{w,Q_0}$  is the absorbed dose to water calibration factor in the  $^{60}\text{Co}$  reference quality,

$k_Q$  is a quality-dependent correction.

It was found that, for chambers of a given type, the quality-dependent correction

$$k_Q = \frac{N_{w,Q}}{N_{w,Q_0}} \quad (6)$$

did not vary from one chamber to another and that, within the measurement uncertainty, there was no significant difference between the NE 2561 and NE 2611 chamber types so far as  $k_Q$  was concerned. Table 1 lists the quality dependent correction factors obtained for each chamber type: although given to four significant figures, this should not be taken as an indication of the uncertainty on the absorbed dose calibration factor  $N_{w,Q}$  in Equation (5).

Quality Index, TPR <sub>20/10</sub>	Nominal Energy MV	k <sub>Q</sub>		
		NE 2561	NE 2611	NE 2571
0.568	<sup>60</sup> Co	1.0000	1.0000	1.0000
0.621	4	0.9986	0.9986	0.9958
0.670	6	0.9941	0.9941	0.9910
0.717	8	0.9885	0.9885	0.9865
0.746	10	0.9815	0.9815	0.9808
0.758	12	0.9781	0.9781	0.9766
0.779	16	0.9717	0.9717	0.9695
0.790	19	0.9670	0.9670	0.9635

**Table1** Quality-dependent correction factor k<sub>Q</sub>

## 5. Uncertainties

The uncertainties in the determination of absorbed dose to water are given in Table 2. The uncertainty evaluation was carried out in accordance with UKAS requirements (NAMAS (1997)[10]). The reported uncertainties are based on a standard uncertainty multiplied by a coverage factor  $k = 2$ , providing a level of confidence of approximately 95%.

Source of uncertainty	Standard Uncertainty	
	%	
	Type A	Type B
Calibration of the reference standard ionisation chambers in graphite by comparison with the primary standard calorimeter	0.2	0.5
Conversion of the reference standard calibration from graphite to water	-	0.5
Comparison of the secondary standard dosimeter with the reference standard	0.1	0.1
Quadratic sum	0.2	0.7
Combined uncertainty	0.7	
Expanded uncertainty ( $k = 2$ )	1.4	

**Table 2** Component uncertainties of the absorbed dose to water calibration

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## APPENDIX 1

### High-energy photon qualities used for therapy level absorbed dose to water calibrations

TPR <sub>20/10</sub>	Beam Energy, MV	Target Thickness, mm W	Beam flattening filter, mm	Aluminium Beam filter, cm	Reference depth in water, cm
0.568	<sup>60</sup> Co	-	-	-	5
0.621	4	3	3 Cu	5	5
0.670	6	3	3 Cu	5	5
0.717	8	3	4 Cu	10	5
0.746	10	3	5 Cu	14	5
0.758	12	3	3 W	13	7
0.779	16	5	4 W	13	7
0.790	19	5	5 W	13	7

The TPR<sub>20/10</sub> is the ratio of ionisation measurements at 20 cm and 10 cm depth in water for a constant source to chamber distance and with a 10 x 10 cm field at the chamber. The thickness of the beam flattening filter is measured at the centre of the filter i.e. the thickest point.

The beam energy is the nominal accelerating potential in megavolts applied to the electron beam incident on the X-ray target at NPL and should not be taken to characterise the beam quality.

# Electron Dosimetry Practical Session Course Notes

## 1 Overview

The aim in this session is to cover the IPEM 2003 absorbed dose-based Code of Practice, an overview of the formalism, practical procedures and recommendations. The majority of the session is also relevant to the IAEA's TRS-398 and AAPM's TG-51 protocols.

Under this regime, electron beam therapy level chambers are calibrated at NPL directly in terms of absorbed dose to water over a range of energies. This is similar to the protocol in place for the photon beam calibration service, which has been used since 1988. Each hospital then follows the Institute of Physics and Engineering in Medicine Code of Practice for Electron Dosimetry (IPEM 2003) to derive absorbed dose under reference conditions in the hospital. The electron beam calibration service at NPL currently accepts chambers for calibration during a limited period each year. The designated parallel-plate chamber ionisation chambers for use with the code are the NACP-02 manufactured by Scanditronix and the Roos type 34001 parallel-plate chamber manufactured by PTW. Cylindrical graphite walled Farmer chambers: NE2571 and PTW 30004, can also be used in high-energy ( $> 10$  MeV) beams. The Code of Practice recommends that chambers are calibrated every two years.

The previous regime started from a NPL air kerma-based cobalt-60 photon beam calibration of an NE2561 or NE2611 chamber, and the Institute of Physics and Engineering in Medicine and Biology (IPEMB 1996) code of practice was used to derive absorbed dose under reference conditions in the hospital. This procedure was more complicated involving a transfer of calibration to an NE2571 Farmer chamber, a conversion to take into account the change in modality and quantity, and a transfer of calibration in a high-energy electron beam. The beam quality index has changed and the designated chambers have also changed, in the newer code.

## 2 The absorbed dose calibration service

### 2.1 Overview of its development

In 1989 the National Physical Laboratory (NPL) introduced a calorimeter-based direct absorbed-dose-to-water calibration service for megavoltage photon beams and a Code of Practice based on this service was published by IPSM (1990). Over recent years NPL has developed a similar calibration service for electron beams.

The calibration is a two-step process. First, approximately annually, reference ionisation chambers are calibrated against the primary standard electron beam calorimeter in a graphite phantom (McEwen *et al*, 1998). A theoretical conversion is then carried out to transfer the dose from graphite to water. User chambers are then compared with the NPL reference chambers in a water phantom. The formalism was first proposed by Burns *et al* (1994) and is described in detail in Appendix C of IPEM 2003. The uncertainty in such a calibration is estimated to be  $\pm 2\%$  at the 95% confidence level, representing a significant improvement over air kerma-based protocols (e.g. IPEMB, 1996; IAEA, 1987, 1996).

Prior to the introduction of this new code a number of trial calibrations of the service

have been carried out. The trials are described in detail by McEwen *et al* (2001) but in summary, generally all chambers of a particular type were found to show the same energy response. However, it was also found that polarity and recombination corrections were quite variable for Markus chambers. Differences in the polarity correction of up to 1% were seen for the same chamber at different times and/or for different chambers in the same electron beam. No significant difference in energy response was seen between the NACP and Roos chamber types. The results of the comparison between the NPL calibration and IPEMB 96 Code show agreement between the two methods at the  $\pm 1\%$  level for the NACP and Farmer chambers. However, for Markus chambers the results were much more variable with a mean difference of around 2%.

## 2.2 Calibration procedure

The first step in carrying out the calibration of ion chambers is to define the reference depth at which measurements are made. Burns *et al* (1996) give an expression for the best choice of reference depth  $d_w$ ;

$$d_w = 0.6R_{50} - 0.1 \quad (1)$$

where both  $d_w$  and  $R_{50,w}$  are in cm. This depth is very close to the depth of the dose maximum in clinical beams at low energies, where the dose maximum is well defined. At higher energies, where the depth of dose maximum varies significantly from one accelerator to another for a given value of  $R_{50,w}$ , this equation specifies a more robust reference depth which is generally beyond the dose maximum. The Primary standard is a graphite calorimeter, so a measurement depth in graphite must be chosen. If the reference depth in graphite,  $d_g$ , is chosen such that

$$d_g = \frac{R_{50,g}}{R_{50,w}} d_w \quad (2)$$

(where the subscripts  $w$  and  $g$  refer to water and graphite respectively) then the electron spectrum at the reference depth will be similar for each phantom.

The NPL primary standard graphite calorimeter for electron beam dosimetry covers the dose range from therapy levels of typically 1 Gy up to kilogray dose levels. The main calorimeter body is a graphite core and a graphite jacket. The core, where the dose is measured, is a disc 50 mm in diameter and 2 mm thick. The graphite jacket is 150x150 mm in cross section and 6 mm in thickness. The core is thermally isolated from the jacket by a nominal 1 mm air gap at all faces. Graphite plates are added in front of the calorimeter body to position the core at the desired measurement depth and also added to the rear to provide backscatter. The thickness of this backing depends on the incident beam energy and on the measurement depth and is chosen so that the temperature rise in the backing is as close as possible to that in the core. The entire calorimeter assembly is enclosed in 25 mm of polystyrene foam to provide a degree of thermal isolation. The design is simple because the measurement area at the NPL linear accelerator can be controlled in temperature to  $\pm 0.2$  °C. By working at a dose rate above 5 Gy/min one can obviate the need for complex temperature control and vacuum systems within the calorimeter. The calorimeter has been previously validated by

comparison with the primary standard photon calorimeter in a 16 MeV electron beam. The two calorimeters were found to agree within the measurement uncertainties (DuSautoy, 1996).

The calorimeter is used at NPL to calibrate a set of reference chambers in graphite at this reference depth;

$$N_{ref,g} = \frac{D_d}{M_{ref,g}} \quad (3)$$

where  $N_{ref,g}$  is the absorbed dose-to-graphite calibration factor for each reference chamber and  $M_{ref,g}$  is the corrected chamber reading at the depth  $d_g$  in graphite and  $D_d$  is the dose recorded by the calorimeter.

The absorbed dose to water calibration factor  $N_{D,w}$  for a user chamber is derived by direct comparison of the user chamber against an NPL reference electron chamber at a reference depth  $d_w$  in a water phantom in the NPL beam. It can be shown using cavity ionization theory that

$$N_{D,w} = N_{ref,g} \frac{M_{ref,w}}{M_{user,w}} \frac{p_{ref,w}}{p_{ref,g}} \frac{s_{w/air}}{s_{g/air}} \quad (4)$$

Here,  $M_{ref,w}$  and  $M_{user,w}$  are the corrected chamber readings at the depth  $d_w$  in water, for the reference and user chambers respectively. The perturbation factors,  $p_{ref,w}$  and  $p_{ref,g}$ , for the reference chamber correct for the presence of the chamber in water and graphite respectively (Williams *et al*, 1998), while  $s_{w/air}$  and  $s_{g/air}$  are ratios of mean stopping powers of water and graphite, respectively, to those of air. Burns *et al* (1995) describe one method of obtaining the ratio of stopping powers. To reduce the dependence on any one chamber, the value of  $M_{ref,w}$  is taken as the mean response of all the NPL reference NACP chambers.

One of the principal advantages of this method compared to an air-kerma based approach is that each ion chamber is characterised at a number of electron energies. Measurements made at NPL indicate that there are much larger chamber-to-chamber variations in electron beams compared to photon beams. It is therefore less reliable to assume that all chambers of a certain type behave in the same way, as is done in the majority of codes. By using the calorimeter we obtain the absorbed dose at each electron beam quality directly. Although there is still a two-step process to obtain absorbed dose to water, the uncertainty in this approach is significantly less than that associated with air-kerma based Codes of Practice. Ideally one would use a water calorimeter to derive the absorbed dose to water directly in a water phantom, but this is not a practical solution at the moment.

### 2.3 NPL calibration certificate

The chamber calibration certificate has three sections:

- i) Basic information identifying the customer, calibrated chamber and date of calibration

- ii) Tables giving the calibration data
- ii) Appendices giving detail on the calibration process

A separate certificate will be issued for electrometer calibrations.

Table 1 of the certificate gives the calibration factors,  $N_{D,w}$ , by which the chamber response in coulombs (C) has to be multiplied in order to determine absorbed dose to water in grays. The factors are for air in the chamber at a temperature of 20 °C and a pressure of 101.325 kPa (1013.25 mbar). Corrections for ion recombination and polarity have also been applied. No correction is made for relative humidity. Figure 1 shows the variation in calibration factor with beam quality. Table 2 gives the ion recombination parameters and Table 3 gives information on the recombination and polarity corrections applied at NPL. Recombination measurements are carried out to enable the user to apply a recombination correction if the dose per pulse from the linear accelerator is approximately known.

The Appendix to the certificate gives detail of the calibration procedure and corrections applied. In certificates prior to publication of the IPEM 2003 Code of Practice a second appendix was provided giving the procedure to follow in order to use the supplied calibration factors. Although this procedure was in accordance with the recommendations in IPEM 2003, the Code of Practice itself must now be used instead.

### 3 Codes of Practice

A copy of the IPEM 2003 Code is provided with these lecture notes, so only a brief outline of the main philosophy behind the code is given here. Since the IPEM 1996 Code is not part of the course material the most important practical steps in this air kerma-based Code are given in Appendix A. IPEM has recommended that all hospitals in the UK move to using the IPEM 2003 Code by the end of 2006.

#### 3.1 IPEM 2003 Code of Practice

The formalism for the determination of absorbed dose to water in an electron beam is conceptually simple since the desired quantity is the one for which the ionisation chamber has been calibrated. The application of the chamber calibration factor,  $N_{D,w}$ , to measure absorbed dose is thus straightforward. With the chamber positioned at the reference depth,  $z_{ref}$ , a fully corrected chamber reading  $M_{ch,w}$  is taken and the dose to water,  $D_w$ , is given by

$$D_w \text{ at } z_{ref,w} = M_{ch,w} N_{D,w}(R_{50,D}) \quad (5)$$

where the correct value of  $N_{D,w}$  is interpolated from the table of calibration data for the particular chamber.  $N_{D,w}$  is given as a function of  $R_{50,D}$ , which is the depth in water, expressed in  $\text{g cm}^{-2}$ , where the dose reduces to 50% of the maximum dose on the depth dose curve, and is used as a measure of the beam quality.

The following points are the important pieces of information and steps to pay attention to, and are needed to accurately apply and understand the code:

- Desirable properties for electron ionisation chambers, and designated

- chambers
- Beam quality specification, reference depth and reference conditions for reference dose measurement
- Determination of the absorbed dose to water calibration factor  $N_{D,w}$ .
- Determination of corrections to the instrument reading for temperature, pressure, humidity, polarity, recombination and electrometer calibration.
- Calculation of stopping powers needed for converting ionisation to dose for measurements in non-reference conditions (e.g. the conversion to  $d_{max}$ )
- Use of non-water phantoms
- Measurements in non-reference conditions
- Justification of the procedures and data used

### 3.2 The IPEMB 1996 Code of Practice

This Code was the predecessor of the IPEM 2003 Code. A summary of the main steps needed to apply the code is given in Appendix A.

## 4 Uncertainties.

The uncertainties are given in Appendix B. By using the new absorbed dose code, the uncertainty in measuring absorbed dose is reduced by approximately a factor of two, a significant improvement.

Although a number of these uncertainties are fixed in that they relate to a chamber calibration or to tabulated data, there is still significant scope for the user to influence the overall uncertainty in measuring absorbed dose to water. In order to achieve an uncertainty close to the optimum values given in the IPEM 2003 Code, careful attention must be paid to the following:

- Determination of the beam quality and the absorbed dose to water calibration factor,  $N_{D,w}$ , and determination of stopping powers for converting doses between depths.
- Experimental set up - SSD, field size, position of chamber, phantom size.
- Polarity and recombination corrections
  - Allow sufficient time for the chamber to settle after changing the polarising voltage.
  - Be aware of how the linac operates - some linacs operate with a constant dose per pulse, while others have a different dose per pulse, for different energies. Although the recombination correction is not energy dependant it is possible to obtain an apparent energy dependence, if any change of linac operation with energy is not taken into account.
  - In the interests of saving time, polarity measurements are not always made when measuring output factors. Ensure that any applied polarity correction is relevant to the energy and depth being used.
- Chamber measurement
  - Pre-irradiate the chamber and monitor

- Take enough readings to ensure that the chamber has settled
- Operate the chamber in the linear region of the recombination curve

## 5 References

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## APPENDIX A REVIEW OF THE IPEMB 1996 CODE OF PRACTICE

### A.1 Calibration of a plane-parallel chamber in a high-energy electron beam

There is a quite general consensus that the preferred method for electron dosimetry is to use a plane-parallel ionisation chamber calibrated in an electron beam, since perturbation factors for plane-parallel chambers in photon beams are not well understood. In practice, a hospital using the 1996 Code should therefore calibrate its plane-parallel chamber in a high-energy electron beam against a cylindrical ionisation chamber.

An additional problem with the air kerma-based procedure for electrons is that the recommended secondary standard type NE2561 chamber is not recommended for use in electron beams. So a procedure is given to enable cross calibration of a NE2571 chamber against the secondary standard, followed by a cross calibration of the plane-parallel chamber against the NE2571 in a high-energy electron beam.

#### A.1.1 Calibration of the NE2571 chamber in $^{60}\text{Co}$

The secondary standard (NE2561) chamber and the NE2571 chamber should be placed in turn with their centres at a depth of 5 cm in a Perspex phantom irradiated by  $^{60}\text{Co}$   $\gamma$ -radiation. Phantom size, field size and source-to-surface distance, are all specified in the Code.

From these measurements the calibration factor  $N_{D,air}$  for the NE2571 chamber is given by

$$N_{D,air,2571} = 0.978 N_{K,sec} \frac{M_{sec}}{M_{2571}} \quad (6)$$

where  $M_{sec}$  and  $M_{2571}$  are, respectively, the secondary standard and electron chamber readings (corrected to standard ambient conditions and for ion recombination and polarity effects). The factor 0.978 converts the in-air secondary standard calibration,  $N_{K,sec}$ , to an in-phantom calibration. Although  $^{60}\text{Co}$  is recommended, this measurement is usually made in a 6 MV linac beam. This should not significantly affect the determination of  $N_{D,air}$  for the Farmer chamber.

#### A.1.2 Comparison of parallel-plate chamber with NE2571 chamber

This should be carried out in a high-energy electron beam ( $E_0 > 15$  MeV) with both chambers positioned at the reference depth. The calibration factor,  $N_{D,ai,pp}$  for the parallel plate chamber is given by

$$N_{D,air,pp} = \frac{M_{2571} N_{D,air,2571} p_{cav,2571}^e(E_z)}{M_{pp} p_{pp}^e(E_z)} \quad (7)$$

All chamber readings should be corrected to standard ambient conditions and for ion recombination and polarity effects.  $p_{cav,2571}^e$  is the in-scattering perturbation factor in electrons for the NE2571 and  $p_{pp}^e$  is the overall perturbation factor for the parallel plate chamber. These factors are dependent on the energy at the measurement depth  $E_z$  and

are given in the Code. A high-energy electron beam is used for this transfer to minimise the perturbation correction for the Farmer chamber.

## A.2 Dose at the reference point in the user electron beam

For measurements in the user electron beam the electron chamber should be used in a water phantom whenever possible. The NACP and Roos chambers are waterproof. The Farmer chamber must be used with a waterproof sheath and the Markus chamber must be used with the waterproof window supplied with the chamber. The electron chamber should be placed with its effective point of measurement at a depth  $z_{ref,w}$  in the water phantom (or at an equivalent scaled depth for non-water phantoms). The reference depth is defined as  $d_{max}$  or  $0.5R_{50}$ , whichever is the greater. The absorbed dose to water  $D_w(z_{ref,w})$  at the depth  $z_{ref,w}$  is given by

$$D_w(z_{ref,w}) = M_{ch,w}^e N_{D,air,ch} S_{w/air}^e(\bar{E}_0, z_{ref,w}) P_{ch}^e(\bar{E}_z) \quad (8)$$

where  $M_{ch,w}^e$  is the corrected chamber reading in water,  $S_{w/air}$  is the appropriate water-to-air stopping power ratio for an electron beam of mean surface energy  $E_0$  at depth in water  $z_{ref,w}$ .  $P_{ch}^e$  is the perturbation factor applicable to the particular ion chamber. Values for these last two factors are given in the Code.

## A.3 Extracting data

### A.3.1 Determination of energy parameters of electron beams

Energy parameters are required in the IPEMB 1996 Code to determine the water/air stopping power ratio and for the selection of the fluence-ratio correction factor,  $h_m$  when using non-water phantoms. In the new Code, calibration factors are given as a function of  $R_{50}$ .

The mean energy of an electron beam at the surface of the phantom,  $\bar{E}_0$ , can be related to the depth in water at which the ionisation or dose is 50% of the maximum ( $R_{50,I}$  and  $R_{50,D}$  respectively). This can be either at fixed source-to-chamber distance (SCD), i.e. corresponding to a non-divergent beam, or at a fixed source-to-surface distance (SSD) as long as appropriate relationships are used for the link between  $R_{50}$  and  $\bar{E}_0$ . It is generally more convenient to use a fixed SSD geometry. All practical measurements should be made at an SSD of at least 100 cm and in a field size at least large enough to give scatter equilibrium at the central axis, i.e. so that the values are independent of field size. This is generally achieved with field sizes of approximately 12 cm x 12 cm for energies up to 15 MeV and approximately 20 cm x 20 cm for higher energies.

The relationship between  $\bar{E}_0$  and  $R_{50}$  for a fixed SCD is of the general form

$$\bar{E}_0 = CR_{50} \quad (9)$$

where  $C$  is a constant. (Here  $R_{50}$  is given no qualifying subscript, as this can be applied to both  $R_{50,D}$  and  $R_{50,I}$ .) The constant  $C$  is taken to be  $2.33 \text{ MeV cm}^{-1}$  for  $R_{50,D}$  in centimetres in water and  $2.38 \text{ MeV cm}^{-1}$  for  $R_{50,I}$  in centimetres in water.

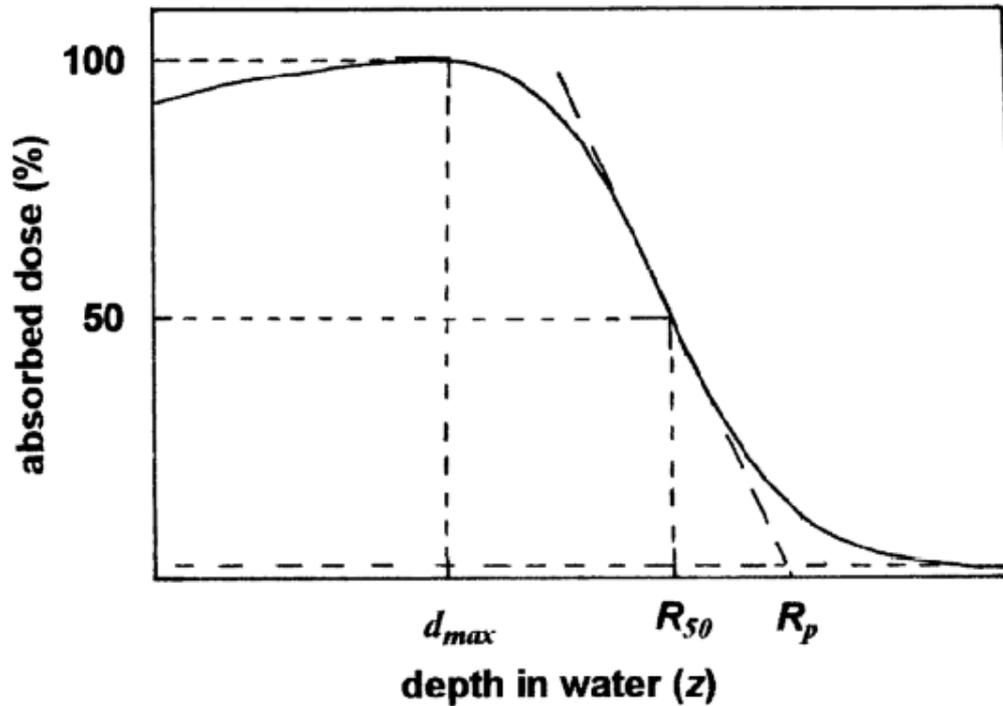


Figure 1. An electron beam depth-dose distribution in water showing the various range parameters.

When the  $R_{50}$  is taken from a dose distribution obtained with a constant SSD this equation is not valid. In this case NACP (1980) have provided tabulated data for determining  $\bar{E}_0$  either from ionisation curves measured at SSD = 100 cm with an ionisation chamber or from depth-dose distributions at SSD = 100 cm; this has also been given by IAEA (1987). For convenience these tabulated data are given here in the form of a second-order polynomial (IAEA 1996):

$$\bar{E}_0 \text{ (MeV)} = 0.818 + 1.935R_{50,I} + 0.040(R_{50,I})^2 \quad (10)$$

$$\bar{E}_0 \text{ (MeV)} = 0.656 + 2.059 R_{50,D} + 0.022(R_{50,D})^2 \quad (11)$$

for the cases of  $R_{50}$  determined from a depth-ionisation and depth-dose curve respectively.

It must be noted that the value of  $\bar{E}_0$  determined as above must then be used for all situations using that particular beam setting on that machine, including measurements and calculations for small field sizes which have depth-dose curves that are different in shape from those of larger field sizes.

The practical range  $R_p$  is required to obtain an estimate of the mean energy at depth,  $\bar{E}_0$  (this is only required for the selection of the fluence-ratio correction factor,  $h_m$ , when using non-water phantoms). It is defined as the depth at which the tangent to the steepest part of the descending region of the depth-dose, or depth-ionisation, curve intersects with the extrapolation of the bremsstrahlung tail of the distribution (see Figure 1). Again this must be determined from measurements in a reasonably large field

and at an SSD of at least 100 cm. There is no  $D$  or  $I$  subscript here as the value should be the same irrespective of which curve is used.

## A.4 Dose measurement

### A.4.1 Choice of reference depth and the effective point of measurement

The reference depth in the IPEMB 1996 Code this is defined as  $d_{max}$  or  $0.5R_{50,w}$ , whichever is greater. Although  $d_{max}$  is the depth of clinical interest, the peak is often shifted to very shallow depths due to the presence of low energy scatter. It was explained in the IPEMB 1996 that for such shallow values of  $d_{max}$  the stopping power ratios for clinical beams can deviate substantially from the tabulated stopping powers for mono-energetic electron beams, hence the use of an alternative reference depth.

A practical ionisation chamber does not sample the true electron fluence which is present in the undisturbed phantom at the point corresponding to the geometrical centre of the chamber cavity. The difference between this and the fluence in the cavity depends on a number of factors, one of which is the fluence gradient across the chamber. This gives rise to the concept of the effective point of measurement  $P_{eff}$ . The displacement of  $P_{eff}$  from the geometrical centre depends mainly on the chamber geometry; and for practical use it is assumed to be independent of depth. The important point to note is that the same effective point of measurement is used during calibration of the chamber and its subsequent use. This ensures the accurate transfer of the dose from the primary laboratory to the reference point in the user's beam.

For cylindrical chambers used in megavoltage electron beams around and beyond the depth of dose maximum a displacement of  $0.6r$  towards the radiation source gives a reasonable representation of the experimental data (but see Kawrakow 2006 in the references!), where  $r$  is the internal radius of the cavity. For parallel-plate chambers,  $P_{eff}$  is taken to be at the centre of the inside surface of the chamber window.

The absorbed dose calibration of parallel-plate chambers takes account of the water equivalent thickness of the chamber front window therefore this should also be taken into account when using such chambers to determine dose. For cylindrical chambers no correction is made for the non-water material of the sheath (assuming that the sheath is thin).

Chamber type	Front window	Water equivalent thickness (mm)
NACP	0.5 mm graphite + 0.1 mm Mylar <sup>®</sup>	1.0
Roos	1 mm PMMA	1.2

### A.4.2 Choice of non-water phantom, depth scaling and the fluence-ratio correction

It is recommended that water phantoms should be used wherever possible for the experimental procedures involved in the absolute calibration of electron beams. The designated electron chambers either have built-in waterproofing or can be readily

waterproofed and the use of modern water tank systems can give precise positioning even for relatively shallow measurement depths. However it is recognised that in certain situations, particularly for lower-energy electron beams and the use of parallel-plate chambers, it may be more convenient to use solid plastic phantoms. In this case the depths need to be scaled to water-equivalent depths and the chamber reading needs to be multiplied by an appropriate fluence-ratio correction. All other points mentioned earlier with regard to measurements in water phantoms should be essentially unchanged. In particular, the stopping-power ratios selected should be the same as in the water case, but at the appropriate scaled depth.

Whilst the use of any plastic phantom may decrease positional uncertainties, it will increase the uncertainty on the dose value obtained due to the inclusion of the fluence-ratio correction and due to differences in behaviour of different samples of the same nominal material. The allowed plastic phantoms in this code of practice are polystyrene, polymethylmethacrylate (PMMA, Perspex or Lucite) and epoxy-resin-based water-substitute phantom materials (Solid Water, WTe etc). Epoxy-based materials are preferred because they are less likely to have batch-to-batch variations. Greater uncertainties are attached to measurements made with polystyrene and PMMA.

PMMA is a good insulator and can exhibit charge storage effects as a result of the stopped electrons being trapped in the material, which can significantly change the measured chamber reading in a non-predictable way. These effects appear to be negligible in the epoxy-resin-based materials. To reduce the impact of charge storage on measurements in an insulating plastic, a phantom should be constructed of several sheets, with that containing the chamber preferably not greater than 12 mm in thickness. The use of the Farmer chamber is not recommended in an insulating plastic phantom unless regular checks are made by comparing its response in a conducting (or epoxy resin) material to ensure that charge storage is not affecting the measurements. When using parallel-plate chambers, the effects are typically reported as insignificant.

The effective water depth,  $z_{w,eff}$ , which can be taken as an approximation to the depth of water, which is equivalent to a given depth in a plastic phantom, can be obtained from scaling:

$$z_{w,eff} = w_{non-w} C_{pl} \quad (12)$$

The recommended values of the scaling factors,  $C_{pl}$ , are given in the Code, based on experimental measurements and normalised to the stated densities for the given plastics. It is recommended that the density of the plastic to be used is measured and the scaling factor is multiplied by the ratio of the measured density to the quoted standard density. If the densities are significantly different to the quoted standard densities for the sample of plastic to be used in the hospital,  $R_p$  can be measured for a higher-energy electron beam both in water and in the plastic and the ratio  $R_{p,w} / R_{p,non-w}$  determined, to use in place of  $C_{pl}$ . Note that  $C_{pl}$  is taken to be energy independent.

Measurements to determine the absorbed dose in an electron beam, using a plastic phantom, are to be made following the *same* general principles as for a measurement in water. The SSD and the field size are not to be scaled and the phantom must be of a sufficient size to provide full side and back scatter. The chamber must be positioned with its effective point of measurement at the equivalent scaled reference depth in the plastic

phantom.

The expression to be used to evaluate the absorbed dose to water for the IPEM 2003 code in this situation is

$$D_w(z_{w,eff}) = M_{ch,non-w} h_m N_{D,w} \quad (13)$$

and

$$D_w(z_{w,eff}) = M_{ch,non-w}^e h_m N_{D,air,ch} S_{w/air}^e(\bar{E}_0, z_{ref,w}) P_{ch}^e(\bar{E}_z) \quad (14)$$

for the IPEM 1996 Code.  $h_m$  is the fluence-ratio correction, which must be selected from the data given in Codes.

Note that only representative values are given in the 2003 code and the user is referred to the 1996 Code for more detail. The stopping power ratio and perturbation factors in Equation (14) are as derived for a measurement in water. The interpolated value of  $N_{D,w}$  in Equation (13) should be derived from the calibration data for  $R_{50,D}$  measured in water, not plastic.

## APPENDIX B UNCERTAINTIES

### B.1 IPEM 2003 Absorbed dose Code of Practice

#### i) Uncertainty in chamber calibration factor

The uncertainties for all energies (quoted as standard uncertainties according to UKAS document M3003 (1997)) are given below.

Uncertainties in the calibration of an ionisation chamber in terms of absorbed dose to water

Source of uncertainty	Standard Uncertainty ( $\pm$ %)	
	Type A	Type B
Graphite calibration factor for NPL chambers	0.25	0.25
Ratio of chamber measurements	0.1	
Ratio of stopping powers		0.5
Ratio of perturbation factors		0.7
Recombination correction	0.17	
Polarity correction	0.1	
Electrometer calibration	0.05	
Quadratic sum	0.34	0.90
Combined uncertainty		0.96

#### ii) Realisation of absorbed dose-to-water in a water phantom by user

The uncertainties in the determination of absorbed dose to water with a calibrated ion chamber are given below (optimum values are given).

Uncertainties in the determination of absorbed dose to water

Source of uncertainty	Standard Uncertainty ( $\pm$ %)	
	Type A	Type B
Water calibration factor for user chambers	0.34	0.90
Matching of NPL and clinical beam qualities		0.3
Practical set and chamber measurement per MU <sup>[a]</sup>	0.50	
Influence factors	0.25	
Measuring chamber stability	0.25	
Electrometer calibration	0.05	
Quadratic sum	0.7	0.95
Combined uncertainty		1.2

<sup>a</sup> This is a conservative estimate of the uncertainty and a significant increase on what was included in the uncertainty estimate in the 1996 Code.

### iii) Non-water phantoms

These will increase the uncertainties due to the use of scaling factors and fluence ratios, but decrease the positional uncertainties a little. Due to the likely batch-to-batch variations in polystyrene and PMMA the estimated uncertainty is increased relative to epoxy-based water substitutes. Overall an estimated additional uncertainty of around 0.7% and 1.0% (1 sd) may be introduced for epoxy materials and the "ordinary" plastics respectively. Thus, using a non-water phantom, the equivalent estimated uncertainties are:

Epoxy-based water substitutes	Combined standard uncertainty	1.4%
PMMA	Combined standard uncertainty	1.5%
Polystyrene	Combined standard uncertainty	1.6%

These values are valid for both parallel-plate and Farmer chambers.

## B.2 IPEMB 1996 air kerma based Code of Practice

### i) NE2571 $N_{D,air}$

Source of uncertainty	Type A	Type B
$N_K$ (Sec Std)	0.25	0.6
Stability of Sec Std	0.2	
Chamber ratio <sup>[1]</sup>	0.15	
Factors to convert to $N_{D,air}$		0.5
Combined	0.35	0.78
Total uncertainty	0.85	

<sup>[1]</sup> The charge calibration of the electrometer can be a type B uncertainty but it appears as a type A when comparing  $N_{D,air}$  values obtained at different times.

### ii) Parallel plate $N_{D,air}$

Source of uncertainty	Type A	Type B
Calibration of NE2571	0.35	0.78
Chamber ratio <sup>[2]</sup>	0.2	
Perturbation factors for chambers		0.7
Combined	0.40	1.05
Total uncertainty	1.12	

<sup>[2]</sup> The polarity and recombination corrections are treated as Type A for the purpose of comparing  $N_{D,air}$  values obtained at different times.

### iii) Dose measurements - Parallel plate chamber

Source of uncertainty	Type A	Type B
$N_{D,air}$	0.40	1.05
Set up	0.1	
Instrument reading <sup>[3]</sup>	0.1	0.2
Physical constants ( $s_{w/air}$ , $p_{ch}$ ) <sup>[4]</sup>	0.3	0.9
Combined	0.52	1.40
Total uncertainty	1.5	

<sup>[3]</sup> The recombination and polarity corrections are treated as Type B for the purpose of comparing dose measurements in the same electron beam

<sup>[4]</sup> The Type A component is due to the determination of  $R_{50}$  etc to derive these parameters

# HDR Brachytherapy Dosimetry at the NPL

## 1 Introduction

Brachytherapy is a special procedure in radiotherapy that utilises the irradiation of a target volume (e.g. malignant cells) with radioactive sources placed at short distances from the target. 'Brachytherapy' is the Greek word for 'short distance treatment'. The opposite is 'teletherapy' where an external radiation source is used, e.g. an X-ray tube or a linear accelerator.

The radioactive sources are either implanted in the target tissue directly (interstitial brachytherapy) or are placed at distances of the order of a few millimetres from the target tissue, in body cavities such as the uterus, lung, mouth, etc. (intracavitary brachytherapy), or externally on structures such as the eye or the skin (ophthalmic applicators or surface moulds).

Shortly after the discovery of radium by Marie and Pierre Curie in 1898, the naturally occurring radioisotope  $^{226}\text{Ra}$  and also the daughter nuclide radon ( $^{222}\text{Rn}$ ) were used for cancer treatment (Mould *et al.* 1994). When artificially produced radionuclides became available from nuclear reactors and particle accelerators, many new radionuclides entered the brachytherapy field. Nowadays radionuclides used in brachytherapy include photon emitters, beta emitters and neutron emitters (Thomadsen *et al.* 2005).

Brachytherapy dose rates cover a very wide range leading to treatment times varying from minutes to months and have been divided into low, medium and high dose rates by the International Commission for Radiation Units and Measurements (ICRU) Report No. 38 as follows:

Low dose rate (LDR)	0.4 – 2.0 Gy/h
Medium dose rate (MDR)	2 – 12 Gy/h
High dose rate (HDR)	>12 Gy/h (usually 100 – 300 Gy/h)

In the following chapters we will only consider high dose rate (HDR) brachytherapy dosimetry for  $^{192}\text{Ir}$ , at present the most commonly used radioisotope worldwide for HDR brachytherapy.

Iridium-192 is produced in a nuclear reactor via neutron capture by stable  $^{191}\text{Ir}$  and has a half-life of  $73.827 \pm 0.013$  days (Bé *et al.* 1999).  $^{192}\text{Ir}$  decays by beta emission and electron capture to excited states of  $^{192}\text{Pt}$  and  $^{192}\text{Os}$ . The daughters decay to the ground states by gamma emission. The beta particles emitted from the  $^{192}\text{Ir}$  source are either absorbed within the source encapsulation or in the tissue very close to the source, so it is effectively a gamma source.

Iridium-192 has a very complicated gamma ray spectrum. The average energy of the gamma rays emitted by the commercially available Nucletron microSelectron  $^{192}\text{Ir}$ -source, which is placed in a sealed stainless steel capsule, is approximately 397 keV. At NPL we use this type of source for the calibration service, however, there are other afterloaders available, marketed for instance by Varian.

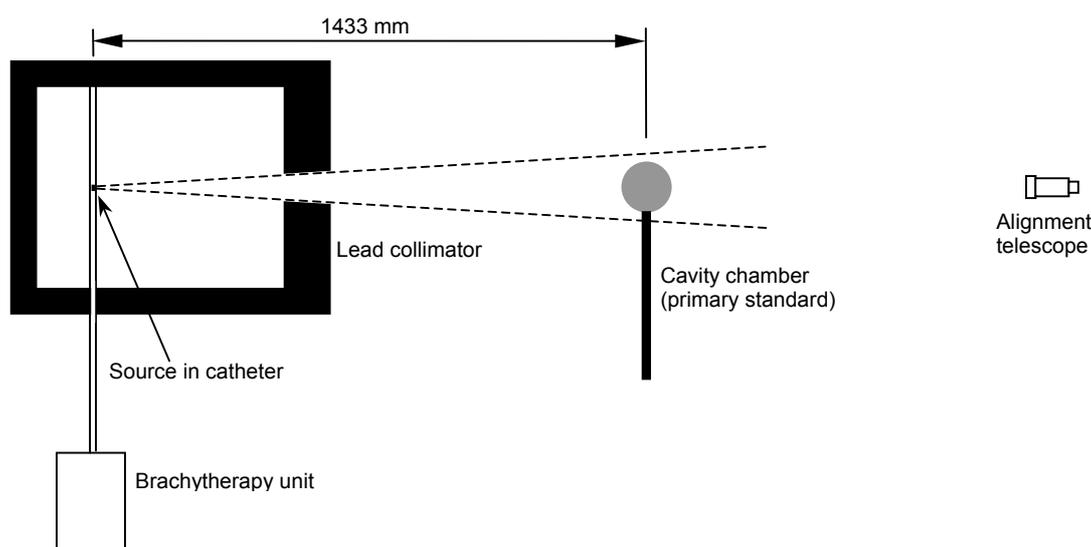
HDR treatments are delivered by remote controlled afterloaders, which are stepper motor driven systems that transport the radioactive source from a shielded safe into the applicator placed inside the patient. After a few minutes the source is driven back to the safe.

## 2 Determination of reference air kerma rate at NPL and in the hospital

In 1985 the ICRU (report no. 38) defined a quantity for the characterisation of gamma ray sources used for brachytherapy, the reference air kerma rate (RAKR), which is the kerma rate to air at a reference distance of 1 m (SI units: Gy/s). The definition assumes a vacuum between the source and the point of measurement. Since this is not the case under ambient conditions in a laboratory, the measurements need to be corrected for air attenuation and scatter due to the air molecules between the source and the point of measurement. The ICRU report also states the direction from the source centre to the reference point shall be at right angles to the long axis of the source (IAEA 2002).

### 2.1 The calibration set-up at NPL

Figure 1 shows the set-up used at NPL for the RAKR measurement.



**Figure 1.** Set-up for  $^{192}\text{Ir}$  HDR source calibration at NPL (not to scale)

NB Measurements are carried out at a source to chamber distance of 1.433 m and corrected to the reference distance of 1 m by applying the inverse square law. At 1.433 m the whole chamber volume is flooded by the collimated beam, at 1 m this wouldn't be the case due to the size of the conical aperture. The lead collimator was developed to reduce the amount of scattered radiation from the floor and the walls of the exposure room reaching the collecting volume of the cavity chamber and to avoid irradiating the chamber stem and connectors.

## 2.2 The measurement of RAKR in the hospital

Hospital physicists need to determine the source strength of their own brachytherapy source before they can write an effective treatment plan. A calibrated dosimeter comprising an ionisation chamber and an electrometer is needed to measure the source strength, i.e. the ionisation current produced in the ionisation chamber being irradiated is measured and then converted to reference air kerma rate.

Let's assume the ionisation chamber and the electrometer are already calibrated, then the source strength can be calculated using the following equation:

$$I \cdot N_{\dot{K}_R} = RAKR \quad (1)$$

where  $I$  is the corrected ionisation current (A) measured by the hospital physicist (= displayed current  $\times$  correction factor (see electrometer calibration certificate)  $\times$  ion recombination correction (see 3.3.1)),  
 $N_{\dot{K}_R}$  is the calibration coefficient of the ionisation chamber (Gy/C) and  
 $RAKR$  is the reference air kerma rate of the hospital source (Gy/s).

In the next chapter we will learn how ionisation chambers are calibrated against the NPL primary standard and how the calibration coefficient of the secondary standard,  $N_{\dot{K}_R}$ , in terms of Gy/C is determined.

## 3 The NPL calibration service for HDR $^{192}\text{Ir}$ dosimeters

### 3.1 Traceability to the NPL primary standard

The HDR brachytherapy calibration service at NPL is for dosimeters (ionisation chambers and electrometers) intended to be used as secondary standards or instruments required for measurement of the greatest accuracy. The ionisation chambers used in the hospital are calibrated directly against the NPL primary standard for  $^{192}\text{Ir}$ .

The calibration is a two-step process:

First, the RAKR of the Nucletron microSelectron Classic  $^{192}\text{Ir}$  HDR source held at NPL is determined using the NPL primary standard cavity chamber. The source is characterised in terms of Gy/s at 1 m.

Once the source strength is known, the  $^{192}\text{Ir}$  source can be used to calibrate an ionisation chamber. The customer's ionisation chamber is connected to a calibrated electrometer, the calibrated source is moved to a reference point near the collecting volume of the chamber and the ionisation current is measured.

The calibration coefficient of the ionisation chamber,  $N_{\dot{K}_R}$ , is the ratio of the primary standard measurement of RAKR to the secondary standard measurement of ionisation current

$$N_{\dot{K}_R} = \frac{(\text{Gy}/\text{s})}{(\text{A})} = (\text{Gy}/\text{C}). \quad (2)$$

The calibration coefficient,  $N_{\dot{K}_R}$ , will be reported on the calibration certificate for the ionisation chamber and enable the hospital physicist to determine the source strength of the hospital source (see equation (1)).

Up to this point we haven't mentioned correction factors and uncertainties, however, the next sections will go into a bit more detail.

### 3.2 Measurement of RAKR at NPL

Let's have a look at the first step of the calibration process, the determination of the RAKR of the NPL  $^{192}\text{Ir}$  source. The NPL has established a spherical graphite-walled ionisation chamber as primary standard for  $^{192}\text{Ir}$ . This chamber was originally used as a high-energy transfer standard for protection level calibrations. The graphite wall of the cavity chamber is 4 mm thick, i.e. there is sufficient build-up material in the chamber wall to provide charged particle equilibrium for secondary electrons produced by  $^{192}\text{Ir}$   $\gamma$ -rays (Goetsch *et al.* 1991).

The primary standard realises the physical quantity of interest (here: RAKR in terms of Gy/s) from first principles. The following measurement equation applies to the NPL primary standard and shows how the RAKR of an HDR  $^{192}\text{Ir}$  source is determined from the measured ionisation current:

$$\dot{K}_R = \frac{I}{\rho_{air} V_{air}} \cdot \frac{W_{air}}{e} \cdot \left(\frac{\bar{S}}{\rho}\right)_{air}^c \cdot k_{fl} \cdot \left(\frac{\mu_{en}}{\rho}\right)_{air}^c \cdot \left[ \frac{1}{(1-\bar{g})} \cdot k_h \cdot \prod_i k_i \cdot \left(\frac{d}{d_{ref}}\right)^2 \cdot k_{air} \cdot \exp\left(\frac{\ln 2 \cdot (t_{now} - t_{ref})}{\tau_{1/2}}\right) \right] \cdot k_{TP} \quad (3)$$

Luckily this equation fits into one row (just). Let's try to understand the physics behind it by following the instructions given to the White Rabbit in Alice's Adventures in Wonderland: begin at the beginning, go on until the end: then stop. We need to convince ourselves that this equation does model the actual RAKR measurement. It is usually a good idea to check the equation by looking at the units.

$\dot{K}_R$  is the reference air kerma rate (Gy/s),  $I$  is the ionisation current (A=C/s) measured at distance  $d$ ,  $\rho_{air}$  is the density of dry air ( $\text{kg}/\text{m}^3$ ),  $V_{air}$  is the internal volume of the chamber cavity ( $\text{m}^3$ ) which was measured in the Centre for Basic, Thermal and Length Metrology at NPL using a co-ordinate measuring machine.  $V_{air}$  was found to be  $1.0252\text{E}-04 \text{ m}^3$  with an uncertainty of 0.12% ( $k=2$ ).

$W_{air}$  is the average energy (J) spent by an electron of charge  $e$  (C) to produce an ion pair in dry air ( $W_{air}/e = 33.97 \pm 0.05 \text{ J/C}$ ).

Check:  $(\text{Gy}/\text{s}) = \frac{(\text{C}/\text{s})}{(\text{kg}/\text{m}^3) (\text{m}^3)} \cdot \frac{(\text{J})}{(\text{C})} = \frac{(\text{J})}{(\text{kg}) (\text{s})} = \frac{(\text{Gy})}{(\text{s})}$

So far, so good! The next two terms follow from cavity theory and need to be applied since the ionisation chamber is made of graphite and not air. The values were evaluated by calculation using Monte Carlo techniques.

$\left(\frac{\bar{S}}{\rho}\right)_{air}^C \cdot k_{fl} = 1.0082$  is the product of the ratio of the mean electron-fluence-weighted electron mass stopping power of graphite to that of air and the fluence perturbation correction factor and

$\left(\frac{\overline{\mu_{en}}}{\rho}\right)_C^{air} = 1.0016$  is the ratio of the mean photon-energy-fluence-weighted photon mass energy-absorption coefficient of air to that of graphite.

The terms in the square brackets are just correction factors (i.e. without units or the units cancel).  $\bar{g} = 0.0007$  is the fraction of secondary electron energy lost to bremsstrahlung in air,  $k_h = 0.9970$  is the humidity correction factor,  $\prod_i k_i$  is the product of further correction factors to be applied to the primary

standard. The biggest correction is the wall correction factor = 1.0453 which needs to be applied because the collecting volume is surrounded by a graphite wall which attenuates and scatters the primary photon beam. Remember, we want to determine air kerma and in the ideal world the photons should only interact with air molecules. There are nine other primary standard correction factors to be applied to the cavity chamber measurements. The stem scatter correction, the recombination correction and the polarity correction were determined by measurement. The other factors were calculated by MC simulation.

The next factor,  $(d/d_{ref})^2$ , follows from the inverse square law and corrects the measured current at distance  $d = 1.433$  m (see Figure 1) to the current that would have been measured at the reference distance  $d = 1$  m.

$k_{air}$  (uncertainty: 0.02%,  $k=2$ ) is the combined air attenuation and scatter correction factor which corrects the measured current at  $d = 1.433$  m for air attenuation and scatter due to the air molecules between the source and the point of measurement (see definition of RAKR in chapter 2).  $k_{air}$  depends on air temperature and pressure and the air attenuation and scatter correction factor is usually in the order of  $1.0158 \pm 0.0006$ .

The next term is the decay correction.  $^{192}\text{Ir}$  has a relatively short half-life,  $\tau_{1/2}$ , and the measured ionisation current at the actual measurement time,  $t_{now}$ , needs to be corrected to a reference time,  $t_{ref}$ . When the secondary standard ionisation chamber is calibrated with the calibrated source, the ionisation current is corrected to the same reference time,  $t_{ref}$ , before the primary standard to secondary standard ratio is calculated.

The last term of Equation 3 is the air temperature and pressure correction factor which converts the ionisation current measured at temperature  $T$  and pressure  $p$  to the standard temperature  $T_{STD} = 293.15$  K and the standard pressure  $p_{STD} = 101.325$  kPa.

That's everything. By applying all correction factors of Equation 3 to the measured primary standard ionisation current,  $I$ , it is possible to derive the RAKR of the  $^{192}\text{Ir}$  source from first principles.

The total uncertainty of the source calibration is 0.7% ( $k = 2$ ).

The next step is the calibration of the secondary standard chamber.

### 3.3 Secondary standard ionisation chambers for $^{192}\text{Ir}$ brachytherapy sources

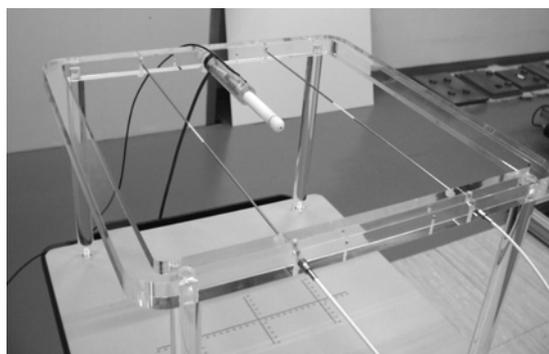
Suitable secondary standard ionisation chambers for HDR  $^{192}\text{Ir}$  brachytherapy sources are both well-type ionisation chambers, also referred to as re-entrant chambers, and thimble-type ionisation chambers. Thimble chambers need to be clamped in a suitable calibration jig with a source to chamber distance of typically 10 cm.

Figure 2 shows a few well chambers suitable for measuring HDR sources. The source can be moved through a suitable transfer tube or a plastic catheter connected to the treatment head of the afterloader and the insert of the well chamber.

Figure 3 shows a thimble chamber clamped on a source calibration jig. In the bottom right hand corner two transfer tubes can be seen which link the two catheters left and right of the thimble chamber to the brachytherapy treatment unit.



**Figure 2.** Well chambers for HDR brachytherapy sources



**Figure 3.** Thimble chamber and Nucletron Source Calibration Jig

In well chambers a 370 GBq  $^{192}\text{Ir}$  source will produce ionisation currents in the order of, say, 50 – 70 nA as the collection volume is quite large ( $\geq 200 \text{ cm}^3$ ) and the source is close to the collecting volume. In thimble chambers (collecting volume  $\leq 0.7 \text{ cm}^3$ ) mounted on a calibration jig, the same source will generate ionisation currents of only a few pA.

The calibration procedure for both chamber types is very similar.

#### 3.3.1 Well chamber calibration at NPL

The well chamber is positioned at least 1 m from any wall and 1 m above floor level on a low scatter surface. Before commencing measurements, sufficient time is allowed for the chamber to reach thermal equilibrium with the surrounding air. The well chamber is then connected to a calibrated electrometer. Measurements are taken after a warm-up period of at least 30

minutes in which time the electrometer, ionisation chamber and cables are allowed to settle.

The point of maximum response (sweet-spot) of the well chamber is found by stepping the  $^{192}\text{Ir}$  source through the chamber and by plotting the corrected ionisation current *versus* the dwell position of the source. The point of maximum response is the reference point and the hospital physicist needs to place the hospital source at the same position. The ionisation current will increase and then decrease when moved from the top to the bottom of the chamber. The  $^{192}\text{Ir}$  source is then sent to the dwell position corresponding to the maximum chamber response and at least five measurements of the ionisation current are taken. The electrometer correction factor is applied and all currents are corrected to the same reference time,  $t_{ref}$ , as mentioned in section 3.2 by applying a decay correction. A recombination correction,  $k_{ion}$ , is also applied.  $k_{ion}$  is determined by using the two-voltage technique (Attix 1984). The ionisation current is normalised to standard atmospheric conditions:  $T_{STD} = 293.15 \text{ K}$ ,  $p_{STD} = 101.325 \text{ kPa}$ .

The well chamber calibration coefficient can now be obtained by applying Equation 2, i.e. the RAKR of the calibrated source (Gy/s) is divided by the corrected ionisation current (A) to give the calibration coefficient,  $N_{\dot{K}_R}$ , in terms of (Gy/C).

The total uncertainty of the well chamber calibration coefficient is 0.8% ( $k = 2$ ).

### 3.3.2 Thimble chamber calibration at NPL

For thimble chambers the calibration procedure is similar to the well chamber calibration procedure. When using the Nucletron Source Calibration Jig, the thimble chamber is set up between two catheters, such that the distance from the centre of the  $^{192}\text{Ir}$  source to the centre of the thimble is 10 cm for both catheters.

The point of maximum response (sweet-spot) of the thimble chamber is found by stepping the  $^{192}\text{Ir}$  source through both catheters and by plotting the corrected ionisation current *versus* the dwell position of the source. The graphs look similar to a well chamber response curve. The ionisation current increases and then decreases when the source is moved through the catheter parallel to the long axis of the chamber (see Figure 3). The corrected ionisation current is calculated for both channels and the mean current is used for the calculation of the calibration coefficient,  $N_{\dot{K}_R}$ , again in terms of (Gy/C).

The recombination correction for thimble chambers measuring HDR  $^{192}\text{Ir}$  sources is negligible and therefore not applied.

The total uncertainty of the thimble chamber calibration coefficient is 1.1% ( $k = 2$ ). This is greater than the uncertainty quoted for well chamber calibration coefficients, which is mainly due to the positional uncertainty in the set up of the thimble chamber in the calibration jig.

### 3.3.3 Back in the hospital

The calibrated ionisation chambers and electrometers are returned to the brachytherapy centres and the hospital physicists can now use the calibrated

instruments to determine the RAKR of their own HDR  $^{192}\text{Ir}$  sources. The ionisation current needs to be measured at the sweet-spot and by applying Equation 1 the RAKR of the hospital source can be determined in terms of Gy/s at 1 m, traceable to the NPL primary standard for  $^{192}\text{Ir}$ .

Although brachytherapy gamma ray sources are currently calibrated for RAKR, patient dosimetry is based on absorbed dose to water. The American Association of Physicists in Medicine (AAPM) published the Task Group 43 protocol (Nath *et al.* 1995) and an update (TG-43U1) by Rivard *et al.* in 2004. This protocol allows the calculation of absorbed dose to water at a point  $(r, \theta)$  near the source from air kerma strength<sup>1</sup> or RAKR. Many treatment planning systems are based on the TG-43 formalism.

The reference point  $(r_0 = 1 \text{ cm}, \theta_0 = \pi/2)$  for dose calculations is chosen to lie on the transverse axis of the source at a distance of 1 cm from its centre. The dose rate to water at a distance of 1 cm is

$$\dot{D}(r_0, \theta_0) = S_k \Lambda \quad (4)$$

where  $\dot{D}(r_0, \theta_0)$  is the dose rate to water at the reference point in terms of  $\text{cGy h}^{-1}$ ,  $S_k$  is the air kerma strength in terms of  $\text{cGy cm}^2 \text{ h}^{-1}$  and  $\Lambda$  is the dose rate constant which is defined as the dose rate to water at a distance of 1 cm on the transverse axis of a unit air kerma strength source ( $1 \text{ U} = 1 \text{ cGy cm}^2 \text{ h}^{-1}$ ) in a water phantom. The constant includes the effects of source geometry, the spatial distribution of radioactivity within the source, encapsulation and self-filtration within the source and scattering in water surrounding the source. The numerical value of  $\Lambda$  depends on the source type.

Equation 4 is only a special case and the general equation for the dose rate  $\dot{D}(r, \theta)$  at point  $(r, \theta)$  can be written as

$$\dot{D}(r, \theta) = S_k \Lambda [G(r, \theta)/G(r_0 / \theta_0)] g(r) F(r, \theta) \quad (5)$$

where  $S_k$  is the air kerma strength,  $\Lambda$  is the dose rate constant,  $G(r, \theta)$  is the geometry factor,  $g(r)$  is the radial dose function and  $F(r, \theta)$  is the anisotropy function as defined in TG-43 (Nath *et al.* 1995).

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<sup>1</sup> Air kerma strength is the quantity used in North America for the specification of brachytherapy gamma ray sources. Air kerma strength has units of  $\text{cGy cm}^2 \text{ h}^{-1}$ .

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# Setting up and carrying out a check source measurement

## 1 Introduction

Ionisation chambers are relatively fragile devices and can be faulty with little or no visible sign of damage. Because of this, most instruments used as secondary standards are supplied with a radioactive source that can be used to check the overall sensitivity of the ionisation chamber and its measuring assembly. The source, usually a  $^{90}\text{Sr}$  foil, is incorporated in a holder designed to make it safe to handle. The ionisation chamber can be inserted in the holder in a reproducible position close to the source and the instrument then used in the normal manner to determine the time required to give a specified reading or the ionisation current. Since the decay constant for the source is known the instrument reading at any time in the future can be predicted and compared with the actual indication. Any discrepancy greater than the normal random variation indicates that a fault exists in the instrument.

## 2 Method of Measurement

### 2.1 General

When an instrument is submitted for calibration at the National Physical Laboratory a set of measurements with the check source is the first operation that would be carried out following its receipt. The check-source time/current is then compared with any previous determinations, for example a previous calibration, and any discrepancy investigated. The last operation before the newly calibrated secondary standard is returned to the customer is also a determination of the check-source time/current. Again, any discrepancy between the results obtained before and after the X-ray calibrations would be investigated.

### 2.2 Equipment Required

All test equipment used must have a valid calibration.

- a) Timer (if used)
- b) Barometer
- c) Thermometer
- d) Measuring assembly

### 2.3 Data To Be Recorded

All measurements should be entered in the attached sheets given in Appendix 2; where corrections have to be applied to an instrument reading and the reading, correction and corrected value must all be recorded.

The following are the minimum data that must usually be recorded.

- a) Type and serial number of measuring assembly, ionisation chamber and source.
- b) Type and serial number of thermometer and barometer used.
- c) Date of measurement.
- d) Source temperature at start and end of measurements.
- e) Atmospheric pressure during the measurements.
- f) Air density correction applied (calculated from **d**) and **e**) above).
- g) All measuring assembly and time readings.
- h) Mean readings and standard uncertainty of the mean.
- i) Corrected mean of readings and comparison with previously recorded measurements.

## 2.4 Measurement Sequence

Source, chamber and measuring assembly should be brought together in the measuring room at least  $\frac{1}{2}$  hour before the measurements are to be carried out. This will need to be longer depending on any temperature difference between the store and measurement room in order to ensure that the source and chamber are at similar temperatures. In the case of Grenz-ray, Roos and NACP chambers this time is much reduced owing to the much smaller size of the chamber and check source.

Note: to ensure that the temperature of the Grenz-ray, Roos and NACP chamber systems are sufficiently stable, the chamber, source and holder should be placed in a thermally insulating box (e.g. made of expanded polystyrene). The thermometer should be rested in the box on or as close as possible to the chamber.

If the electrometer is mains powered it should be switched on approximately 3 hours before measurements are started. If the measuring assembly is battery-powered it should be switched on about  $\frac{1}{4}$  hour before measurements are started. About  $\frac{1}{4}$  hour before measurements commence the chamber should be inserted in the source housing or placed on the source holder to allow the equipment to stabilise. Before starting, ensure that the source temperature is sufficiently stable. In the case of Grenz-ray, Roos and NACP chambers, measurements should be made only with the chamber fitted in its own holder. Ensure that the chamber is pushed fully into the holder and that it is not pulled out again by the weight of the cable.

The measurement sequence below illustrates the general principles and may be modified for a particular system.

- a) Carry out and record the results of any pre-measurement checks specified by the instrument manufacturer, e.g. check and if necessary adjust instrument zero, check batteries, check saved instrument factors etc.
- b) Record the initial temperature of the check-source housing.
- c) For each measurement, record the measuring assembly indication (normally close to the reference setting) and the time to reach that indication. The number of readings will depend on the system and the uncertainty required; normally five will be taken. After each reading check that the zero of the instrument has not changed significantly.
- d) About half-way through the measurements, record the atmospheric pressure at the height of the chamber (mbar or kPa). If the atmospheric pressure is changing rapidly, i.e. more than 1mbar between the start and end of the readings then the measurement should normally be repeated when the pressure is more stable.
- e) After the final reading note the check-source housing temperature.
- f) If the temperature of the source housing has changed rapidly, i.e. by more than  $0.3^{\circ}\text{C}$  between the start and end of the readings then the measurement should normally be repeated. However, if it is impossible to avoid a large temperature variation then the temperature should be noted about half-way through each reading.

## 2.5 Calculations

- a) Calculate and record the average of the initial and final temperatures.
- b) Calculate and record the air-density correction, i.e. the correction to give the check-source reading at 20 °C and 1013.25 mbar. The final requirement is normally the time required to give a specified instrument reading; the air density correction is thus: -

$$\frac{p}{1013.25} \times \frac{293.15}{273.15 + t} \quad (1)$$

where  $p$  = atmospheric pressure in mbar  
 $t$  = mean source temperature in °C

If it is necessary, because the temperature change is large, to measure the temperature for each reading, then an air-density correction must be calculated for each reading in exactly the same way.

**Note: if applying air-density corrections to current measurements equation (1) should be inverted.**

- c) For each reading, if appropriate, calculate the time taken for the instrument to reach the reference setting, multiplying by the air density correction determined in b) above if the temperature change was large.
- d) Calculate and record the mean time taken to reach the reference setting or the mean current and the standard uncertainty. You will need to repeat the check source measurement if there is a trend in the readings or if the standard uncertainty of the mean is too large [i.e. greater than 0.015%].

### ***Q. What might cause a trend in the readings?***

- e) If the air-density correction was not applied to the individual reading, multiply the mean calculated in **d)** by the air-density correction calculated in **b)** and record the results as the mean corrected to 20 °C and 1013.25 mbar.
- f) The mean time should be corrected for the decay of the source using the relationship below. The reference date should be recorded and the decay-corrected value. The correction factor may be found from decay tables (see Appendix 1) or calculated using the relationship: -

$$T_o = T e^{-\lambda t} \quad (2)$$

Where  $T$  = Mean air-density-corrected time on the day of measurement  
 $T_o$  = Mean air-density-corrected time on the reference day  
 $\lambda$  = Decay constant (see Appendix 1)  
 $t$  = Time difference between measurement day and reference day in the same units as decay constant

- g)** If the mean ionisation current is required then the decay corrected value is calculated using the expression:-

$$I = I_o e^{-\lambda t} \quad (3)$$

Where  $I$  = mean air-density-corrected current on the day of measurement

$I_o$  = mean air-density-corrected current on the reference day

- h)** Record the decay-corrected mean value of the time or current, as appropriate, and compare with any previous determinations. Agreement between successive measurements within a period of 2-3 months should be better than 0.2%.

## APPENDIX 1

### Decay table, strontium-90

$e^{\lambda t}$		$e^{-\lambda t}$
	t (days)	
1.000066	1	0.999934
1.000131	2	0.999869
1.000197	3	0.999803
1.000263	4	0.999737
1.000329	5	0.999672
1.000394	6	0.999606
	t (weeks)	
1.000460	1	0.999540
1.000920	2	0.999081
1.001381	3	0.998621
1.001841	4	0.998162
	t (months)	
	(30 days)	
1.001973	1	0.998031
1.003949	2	0.996066
1.005930	3	0.994105
1.007915	4	0.992148
1.009903	5	0.990194
1.011895	6	0.988245
1.013892	7	0.986299
1.015892	8	0.984357
1.017896	9	0.982419
1.019904	10	0.980484
1.021916	11	0.978554
	t (years)	
	(365 days)	
1.024268	1	0.976307
1.049126	2	0.953174
1.074587	3	0.930591
1.100665	4	0.908542
1.127376	5	0.887015

Half-life for  $^{90}\text{Sr}$  = 10551 days,  $\lambda = 0.0239786$  per year

**APPENDIX 2**

**Check Source Measurement Record I**

Ionisation chamber type	<input type="text"/>	s/n	<input type="text"/>
Check source type	<input type="text"/>	s/n	<input type="text"/>
Measuring assembly type	<input type="text"/>	s/n	<input type="text"/>
Thermometer	<input type="text"/>	s/n	<input type="text"/>
Barometer	<input type="text"/>	s/n	<input type="text"/>
Reference settings:- Reading	<input type="text"/>	<b>a</b>	Quantity <input type="text"/>
Range	<input type="text"/>		
MA charge calibration	<input type="text"/>	<b>b</b>	(pC/scale rdg)
Scale Linearity Correction	<input type="text"/>	<b>c</b>	
HT set to	<input type="text"/>	Volts	

Measurements made by

Measurement date

	reading	corr	corr rdg	
Atm pressure (mbar)	<input type="text"/>	<input type="text"/>	<input type="text"/>	<b>d</b>
Source temp, start (degC)	<input type="text"/>	<input type="text"/>	<input type="text"/>	
Source temp, end (degC)	<input type="text"/>	<input type="text"/>	<input type="text"/>	
Source temp, mean (degC)			<input type="text"/>	<b>e</b>
Air density correction = $(d/(273.15+e)) \times (293.15/1013.25)$			<input type="text"/>	<b>f</b>

Reading	Time (s)	
<input type="text"/>	<input type="text"/>	<input type="text"/>
<input type="text"/>	<input type="text"/>	<input type="text"/>
<input type="text"/>	<input type="text"/>	<input type="text"/>
<input type="text"/>	<input type="text"/>	<input type="text"/>
<input type="text"/>	<input type="text"/>	<input type="text"/>

Mean corr d time to reference setting	<input type="text"/>	s <b>g</b>
Standard uncertainty of mean (%)	<input type="text"/>	
Corrd to 20 degC, 1013.25 mbar [fxg]	<input type="text"/>	s <b>h</b>
Reference date	1-Oct-06	
Decay period	<input type="text"/>	days <b>i</b>
Sr-90 half life	10551	days <b>j</b>
Decay correction=EXP((LN(2)/j)xi)	<input type="text"/>	<b>k</b>
Mean time on reference date [h/k]	<input type="text"/>	s <b>l</b>
Mean current on reference date [axbxc/l]	<input type="text"/>	pA <b>m</b>

### Check Source Measurement Record II

Ionisation chamber type		s/n	
Check source type		s/n	
Measuring assembly type		s/n	
Thermometer		s/n	
Barometer		s/n	
Reference settings:- Reading		<b>a</b>	Quantity <span style="background-color: #cccccc;"></span>
Range			
MA charge calibration		<b>b</b>	(pC/scale rdg)
Scale Linearity Correction		<b>c</b>	
HT set to			Volts

Measurements made by

Measurement date

	reading	corn	corrd rdg	
Atm pressure (mbar)				<b>d</b>
Source temp, start (degC)				
Source temp, end (degC)				
Source temp, mean (degC)				<b>e</b>
Air density correction = $(d/(273.15+e)) \times (293.15/1013.25)$				<b>f</b>

Reading	Time (s)	

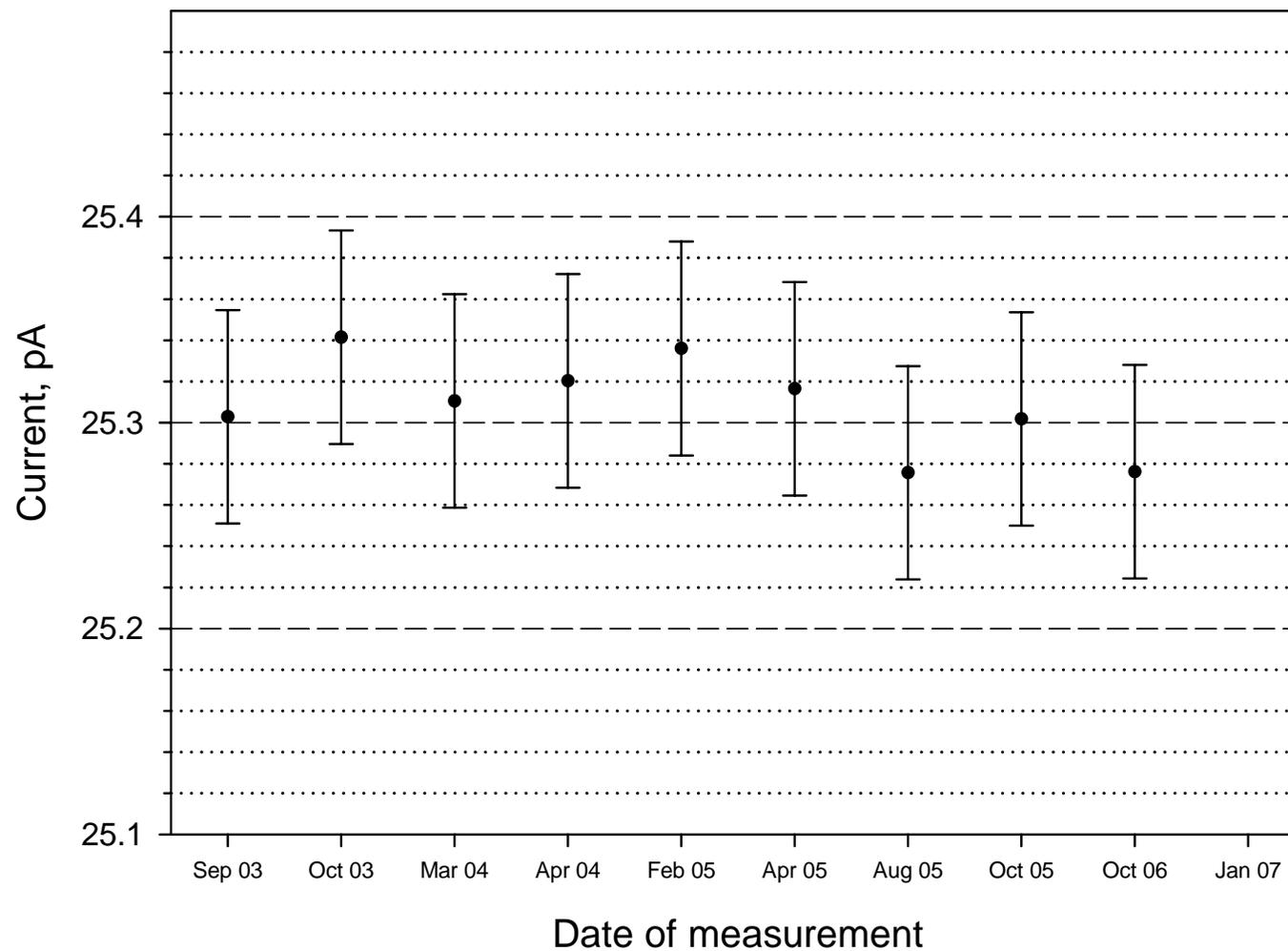
Mean corrd time to reference setting		s <b>g</b>
Standard uncertainty of mean (%)		
Corrd to 20 degC, 1013.25 mbar [fxg]		s <b>h</b>
Reference date	1-Oct-06	
Decay period		days <b>i</b>
Sr-90 half life	10551	days <b>j</b>
Decay correction=EXP((LN(2)/j)xi)		<b>k</b>
Mean time on reference date [h/k]		s <b>l</b>
Mean current on reference date [axbxc/l]		pA <b>m</b>

## Check source measurement

(Reference date: 1 October 2006)

Chamber type 2611A s/n 204

Check source type 2562 s/n 146

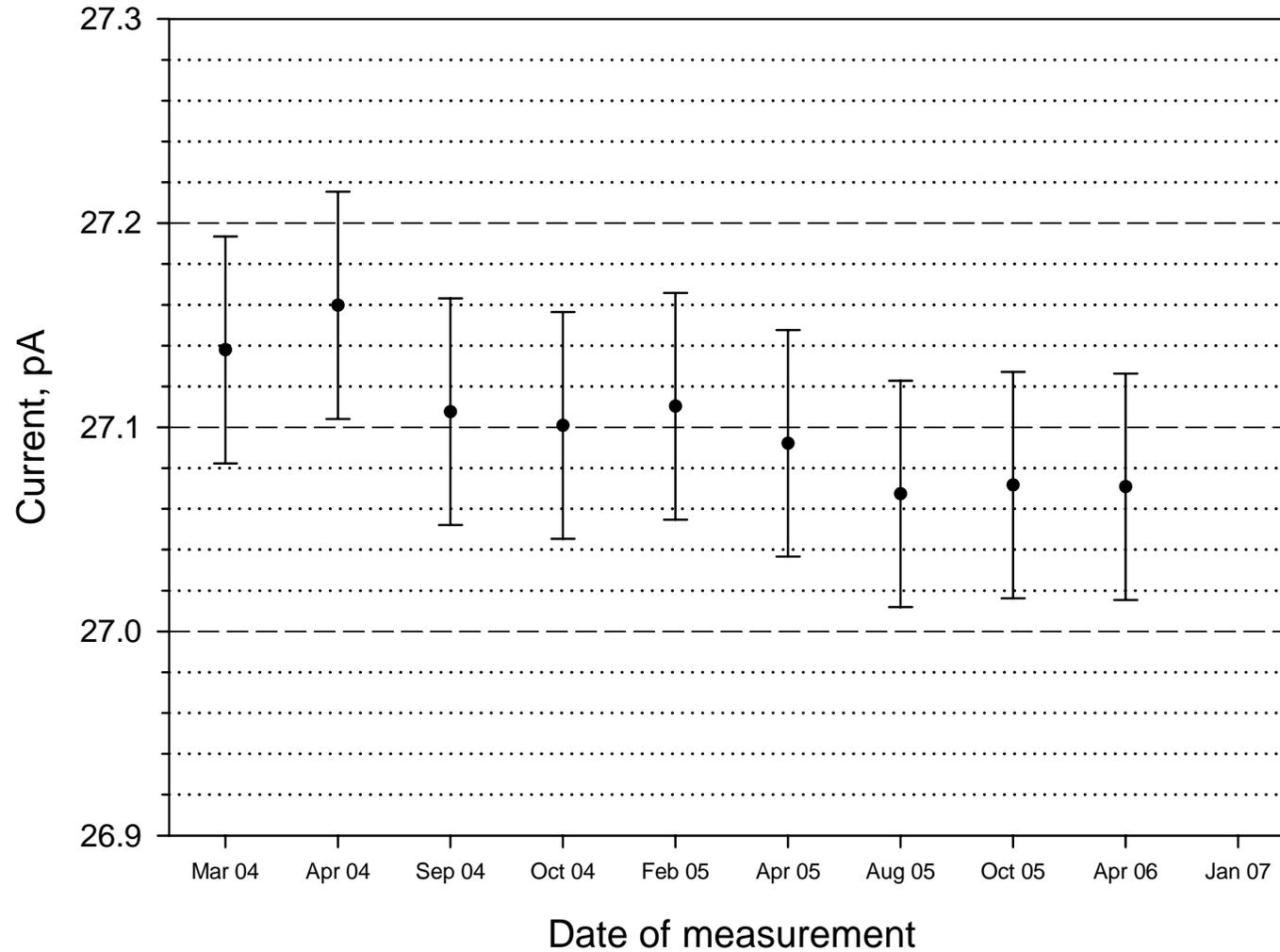


## Check source measurement

(Reference date: 1 October 2006)

Chamber type 2611A s/n 215

Check source type 2562 s/n 219



## Check source measurement

(Reference date: 1 October 2006)

Chamber type TW23344 s/n 0792

Check source type 8921 s/n 616

