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IPEM guidelines on dosimeter systems for use as transfer instruments between the UK primary dosimetry standards laboratory (NPL) and radiotherapy centres*

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Abstract. United Kingdom dosimetry codes of practice have traditionally specified one electrometer for use as a secondary standard, namely the Nuclear Enterprises (NE) 2560 NPL secondary standard therapy level exposure meter. The NE2560 will become obsolete in the foreseeable future. This report provides guidelines to assist physicists following the United Kingdom dosimetry codes of practice in the selection of an electrometer to replace the NE2560 when necessary. Using an internationally accepted standard (BS EN 60731:1997) as a basis, estimated error analyses demonstrate that the uncertainty (one standard deviation) in a charge measurement associated with the NE2560 alone is approximately 0.3% under specified conditions. Following a review of manufacturers' literature, it is considered that modern electrometers should be capable of equalling this performance. Additional constructural and operational requirements not specified in the international standard but considered essential in a modern electrometer to be used as a secondary standard are presented.

1. Introduction

For over 25 years, the approved secondary standard electrometer for use as a transfer instrument between the United Kingdom primary dosimetry standards laboratory (National Physical Laboratory, NPL) and the UK radiotherapy centres has been the Nuclear Enterprises (NE) 2560 NPL secondary standard therapy level exposure meter. This electrometer is no longer commercially available and while a repair service is still available at this time, spare parts will not be obtainable indefinitely. The NE2590 Ionex Dosemaster dosimeter has gained acceptance as a secondary standard therapy level electrometer over the last decade, but this instrument has been criticized for its size and weight where one secondary standard is shared between several hospitals and ease of transport is an important issue.

Following correspondence from UK radiotherapy physicists concerned at the restricted choice of secondary standard therapy level electrometers and further to discussions with representatives from the Centre for Ionising Radiation Metrology (CIRM) at the NPL, the Institute of Physics and Engineers in Medicine (IPEM) Radiotherapy Special Interest Group established a working party to review the current situation and produce guidelines on the choice of secondary standard electrometer when the need to purchase a replacement arises.

* Prepared by a working party of the IPEM.

It is considered that a major contributing factor to the high standards of dosimetric accuracy in the UK, as highlighted in recent audits (Thwaites *et al* 1992, Thwaites 1996, Nisbet and Thwaites 1997) may be the use by all UK radiotherapy centres of a common type of transfer instrument. However, the working party believes that a number of commercially available electrometers meet the requirements of international standards and may be used as secondary standards without discernible change in either the consistency or the uncertainty of dosimetry traceable to national standards provided that the designated ionization chamber assemblies, e.g. NE2561/2611, remain unchanged.

It must be emphasized that this document pertains only to the measuring assembly. It is *not* intended to change any of the recommendations concerning the chambers which are designated as transfer instruments in existing IPEM codes of practice (IPSM 1990, IPEMB 1996a, b, IPEM 2000) for the determination of absorbed dose in clinical radiation beams. It must be the user's responsibility to ensure compatibility of electrical connectors between any electrometer purchased and the recommended transfer chamber.

Metrologically speaking, the term 'secondary standard' denotes an instrument which has been calibrated against a primary standard; it implies nothing about its performance. The performance, however, must match or be better than that of a reference class electrometer as defined in BS EN 60731:1997 (IEC 60731:1997) 'Medical electrical equipment. Dosemeters with ionisation chambers as used in radiotherapy', which specifies performance requirements for field and reference electrometers used in radiotherapy.

Annex A of BS EN 60731:1997 contains information which can be used to demonstrate that the combined standard uncertainty associated with a hypothetical reference-class electrometer operating at the maximum limits of variation allowed for stated performance characteristics is $\pm 1.6\%$, which seems generous. Here and in all other instances, combined standard uncertainty should be interpreted as one standard deviation. This figure excludes performance characteristics for dose-rate measurement, as the option to measure dose rate is not considered essential for a secondary standard electrometer. In practice, electrometers operate within a narrower range of limits. A survey of manufacturers' literature has shown that tighter limits of variation of certain individual performance characteristics than those stated in BS EN 60731:1997 are quoted for a number of modern, high quality electrometers and should therefore be achievable in practice.

On the basis of this survey and from a discussion of the estimated uncertainties associated with various typical measurement situations in section 4, it is concluded that an electrometer purchased for use as a secondary standard (transfer) electrometer should have a combined standard uncertainty of $\pm 0.3\%$ for a typical measurement with an NE2561/2611 (0.33 cm^3) chamber in a megavoltage photon beam. These guidelines indicate the minimum requirements which an electrometer should satisfy in order for this figure to be possible.

The guidelines are intended to supplement information available in BS EN 60731:1997. They have been specifically drawn up by the IPEM for use with the United Kingdom dosimetry codes of practice where one only type of electrometer, the NE2560, has traditionally been specified for use as a secondary standard. However the principles contained herein may be of interest to users of other dosimetry protocols.

2. Performance requirements

These requirements are based on those for a *reference-class measuring assembly* as given in BS EN 60731:1997. Any terms appearing in italics are as defined in BS EN 60731:1997 and the definitions of these terms are reproduced in appendix A of this paper with the kind permission of British Standards Institute (BSI). Complete editions of the standard can be obtained by post from BSI Customer Services, 389 Chiswick High Road, London W4 4AL, UK.

These requirements apply only to measurements of dose, not to those of dose rate (see section 5.1).

Some of the requirements for a secondary standard electrometer listed here are more restrictive than in BS EN 60731:1997, namely those for long-term stability, *non-linearity* and variation of *response* (reading/unit charge) due to the influence of stabilization time, range changing, temperature, input current, mains or battery voltage.

Many of the performance requirements in BS EN 60731:1997 are given in terms of the minimum and maximum *rated* (or *effective*) input current or charge and for the purposes of this secondary standard electrometer specification the following values (which cover the extremes of use of a therapy secondary standard—see appendix B) have been assigned to these quantities:

Minimum input current: 1×10^{-12} A	Maximum input current: 5×10^{-9} A
Minimum input charge: 1×10^{-9} C	Maximum input charge: 5×10^{-7} C.

Under *standard test conditions* the *performance characteristics* of a *measuring assembly* suitable for use as a secondary standard electrometer should be at least as good as those listed in table 1.

Within the *rated range* of each of the *influence quantities* and *instrument parameters* identified, the *limits of variation* of the performance characteristics of a measuring assembly suitable for use as a secondary standard electrometer should be at least as good as those listed in table 2.

The limits of variation of response due to any other influence quantity or instrument parameter should not be more than ±0.2%. If the *variation* in response for any influence quantity or instrument parameter undefined in these guidelines exceeds ±0.1% then the supplier should specify the influence quantity or instrument parameter and the range of variation for which the limit of ±0.2% applies.

The combined standard uncertainty should not exceed ±0.3%. In practice this implies that no one individual uncertainty can be greater than ±0.25% and that if one uncertainty is equal to this limit all the others must be negligible.

Purchasers should be convinced of the suitability of any electrometer intended for use as a secondary standard and may choose to obtain evidence of performance from suppliers. Purchasers wishing to verify the performance of a selected electrometer against the limits stated in tables 1 and 2 will find information on testing procedures in the appropriate sections of BS EN 60731:1997, denoted by BS§ in the tables. The feasibility of such testing will depend on the resources available locally. IPEM (1999) contains details of commissioning and ongoing quality control procedures for electrometer/ion chamber combinations in the departmental environment.

3. Additional requirements

There are additional requirements for a secondary standard electrometer given here which are not in BS EN 60731:1997, for example the discrete values of polarizing voltage available and the accuracy of a measurement elapsed timer, if fitted (it is not essential for a secondary standard electrometer to have an integral elapsed timer—see 8 below). These parameters have been integrated into tables 1 and 2 as appropriate.

In addition to meeting the performance specification, a secondary standard electrometer needs to satisfy the following constructional/operational requirements:

1. It must be possible to start and stop measurements of charge manually.

Table 1. Limits of performance characteristics at standard test conditions.

Standard test conditions		Performance characteristic	Limits	BS§
Temperature:	+15 °C to +25 °C	Electrometer:		
Relative humidity:	30% to 75%	Maximum full scale reading	$\geqslant 0.5\ \mu$C	—
Stray radiation at *Measuring assembly*	$<7.5\ \mu$Sv h^{-1}	*Resolution* (see table notes for appropriate limit)	2.0 pC[a] or ± 0.05%[b]	6.1.2
Mains voltage:	Nominal ± 1%	Repeatability (reproducibility)	± 0.1%[c,d]	6.1.3
Mains frequency:	Nominal ± 1 Hz	Long-term stability (per year)	± 0.2%[d,e]	6.1.4
Stabilization time	>15 min after switch-on	*Zero drift*	± 5.0 fA[f]	6.2.1
		Zero shift	± 5.0 pC[g]	6.2.2
		Non-linearity	± 0.2%[d,h]	6.2.3
		Polarizing voltage supply:		
		Full voltages available (V)	0, 100, 200 and 300 V dc[i]	—
		Reduced voltages required ($V/2$)	50, 100 and 150 V dc[j]	—
		Polarities required at each voltage	+ and −	—
		Accuracy of full voltages	± 1.0%	—
		Accuracy of ($V/2$) voltage ratio	± 2.0%[k]	—
		Elapsed timer (if fitted):		
		Accuracy	± 0.1%[l]	—
		Resolution	± 0.5 s	—

[a] On single range electrometers or on the most sensitive charge range of multi-range electrometers.
[b] Of full scale, on all other charge ranges.
[c] Relative standard deviation of repeat 5 nC readings.
[d] For this particular performance characteristic, the limits of variation stated in these IPEM guidelines are narrower than those given in BS EN 60731:1997 for a reference-class measuring assembly.
[e] Changes in response (i.e. reading/unit charge input) per year.
[f] Rate of change of reading in 'measure' mode (after zero adjusted) with no chamber connected.
[g] Change in reading when going from 'zero' to 'measure' or from 'measure' to 'hold'.
[h] Of response at 0.5 of full scale reading on each range.
[i] This is the minimum set of full polarizing voltages required for the electrometer to be used with those chambers in use as secondary standards in the UK. The inclusion of several values of polarizing voltage in these recommendations should not be taken to imply that the specific secondary standard chamber connected can be used at any of these voltages. Rather, the HV should be set to the correct value for the chamber as given in the calibration certificate.
[j] This is the minimum set of reduced polarizing voltages required for the electrometer to be used to measure the correction factor for ion recombination within the chamber. Since it is highly desirable to measure a full saturation curve rather than rely on the voltage ratio technique for this purpose, it is useful (though not essential) for the polarizing voltage to be variable over the range 50 to 300 V dc.
[k] For conditions under which the ion collection efficiency is greater than 98% an error of this magnitude in the $V/2$ ratio will introduce a corresponding error of less than ± 0.1% in the measured value of the ion recombination correction factor.
[l] This is the accuracy with which the charge accumulation period is timed.

2. If the electrometer has a facility for modifying the value of charge displayed, for the purposes of calibration, it must be possible to disable any internal calibration factors when making measurements of charge. It must be clear when such a facility is in use.
3. If the electrometer has a facility for making corrections to the value of charge displayed, e.g. for ambient temperature, pressure etc, it must be possible to disable these corrections when making measurements of charge. It must clear from the display or otherwise when such corrections are being made.
4. If the electrometer has more than one range it must be clear from the display or otherwise which range is in use and if the maximum input has been exceeded.

Table 2. Limits of variation of performance characteristics for effects of influence quantities and instrument parameters.

Minimum rated range of influence quantity or instrument parameter		Performance characteristic of electrometer	Limits of variation	BS§
Stabilization time	15 min to 6 h	Response	±0.2%[a,b]	6.1.5
Range changing	All ranges	Response	±0.2%[b,c]	6.2.4
Dead time	As specified by *manufacturer*	Response	—[d]	6.2.5
Temperature	+15 °C to +35 °C	Response	±0.015% $°C^{-1}$ [b]	6.2.6
		Zero drift	±1.0 fA $°C^{-1}$ [e]	6.2.6
Humidity	20 to 80% R.H. (<20 g m^{-3})	Charge leakage	±10 fA[f]	6.2.7
Stray radiation effect	0 to 0.2 mSv h^{-1}	Zero drift	±10 fA[g]	6.2.8
Accumulated charge	All ranges at 90% of full scale	Charge leakage	±5.0 fA[h]	6.2.9
Input current	1 pA to 5 nA	Response	±0.2%[b,i]	6.2.10
Battery operation				
Battery condition	Useful life	Response	±0.2%[b,i]	6.4.1
Mains operation				
Mains voltage (static)	−12% to +10% of nominal	Response	±0.2%[b,i]	6.5.1
Mains voltage (*variation*)	−12% to +10% of nominal in 10 s or less	Response	±5.0% pC	6.5.2

[a] Of value 1 h after switch-on.
[b] For this particular performance characteristic the limits of variation stated in these IPEM guidelines are narrower than those given in BS EN 60731:1997 for a reference-class measuring assembly.
[c] Change from response on calibrated range (this requirement only applies to electrometers which change range by switching gain).
[d] The working party considers that an auto-discharge integrating capacitor electrometer is not suitable as a secondary standard.
[e] Change of zero drift with temperature in 'measure' with no input current.
[f] Rate of change of reading in 'measure' with input current disconnected after ⩾90% full-scale reading at 80% R.H.
[g] In 'measure'.
[h] Rate of change of reading in 'measure' with input current disconnected after ⩾90% full-scale reading at 50% R.H.
[i] Percentage change of response.

5. Any user-settable parameters which can affect the instrument reading must be readily apparent to the user (e.g. displayed when operative) or protected from inadvertent or malicious alteration by a password system, key switch or other security arrangement.
6. If the electrometer is fitted with circuitry which corrects automatically for the effects of ambient temperature on the response of the chamber, the temperature sensor must not be contained within the electrometer. Rather it must be possible for this sensor to be positioned remotely in thermal equilibrium with the chamber. It must be clear from the display or otherwise when such automatic temperature correction is being made.
7. The electrometer must comply with the requirements on electromagnetic compatibility, construction and documentation for a reference-class measuring assembly given in BS EN 60731:1997.
8. The electrometer must be fitted with either
   (a) an internal elapsed timer, or
   (b) an output to which the user can connect an external timer.

4. Estimated uncertainty in dose measurement due to electrometer performance

Physicists needing to purchase a modern electrometer for use as a therapy level secondary standard may wish to consider the relative combined standard uncertainty (due to the

Table 3. Estimate of the combined standard uncertainty associated with a typical measurement of dose in a mega-voltage photon field using an NE2561 or 2611 chamber connected to an NPL therapy level secondary standard dosimeter NE2560. For this case: 2.0 Gy min^{-1} → signal current = 351 pA; 0.5 Gy → signal charge = 5.26 nC.

	Limits applicable to NE2560 exposure meter			Uncertainties associated with measurement	
Performance characteristic	Limit or limits of variation	Standard uncertainty	Qualifying statement	Remarks/assumptions relating to conditions of measurement	Relative standard uncertainty
Resolution	±0.020%	±0.012%	of full scale of range in use	readings made at 53% of full scale on X1 range	±0.022%
Repeatability	±0.100%	±0.050%	relative standard deviation	—	±0.100%
Long-term stability	±0.200%	±0.115%	change in response per year	1.5 years after calibration	±0.173%
Zero drift	±5.56 fA	±3.21 fA	residual leakage after zeroing	percentage of signal current	±0.001%
Zero shift	±10.0 pC	±5.77 pC	on starting/stopping measurement	percentage of signal charge	±0.110%
Non-linearity	±0.050%	±0.029%	of full scale range in use	uncertainty of NPL calibration factor for 53% scale point	±0.001%
Stabilization time	*±0.500%*	±0.289%	change in response over 15 min to 6 h	after 1 h response should be half way to final value	±0.144%
Range changing	*±0.500%*	±0.289%	of response	uncertainty on NPL calibration factor of X1 range	±0.000%
Temp. response	±0.022%	±0.013%	change in response per °C	used within 5 °C of calibration temperature	±0.063%
Temp. zero drift	×2	6.42 fA	change in zero drift per 5 °C change after zeroing	temp. varies by <2 °C after zeroing	±0.001%
Humidity	*±10.0 fA*	±5.77 fA	charge leakage at 80% R.H. and 90% of full scale	used at 65% R.H. and 53% of f.s. X1 range, so effective charge on capacitor only 2.7% of full	±0.000%
Stray radiation	*±10.0 fA*	±5.77 fA	change in zero drift over 0 to 0.2 mSv h^{-1}	used at 0.0075 mSv h^{-1}	±0.000%
Accumulated charge	*±5.00 fA*	±2.89 fA	charge leakage at 90% of full scale	used at 53% of f.s. X1 range, so effective charge on capacitor only 2.7% of full	±0.000%
Input current	±0.200%	±0.115%	change in response over 1 pA to 5 nA	standard uncertainty scaled proportional to $\log_{10}$ of current	±0.075%
Mains voltage (static)	±0.010%	±0.006%	of full scale for ±10% voltage	±6% (UK Electricity Supply Regs 1988), 53% of full scale	±0.007%
Mains voltage (variation)	*±5.00 pC*	±2.89 pC	−12 to +10% change in 10 s	assume only −6 to +6% change in 10 s	±0.030%
				Combined standard uncertainty	±0.289%

Limits in italics are not known for 2560, so are taken from BS EN 60731.

electrometer alone) associated with the measurement of dose in each of four different situations, as detailed in tables 3, 4, 5 and 6 and summarized below.

In each table the method used to estimate combined standard uncertainty is the same as that used in annex A of BS EN 60731:1997. This analysis assumes a uniform probability distribution for each of the performance characteristics and therefore uses the relationship:

$$\text{standard uncertainty} = 0.577 \times \text{limit on the performance characteristic.}$$

Table 4. Estimate of the combined standard uncertainty associated with a 'worst case' measurement of dose from HDR brachytherapy photons using an NE2561 or 2611 chamber connected to an NPL therapy level secondary standard dosimeter NE2560. For this case: 6.0 mGy min^{-1} $\rightarrow$ signal current = 1.05 pA; 0.1 Gy $\rightarrow$ signal charge = 1.05 nC.

	Limits applicable to NE2560 exposure meter			Uncertainties associated with measurement	
Performance characteristic	Limit or limits of variation	Standard uncertainty	Qualifying statement	Remarks/assumptions relating to conditions of measurement	Relative standard uncertainty
Resolution	±0.020%	±0.012%	of full scale of range in use	readings made at 11% of full scale on X1 range	±0.105%
Repeatability	±0.100%	±0.100%	relative standard deviation	—	±0.100%
Long-term stability	±0.200%	±0.115%	change in response per year	3 years after calibration	±0.346%
Zero drift	±5.56 fA	±3.21 fA	residual leakage after zeroing	percentage of signal current	±0.306%
Zero shift	±10.0 pC	±5.77 pC	on starting/stopping measurement	percentage of signal charge	±0.550%
Non-linearity	±0.050%	±0.029%	of full scale range in use	uncertainty of NPL calibration factor for 1% scale point	±0.004%
Stabilization time	*±0.500%*	±0.289%	change in response over 15 min to 6 h	after 1 h response should be half way to final value	±0.144%
Range changing	*±0.500%*	±0.289%	of response	uncertainty on NPL calibration factor of X1 range	±0.000%
Temp. response	±0.022%	±0.013%	change in response per °C	used within 5 °C of calibration temperature	±0.063%
Temp. zero drift	×2	6.42 fA	change in zero drift per 5 °C change after zeroing	temp. varies by <2 °C after zeroing	±0.244%
Humidity	*±10.0 fA*	±5.77 fA	charge leakage at 80% R.H. and 90% of full scale	used at 65% R.H. and 11% of f.s. X1 range, so effective charge on capacitor only 0.6% of full	±0.002%
Stray radiation	*±10.0 fA*	±5.77 fA	change in zero drift over 0 to 0.2 mSv h^{-1}	used at 0.025 mSv h^{-1}	±0.069%
Accumulated charge	*±5.00 fA*	±2.89 fA	charge leakage at 90% of full scale	used at 11% of f.s. X1 range, so effective charge on capacitor only 0.6% of full	±0.014%
Input current	±0.200%	±0.115%	change in response over 1 pA to 5 nA	standard uncertainty scaled proportional to $\log_{10}$ of current	±0.114%
Mains voltage (static)	±0.010%	±0.006%	of full scale for ±10%	±6% (UK Electricity Supply Regs 1988), 11% of full scale	±0.031%
Mains voltage (variation)	*±5.00 pC*	±2.89 pC	−12 to +10% change in 10 s	assume only −6 to +6% change in 10 s	±0.150%
				Combined standard uncertainty	±0.814%

Limits in italics are not known for 2560, so are taken from BS EN 60731.

Table 3 provides a derivation of the combined standard uncertainty for a typical measurement in a megavoltage photon beam using the NE2560 electrometer with an NE2561/2611 chamber. The analysis assumes a dose rate at the point of measurement of 2.0 Gy min^{-1} and an accumulated dose of 0.5 Gy. The combined standard uncertainty is shown to be ±0.29%.

Table 4 provides a 'worst case' scenario, using the same equipment with a high dose rate (HDR) brachytherapy photon source where the dose rate is 0.006 Gy min^{-1} and the accumulated dose is 0.1 Gy. The combined standard uncertainty is ±0.81%. This table represents not only

Table 5. Estimate of the combined standard uncertainty associated with a typical measurement of dose in a mega-voltage photon field using an NE2561 or 2611 chamber connected to an electrometer with the performance characteristics listed in the IPEM guidelines. For this case: 2.0 Gy min^{-1} → signal current = 351 pA; 0.5 Gy → signal charge = 5.26 nC.

	Limits applicable to IPEM sec. stand. dosimeter			Uncertainties associated with measurement	
Performance characteristic	Limit or limits of variation	Standard uncertainty	Qualifying statement	Remarks/assumptions relating to conditions of measurement	Relative standard uncertainty
Resolution	±0.050%	±0.029%	of full scale of range in use	readings made at 53% of full scale of range in use	±0.054%
Repeatability	±0.050%	±0.050%	relative standard deviation at (5 nC)	—	±0.050%
Long-term stability	±*0.200%*	±0.115%	change in response per year	1.5 years after calibration	±0.173%
Zero drift	±5.0 fA	±2.89 fA	residual leakage after zeroing	percentage of signal current	±0.001%
Zero shift	±5.0 pC	±2.89 pC	on starting/stopping measurement	percentage of signal charge	±0.055%
Non-linearity	±*0.200%*	±0.115%	of response at 50% of full scale	readings made at half scale, so non-linearity calibrated out	±0.000%
Stabilization time	±*0.200%*	±0.115%	change in response over 15 min to 6 h	after 1 h response should be half way to final value	±0.058%
Range changing	±*0.200%*	±0.115%	of response	—	±0.115%
Temp. response	±*0.015%*	±0.009%	change in response per °C	used within 5 °C of calibration temperature	±0.043%
Temp. zero drift	±1.0 fA	0.577 fA	change in zero drift per °C change after zeroing	temp. varies by <2 °C after zeroing	±0.000%
Humidity	±10.0 fA	±5.77 fA	charge leakage at 80% R.H. and 90% of full scale	used at 65% R.H. and 53% of f.s., so maximum effective charge on capacitor only 27% of full	±0.000%
Stray radiation	±10.0 fA	±5.77 fA	change in zero drift over 0 to 0.2 mSv h^{-1}	used at 0.0075 mSv h^{-1}	±0.000%
Accumulated charge	±5.00 fA	±2.89 fA	charge leakage at 90% of full scale	used at 53% of full scale, so maximum effective charge on capacitor only 27% of full	±0.000%
Input current	±*0.200%*	±0.115%	change in response over 1 pA to 5 nA	standard uncertainty scaled proportional to $\log_{10}$ of current	±0.075%
Mains voltage (static)	±*0.200%*	±0.115%	in response over −12 to +10% voltage	±6% (UK Electricity Supply Regs 1988), 53% of full scale	±0.063%
Mains voltage (variation)	±5.00 pC	±2.89 pC	−12 to +10% change in 10 s	only −6 to +6% change in 10 s	±0.030%
				Combined standard uncertainty	±0.259%

Limits in italics are tighter than reference class limits in BS EN 60731.

the extreme of dose rate likely to be encountered in radiotherapy, but also includes an increased allowance for other factors such as the time elapsed since the last calibration.

Table 5 provides a derivation of the combined standard uncertainty for the same measurement as carried out in table 3 but using an electrometer with a performance meeting the IPEM limits of variation given in tables 1 and 2 of this document. For certain performance characteristics these limits are tighter (though achievable) than those stated in BS EN 60731:1997. The combined standard uncertainty of ±0.26% is of similar magnitude to that derived in table 3 for the same measurement performed with the NE2560 electrometer.

Table 6. Estimate of the combined standard uncertainty associated with a 'worst case' measurement of dose from HDR brachytherapy photons using an NE2561 or 2611 chamber connected to an electrometer with the performance characteristics listed in the IPEM guidelines. For this case: 6.0 mGy min^{-1} $\rightarrow$ signal current = 1.05 pA; 0.1 Gy $\rightarrow$ signal charge = 1.05 nC.

	Limits applicable to NE2560 exposure meter			Uncertainties associated with measurement	
Performance characteristic	Limit or limits of variation	Standard uncertainty	Qualifying statement	Remarks/assumptions relating to conditions of measurement	Relative standard uncertainty
Resolution	±2.00 pC	±1.15 pC	absolute limit on resolution	percentage of signal charge	±0.110%
Repeatability	±0.050%	±0.050%	relative standard deviation at (5 nC)	—	±0.050%
Long-term stability	*±0.200%*	±0.115%	change in response per year	3 years after calibration	±0.346%
Zero drift	±5.0 fA	±2.89 fA	residual leakage after zeroing	percentage of signal current	±0.275%
Zero shift	±5.0 pC	±2.89 pC	on starting/stopping measurement	percentage of signal charge	±0.275%
Non-linearity	*±0.200%*	±0.115%	of response at 50% of full scale	readings made at 11% of full so max. error possible	±0.115%
Stabilization time	*±0.200%*	±0.115%	change in response over 15 min to 6 h	after 1 h response should be half way to final value	±0.058%
Range changing	*±0.200%*	±0.115%	of response	—	±0.115%
Temp. response	*±0.015%*	±0.009%	change in response per °C	used within 5 °C of calibration temperature	±0.043%
Temp. zero drift	±1.0 fA	0.577 fA	change in zero drift per °C change after zeroing	temp. varies by <2 °C after zeroing	±0.110%
Humidity	±10.0 fA	±5.77 fA	charge leakage at 80% R.H. and 90% of full scale	used at 65% R.H. and 11% of f.s., so maximum effective charge on capacitor only 6% of full	±0.018%
Stray radiation	±10.0 fA	±5.77 fA	change in zero drift over 0 to 0.2 mSv h^{-1}	used at 0.025 mSv h^{-1}	±0.068%
Accumulated charge	±5.00 fA	±2.89 fA	charge leakage at 90% of full scale	used at 11% of full scale, so maximum effective charge on capacitor only 6% of full	±0.018%
Input current	*±0.200%*	±0.115%	change in response over 1 pA to 5 nA	standard uncertainty scaled proportional to $\log_{10}$ of current	±0.114%
Mains voltage (static)	*±0.200%*	±0.115%	in response over −12 to +10% voltage	±6% (UK Electricity Supply Regs 1988), 10% of full scale	±0.063%
Mains voltage (variation)	±5.00 pC	±2.89 pC	−12 to +10% change in 10 s	only −6 to +6% change in 10 s	±0.150%
				Combined standard uncertainty	±0.612%

Limits in italics are tighter than reference class limits in BS EN 60731.

The working party therefore suggests that any electrometer purchased for use as a secondary standard should have performance characteristics such that under the measuring conditions stated in table 5 the combined standard uncertainty associated with the measurement of dose is not greater than ±0.3%.

For completeness, table 6 provides a derivation of the combined standard uncertainty for the same measurement as carried out in table 4 but this time using an electrometer meeting the IPEM limits of variation. The combined standard uncertainty is ±0.61%.

5. Calibration procedures at the National Physical Laboratory

5.1. Calibration method and uncertainties

There is one overriding reason why NPL and other primary standardizing laboratories prefer to calibrate measuring assemblies in terms of charge instead of current: this minimizes the calibration uncertainty (NPL 1996). The primary and secondary standards are so different that it is not possible to adopt calibration methods such as those used in a secondary standard laboratory, for example simultaneous irradiation of the two instruments. This means that NPL measurements have to be related by a monitor chamber and a calibration in terms of current would be subject to additional uncertainties. Specifically calibration in terms of rate would be sensitive to variations in x-ray output and errors in timing, sources of uncertainty which do not contribute to a calibration based on integrated measurements controlled by a shutter and related via a monitor chamber. In addition the uncertainties attributable to the electrical quantities involved are less for charge measurements (capacitance and voltage) than for current (voltage and resistance).

5.2. Costs of changing the calibration technique

Modern instruments and x-ray generators have become more stable, measurement techniques and instruments have improved and so, in principle, calibration techniques could change. NPL has made the judgement that the significant cost of the work required to implement and validate the alternative method is not warranted (NPL 1996).

5.3. Implications of NPL's techniques for modern instrumentation

The internal operation of most modern measuring assemblies is based on a measurement of current and, when the user requires it, charge is obtained as the integral of this current. In the case of at least one instrument in use at the present time, this rules out any technique for electrical calibration which directly employs a voltage source and standard capacitor. Instead, NPL uses an indirect method, via a commercial current source. Even though some aspects of the resulting calibration refer to 'displayed' currents (in particular the corrections for scale non-linearity) it is essential that the user be aware that these currents are to be inferred from measurements of charge and time.

5.4. Requirement for the calibration of a dosimeter at NPL

Because of the calibration techniques employed at NPL, these guidelines for secondary standard measuring assemblies require that instruments are calibrated in terms of integrated dose and air kerma.

Appendix A. BS EN 60731:1997 terms used in these guidelines

These terms are listed in alphabetical order. BS EN 60731:1997 paragraph numbers are given in brackets.

B.2.1 (3.15) *Effective range* (of *indicated values*). The range of indicated values for which an instrument complies with a stated performance; the maximum (minimum) *effective indicated value* is the highest (lowest) in this range.
The concept of effective range may also be applied to scale readings and to related quantities not directly indicated by the instrument e.g. input current.

B.2.2 (3.2) *Indicated value*. The value of a quantity derived from the scale reading of an instrument together with any scale factors indicated on the control panel of the instrument.

B.2.3 (3.7) *Influence quantity*. Any external quantity that may affect the performance of an instrument.

B.2.4 (3.8) *Instrument parameter*. Any internal property of an instrument that may affect the performance of this instrument.

B.2.5 (3.14) *Limits of variation*. The maximum *variation* of a *performance characteristic* y permitted by this standard. If limits of variation are stated as $\pm L\%$, the variation $\Delta y/y$, expressed as a percentage, shall remain in the range from $-L\%$ to $+L\%$.

B.2.6 (3.1.2) *Measuring assembly*. A device (part of a *dosimeter*) to measure the charge (or current) from the *ionization chamber* and convert it into a form suitable for displaying the value(s) of *dose* or *kerma* (or their corresponding *rates*).

B.2.7 (3.16.1) *Minimum rated range*. This is the least range of an influence quantity or instrument parameter over which the instrument shall operate within the specified limits of variation in order to comply with this standard.

B.2.8 (3.12.9) *Non-linearity*. Deviation from linearity, quantified as follows: on each range the half full scale reading M is taken as a reference; the input signal Q required to produce this *reference scale reading* is measured. At another scale reading m produced by an input signal q, the percentage deviation from linearity is given by:

$$100((mQ/Mq) - 1).$$

Notes:
1. For a measuring assembly set to the 'dose' mode, the input signal is electric charge;
2. For a measuring assembly set to the 'dose rate' mode, the input signal is electric current.

B.2.9 (3.12) *Performance characteristic*. One of the quantities used to define the performance of an instrument (e.g. *response*, *leakage current*).

B.2.10 (3.16) *Rated range* (of *use*). The range of values of an influence quantity or instrument parameter within which the instrument will operate within the limits of variation. Its limits are the maximum and minimum *rated* values.

B.2.11 (3.23) *Reference-class dosimeter*. Dosimeter whose performance and stability are sufficient for it to be used to calibrate other dosimeters.

B.2.12 (3.12.2) *Resolution* (of the display). The smallest change of scale reading to which a numerical value can be assigned without further interpolation:

- for an analogue display, the resolution is the smallest fraction of a scale interval that can be determined by an observer under specified conditions;
- for a digital display, the resolution is the smallest significant increment of the reading.

B.2.13 (3.12.1) *Response*. For a measuring assembly on its own it is the quotient of the *indicated value* divided by the input charge or current.

B.2.14 (3.12.5) *Stabilization time*. The time taken for a stated *performance characteristic* to reach and remain within a specified deviation from its final steady value after the measuring assembly has been switched on (or the polarizing voltage has been applied to the ionization chamber).

B.2.15 (3.10.1) *Standard test conditions*. Conditions under which all influence quantities and instrument parameters have their *standard test values*.

B.2.16 (3.10) *Standard test values*. A value, values or range of values of an influence quantity or instrument parameter, which are permitted when carrying out calibrations or tests on another influence quantity or instrument parameter.

B.2.17 (3.13) *Variation*. The relative difference, $\Delta y/y$, between the values of a performance characteristic y, when one influence quantity (or instrument parameter) assumes successively two specified values, the other influence quantities (and instrument parameters) being kept constant at the standard test values (unless other values are specified).

B.2.18 (3.12.7) (Measuring assembly) *zero drift*. A continuous change in the near zero scale reading of the measuring assembly in the 'measure' condition with no signal present.

B.2.19 (3.12.8) (Measuring assembly) *zero shift*. A sudden change in the near zero scale reading of the measuring assembly when the setting control is changed from the 'zero' condition to the 'measure' condition, with no signal present.

Appendix B. Extreme case dose/dose rates

Table B1. Conditions giving rise to minimum values of signal current and charge.

Recommended chamber		Typical irradiation conditions			Minimum values			
Type	Sensitivity [Gy C^{-1}]	Radiation type	Depth [cm]	fsd [cm]	Dose rate [Gy min^{-1}]	Dose [Gy]	Signal current [A]	Signal charge [C]
X-rays below 300 kV								
NE2536	7.9×10^7	Low energy x-rays	in air	35	1.5	0.5	3.16×10^{-10}	6.33×10^{-9}
NE2561 or NE2611	9.5×10^7	Medium energy x-rays	2	50	0.4	0.5	7.02×10^{-11}	5.26×10^{-9}
NE2571	4.5×10^7	Medium energy x-rays	2	50	0.4	0.5	1.48×10^{-10}	1.11×10^{-8}
High energy photons								
NE2561 or NE2611	9.5×10^7	Co-60 photons	5	80	0.4	0.5	7.02×10^{-11}	5.26×10^{-9}
Electrons								
NE2561 or NE2611	9.5×10^7	Co-60 photons	5	80	0.4	1.0	7.02×10^{-11}	1.05×10^{-8}
NE2571	4.5×10^7	Co-60 photons	5	80	0.4	1.0	1.48×10^{-10}	2.22×10^{-8}
NACP01 or NACP02	1.5×10^8	High energy electrons	3	100	1.0	1.0	1.11×10^{-10}	6.67×10^{-9}
Markus	5.0×10^8	High energy electrons	3	100	1.0	1.0	3.33×10^{-11}	2.00×10^{-9}
Roos	8.0×10^7	High energy electrons	3	100	1.0	1.0	2.08×10^{-10}	1.25×10^{-8}
HDR brachytherapy								
NE2561 or NE2611	9.5×10^7	Ir-192 photons	in air	10	0.006	0.1	$\mathbf{1.05 \times 10^{-12}}$	$\mathbf{1.05 \times 10^{-9}}$
NPL air kerma calibrations								
NE2536	7.9×10^7	Low energy x-rays	in air	—	0.1	0.1	2.11×10^{-11}	1.27×10^{-9}
NE2561 or NE2611	9.5×10^7	Medium energy x-rays	in air	—	0.1	0.1	1.75×10^{-11}	$\mathbf{1.05 \times 10^{-9}}$
NE2571	4.5×10^7	Medium energy x-rays	in air	—	0.1	0.1	3.70×10^{-11}	2.22×10^{-9}

Table B2. Conditions giving rise to maximum values of signal current and charge.

Recommended chamber		Typical irradiation conditions			Minimum values			
Type	Sensitivity [Gy C^{-1}]	Radiation type	Depth [cm]	fsd [cm]	Dose rate [Gy min^{-1}]	Dose [Gy]	Signal current [A]	Signal charge [C]
X-rays below 300 kV								
NE2536	7.9×10^7	Very low energy x-rays	0	10	10.0	20.0	2.11×10^{-9}	2.53×10^{-7}
NE2561 or NE2611	9.5×10^7	Very low energy x-rays	in air	10	10.0	20.0	1.75×10^{-9}	2.11×10^{-7}
NE2571	4.5×10^7	Very low energy x-rays	in air	10	10.0	20.0	$\mathbf{3.70 \times 10^{-9}}$	$\mathbf{4.44 \times 10^{-7}}$
High energy photons								
NE2561 or NE2611	9.5×10^7	High energy x-rays	5	100	5.0	10.0	8.77×10^{-10}	1.05×10^{-7}
Electrons								
NE2571	4.5×10^7	High energy electrons	3	100	5.0	10.0	1.85×10^{-9}	2.22×10^{-7}
NACP01 or NACP02	1.5×10^8	High energy electrons	3	100	5.0	10.0	5.56×10^{-10}	6.67×10^{-8}
Markus	5.0×10^8	High energy electrons	3	100	5.0	10.0	1.67×10^{-10}	2.00×10^{-8}
Roos	8.0×10^7	High energy electrons	3	100	5.0	10.0	1.04×10^{-9}	1.25×10^{-7}
NPL air kerma calibrations								
NE2536	7.9×10^7	Low energy x-rays	in air	—	0.5	5.0	1.05×10^{-10}	6.33×10^{-8}
NPL absorbed dose to water calibrations								
NE2561 or NE2611	9.5×10^7	High energy x-rays	—	—	1.0	5.0	1.75×10^{-10}	5.26×10^{-8}
NE2571	4.5×10^7	High energy x-rays	—	—	1.0	5.0	3.70×10^{-10}	1.11×10^{-7}

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