

Trial calibrations of therapy level electron beam ionisation chambers in terms of absorbed dose to water

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ABSTRACT

Over several years NPL has been developing a calibration service for electron beam radiotherapy. To test this service, a trial calibration of therapy level electron beam ionisation chambers was carried out in 1996, involving fourteen radiotherapy centres supplying a total of eighteen chambers and twelve electrometers. All chambers were either of the NACP-02 (Scanditronix) or Markus (PTW) type. A second trial was carried out in 1997. This second trial involved nine radiotherapy centres supplying a total of seventeen chambers of the NE2571 Farmer, NACP-02 (Scanditronix), Markus (PTW) and Roos (PTW) types. Measurements were carried out at seven energies in the range 4-19 MeV together with an investigation of ion recombination. Electrometers were also calibrated. The instruments were returned to the radiotherapy centres for measurements to be carried out comparing the NPL direct calibration with the 1996 IPEMB air kerma based Code of Practice.

The trials indicated that not all chambers of the same type exhibit the same behaviour. The results of the comparison between the NPL calibration and IPEMB Code are somewhat unexpected. The NACP and Farmer chambers show agreement between the two methods at the $\pm 1\%$ level but there is a significant difference for the Markus chambers of around 2%, with a higher dose according to the NPL calibration. There is no obvious reason for this discrepancy and further measurements are required to identify the source of the problem.

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1 INTRODUCTION

Over several years NPL has been developing a calibration service for electron beam radiotherapy. This is based on the primary standard electron-beam graphite calorimeter and yields a calibration of an ionisation chamber in terms of absorbed dose to water (Burns *et al*, 1994; McEwen *et al*, 1998). To test this service, a trial calibration was carried out in 1996, involving fourteen radiotherapy centres supplying a total of eighteen chambers and twelve electrometers. All chambers were either of the NACP-02 (Scanditronix) or Markus (PTW) type and six different types of electrometer were supplied. Chambers were calibrated at nominal electron energies of 4, 6, 8, 10, 12, 16 and 19 MeV. A second trial was carried out in 1997. This second trial involved nine radiotherapy centres supplying a total of seventeen chambers and four electrometers, and, in addition, five NPL chambers were also calibrated. The majority of chambers in this second trial were of the NE2571 Farmer type but a number of NACP-02 (Scanditronix) and Markus (PTW) type chambers from the first trial were recalibrated, together with two Roos (PTW) type chambers. Four different types of electrometer were supplied. In the second trial, parallel-plate chambers were calibrated at nominal electron energies of 4, 8, 12, 16 and 19 MeV, while the Farmer chambers were limited to the three highest energies. Electrometers were calibrated independently in terms of absolute charge and neither trial involved customer ^{90}Sr check sources.

In the UK, one major difference between photon and electron dosimetry in radiotherapy centres is that there is no defined secondary standard electron chamber. Any chambers recommended in the IPEMB Code of Practice (1996) can be used, and all types were calibrated in one of the trials - the NACP-02 manufactured by Scanditronix (Mattson *et al*, 1981; NACP, 1981), the Markus design (Markus, 1973) manufactured by PTW (type 23343), the NE2571 Farmer-type chamber manufactured by NE Technology Ltd and the Roos design manufactured by PTW (type 34001). Since this work was completed, Wellhöfer have also released versions of the Markus and Roos chambers (types PPC05 and PPC35 respectively). The lack of a defined secondary standard means that the chambers to be calibrated are used regularly for field measurements and therefore an extra requirement of the service was a fast turnaround. A schedule was drawn up for each trial to ensure that all chambers were returned to their centres within three weeks of receipt. The centres were then asked to carry out measurements comparing the NPL absorbed dose to water calibration protocol with the IPEMB Code of Practice for electron beam dosimetry (IPEMB, 1996).

For convenience, a number of abbreviations are used in this report. The IPEMB Code of Practice is described as the IPEMB Code. Individual chambers are designated by their serial number and the following prefixes: N - Scanditronix NACP, C- Dosetek (Calcam) NACP, M - Markus, R - Roos and F - Farmer (NE2571).

2 DETERMINATION OF ABSORBED DOSE-TO-WATER CALIBRATION FACTORS

The absorbed dose to water calibration factor for a user chamber, $N_{user,w}$, is given by Burns *et al* (1994):

$$N_{user,w} = N_{ref,g} \frac{M_{ref,w}}{M_{user,w}} \frac{p_{ref,w}}{p_{ref,g}} \frac{S_{w/air}}{S_{g/air}} \quad (1)$$

This equation has four components:

- i) $N_{ref,g}$ - graphite calibration factor for NPL reference chamber (taken as the mean response of four chambers)
- ii) $M_{ref,w} / M_{user,w}$ - ratio of reference and user chamber measurements in water
- iii) $p_{ref,w} / p_{ref,g}$ - ratio of perturbation corrections in water and graphite for NPL reference chambers
- iv) $S_{w/air} / S_{g/air}$ - effective stopping power ratio, water to graphite, taking into account the air volume of the chamber

2.1 Graphite calibration factor

The graphite calibration factor, $N_{ref,g}$, has been determined over the last three years by comparing the NPL reference chambers with the primary standard electron-beam graphite calorimeter and this work is detailed by McEwen *et al* (1998). After some years of experimental investigation, NPL has chosen the NACP chamber type (Mattson *et al*, 1981; NACP, 1981) as its reference chamber (specifically the NACP-02 design manufactured by Scanditronix). This chamber is widely used throughout the medical physics community and can operate over the whole energy range of interest. It is also one of the recommended chambers in the IPEMB Code of Practice. A set of at least four reference chambers are maintained - four is the minimum, and these chambers can not be repaired easily if they fail. Each reference chamber is compared with the calorimeter on a regular basis (about every six months) and a simple average is used to give the value of $N_{ref,g}$. Chamber stability measurements using a ^{90}Sr check source are made on a more frequent basis.

2.2 Ratio of chamber measurements

The method used was a direct comparison of the user chamber and NPL reference NACP-02 chambers in a water phantom in the NPL Linac beam. The water phantom was specially designed to position each chamber (NACP, Markus, Roos and Farmer) at the correct depth for that beam quality. The reference depth, d_{ref} , is defined by Burns *et al* (1996) as:

$$d_{ref} = 0.6R_{50} - 0.1 \text{ cm} \quad (2)$$

where R_{50} is the depth at 50% of the peak dose. These measurements were carried out at a source-to-surface distance (SSD) of 2 m with a field size of 15 cm × 15 cm. Seven beam qualities are in routine use for electron dosimetry at NPL - nominal energies of 4, 6, 8, 10, 12, 16 and 19 MeV. Parallel plate chambers are calibrated at all these energies. Farmer chamber measurements were made only at 12, 16 and 19 MeV, since these chambers are only recommended for use at higher energies due to the large perturbation correction for a thimble chamber. The measurement sequence was as follows:

- 1 NPL reference chambers
- 2 User chambers
- 3 NPL reference chambers (to measure linac/measurement system drift)
- 4 User chambers
- 5 NPL reference chambers (to measure linac/measurement system drift)

A number of NPL chambers were also calibrated as “user” chambers to enable comparisons with the IPEMB Code to be carried out at NPL. Measurements were made using the NPL computer-controlled acquisition system, using an NPL-designed transmission monitor as the transfer instrument between chambers. The electrometers used were also of NPL design, and corrections were made for temperature and pressure. Recombination corrections for the NPL reference chambers were made “on-line” (Burns and McEwen, 1998). The polarizing voltage chosen for each user chamber was that stated by the user and these chambers were not corrected for ion recombination in this way since their recombination response had not been characterised (see below). All chambers were operated at negative polarity only and no polarity correction was applied. The PC system meant that it was possible to monitor each chamber to make sure that equilibrium had been reached. One Farmer chamber was found to be faulty during the calibration process, due to a poor contact between the chamber cable and triax-TNC connector. Unfortunately, the fault was intermittent, which meant that the chamber passed the ^{90}Sr check source measurement and the problem was only discovered during linac measurements. This chamber was returned to the user and is not included in the results and discussion. The second trial allowed the recalibration of a number of chambers, one year on, checking the reproducibility of the calibration process and/or chamber stability. Measurements on the NPL NACP chambers have indicated that they are stable over a number of years at the $\pm 0.25\%$ level.

The NPL linear accelerator is a 3-20 MeV research accelerator and the collimation and geometry are quite different from that of a medical accelerator. However, comparisons of depth-ionisation measurements together with Monte-Carlo simulations have shown that measurements made in the NPL electron beam should be equivalent to those made in clinics (Burns *et al*, 1996).

User electrometers were calibrated by using a voltage standard and calibrated capacitor to inject a known amount of charge. Although this does not directly mimic the operation in a radiation beam there is no evidence of any difference between calibration and use.

2.2.1 Check source measurements

All chambers were checked before and after calibration using the NPL check source system. This consists of: ^{90}Sr check source, electrometer, PRT temperature monitor and pressure meter. The source used for the parallel plate chambers is the PTW type supplied with Markus chambers - a small modification to the perspex source/chamber holder makes it suitable for both Markus and NACP chambers; a second holder was modified for the Roos chamber. The source is only 5 mm in diameter to match the Markus chamber and therefore the irradiation of the NACP and Roos chamber is not uniform. However, this system has been used for over 18 months to monitor the stability of the NPL reference chambers and has shown good repeatability (see Figure 1). A NE2503 check source was used for the Farmer chambers. All measurements were corrected to STP (20 °C and 101.33 kPa). After correction for source decay, the chambers showed random differences (max 0.3%) between the before and after measurements, most likely due to relative positioning of the source and chamber. It is anticipated that, once in operation, the calibration service will not involve any user ^{90}Sr sources, due to the problems involved in transportation of radioactive sources.

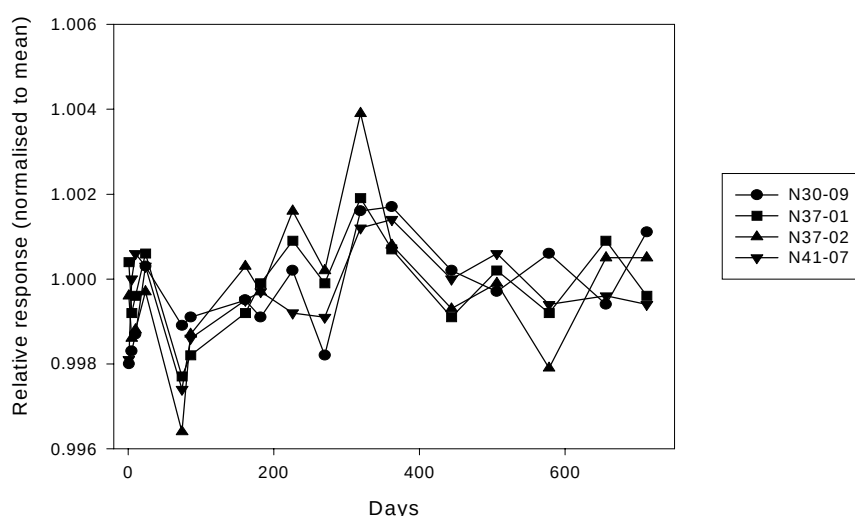


Figure 1. ^{90}Sr check source measurements (corrected for source decay) for four NPL reference chambers

2.2.2 Recombination measurements

Several authors (Burns 1991, Havercroft and Klevenhagen 1993, Burns and Burns 1993, Nisbet and Thwaites, 1998) have indicated that NACP chambers can exhibit a response to changes in polarizing voltage that is not predicted by the accepted Boag theory (1950) which will therefore affect the evaluation of the recombination correction. The problem does not appear to be unique to the NACP chamber, nor indeed to parallel-plate chambers; Derikum and Roos (1993) noted similar effects for some cylindrical chambers. In the course of characterizing the

NPL reference chambers, a large number of recombination measurements were made over a range of dose rates and Burns and McEwen (1998) describe this work in detail. The trials enabled their work to be extended to a much larger sample of chambers.

During the first trial a brief investigation of chamber recombination response was carried out. This was expanded in the second trial to include all chambers calibrated. The polarizing voltage was varied for each chamber between the calibration voltage and around 30V in four steps (e.g. 250, 125, 75, 30) and the first voltage repeated to correct for any measurement drift. The recombination correction was obtained from a plot of the reciprocal of the ionisation current against the reciprocal of the polarizing voltage. For a chamber following the Boag theory such a plot should be a straight line and a linear extrapolation of this line to infinite voltage gives the true ionisation current (i.e. no ion recombination). Plotting the variation in recombination with doserate yields a straight line and allows one to obtain the recombination correction at any doserate. This simplifies measurements in the clinic since one does not need to carry out recombination measurements as long as one knows the doserate (actually, the dose per pulse). Measurements were made at two doserates for the Farmer chambers and three for the parallel plate chambers.

2.2.3 Polarity measurements

As stated above, the calibration process (at present) does not involve polarity measurements. However, there has been concern expressed recently that polarity can be strongly dependent on beam quality, especially for parallel plate chambers, and must be taken into account. The IPEMB Code defines the polarity effect as the difference in chamber readings obtained in the same irradiation conditions but taken with positive and negative polarising voltages. The polarity correction is then given by

$$f_{pol} = \frac{|M^+| + |M^-|}{2M} \quad (3)$$

where the superscripts “+” and “-” indicate the polarity of the polarizing voltage for chamber reading M . Generally, polarity effects will be small (< 1%) for parallel plate chambers such as the NACP and Roos designs although for the NE2571 and Markus chambers, values of over 1% at lower beam energies have been reported. Measurements at NPL were made close to the depth of dose maximum in either a water or graphite phantom, at a range of energies. Polarity corrections were also obtained from the user measurements made in the clinics.

2.3 Perturbation correction

The IAEA Code of Practice for parallel plate chambers (1997) provides a review of chamber perturbation factors, detailing the problems, as does Nahum (1996). It is generally believed that a well-guarded parallel-plate chamber such as the NACP design has a negligible perturbation. However, Equation (1) allows for a perturbation in both graphite and water but assumes that all chambers of the same type have the same perturbation. Monte Carlo simulations were carried out to determine the perturbation corrections in both media and initial results are described by Williams *et al* (1998).

Measurements were also carried out to compare the water/graphite perturbation ratio for a number of NACP chambers (type 01 and 02, Scanditronix and Dosetek) at a number of energies. Such measurements can confirm whether different chambers of the same type are equivalent or whether perturbation corrections are actually chamber dependant. By using scaled depths in water and graphite (scaled by the stopping power ratio) one can obtain a similar energy spectrum in both phantoms. The chambers were then intercompared in the two phantoms to obtain relative perturbation ratios. By taking the ratio of two chambers one cancels out any fluence difference due to chamber positions in water and graphite.

The presence of the Roos chamber in the second trial allowed a second test of the NACP perturbation correction. The Roos chamber is specifically designed to have a perturbation correction in water very close to unity. The chamber is constructed entirely of PMMA (except for the graphite coatings of the electrodes) and has very little

material behind the collector electrode (~ 1 mm). One concern raised by Klevenhagen (1991) was that the large amount of graphite behind the collecting electrode in the NACP chamber could lead to a backscatter correction since graphite is backscatter deficient compared to water - a figure of up to 0.6% has been quoted. Measurements by McEwen *et al* (1998) have shown that the backscatter contribution to the chamber reading is almost entirely due to the first few millimetres of material behind the cavity. A graphite disk was manufactured to fit into the recess at the rear of the Roos chamber and effectively simulate the construction of the NACP chamber. Measurements were carried out in water at a number of electron energies (with the chamber positioned at the reference depth) and the response of the chamber was compared with and without this graphite disk in place.

If one assumes that the NACP chamber has a unity perturbation correction then one can obtain relative perturbation corrections for the Markus and Farmer chambers from the calibration measurements. These can then be compared with other published data.

2.4 Stopping power ratio

Stopping powers are determined following the procedure proposed by Burns *et al* (1995), which combines measurements of electron depth-dose curves in water and graphite with Monte Carlo calculations of the full experimental geometry. This method allows “fine tuning” of the standard stopping power data and should result in a lower uncertainty in the stopping power ratio. The method does not attempt to measure the stopping powers directly, but uses experimental determinations of ranges in water and graphite to constrain the Monte Carlo simulations (see also the comments by Ross and MacPherson (1996) on this method). A complex series of steps were undertaken to ensure the best possible accuracy in the calculation.

First an EGS4 (Nelson *et al*, 1985) user code (called ELINAC) was written to simulate the NPL electron linear accelerator. The code includes conical geometry and predates the BEAM code (Rogers *et al*, 1995). To perform the simulation, data (giving cross section and probability distributions) are prepared by adjusting the EGS default data for the density effect given in ICRU Report 37 (ICRU, 1984). A simulation of the linac was performed using ELINAC to generate a list of phase space data (recording particle type, position, direction and energy) just past the last electron scattering foil for each nominal energy used in the calibration service.

Next this phase space data was used as the radiation source for a further simulation using the EGS code DOSRZ. The simulation modelled the radiation beam as it passed into a homogeneous block of water. The depth versus dose profile in water was calculated and compared with the experimentally measured range (McEwen *et al*, 1996). To reduce the possibility of a systematic error, the same program was used to determine both the experimental and calculated ranges. This indicated the mismatch, if any, between the incident energy used in the calculation and the actual energy of the NPL linac.

The actual energy was found to be about 7% lower than the nominal energy for the 19 MeV beam, reducing to around 1% at 4 MeV. The calculations above were repeated with the incident electron energy set to the energy needed to match the experimental range. The resulting calculated ranges were then within 0.1% of the measured range and the resulting phase space data are referred to as the ‘range matched’ phase space data. This data was then used to calculate the energy spectra (in 10 keV bins) at the appropriate reference depth in water and in graphite (the range matched spectra at depth).

The effective stopping power of water for the range matched spectra at depth in water was simply calculated by multiplying the range matched energy spectra at depth by the monoenergetic stopping power data given in ICRU Report 37. The effective stopping power of air for the range matched spectra at depth in water was calculated in the same way. The effective stopping power ratio water to air were compared with values published by IAEA (1987) and others. The calculations suggested the published values (using many compromises not used here) of the stopping power water to air are about 1% high at low energies and within 0.5% at high energies. This agreement is within the uncertainties. The effective stopping power of graphite and air for the range matched spectra at depth in graphite were calculated in the same way. These stopping power values are then combined to give the effective stopping power ratio of graphite to water at the appropriate reference depths.

2.5 Radiographing of chambers

Radiographs are a simple but powerful way to check the construction of an ion chamber. New chambers are now routinely radiographed at NPL, face on and from the side. This is done because previous radiographs of NPL chambers have shown up a design fault in the Dosetek-manufactured NACP chambers as well as a slight design difference in the guarding arrangement between certain Scanditronix NACP chambers. Figure 2 shows side-on radiographs of a Scanditronix and a Dosetek NACP chamber. As can be seen, the Dosetek chamber has the collector wire passing through the air volume and almost touching the HT electrode, which could significantly affect the chamber's performance. Whether all Dosetek-manufactured NACP chambers follow this design remains to be seen, and Dosetek have now ceased production. As stated above, all the NPL reference chambers are manufactured by Scanditronix. Figure 3 shows a typical radiograph of a Markus chamber. Although radiographs are simple to carry out, parallel plate chambers are all constructed from low-Z plastic materials and it can be a matter of trial and error to obtain sufficient contrast to identify the various components. Klevenhagen (1993) gives a description of a large number of electron chambers, together with constructional diagrams. Radiographs of Farmer chambers tend to be clearer because of the increased contrast due to the aluminium electrode and body. It was found that for a number of chambers, the central electrode was not straight. This will affect the electric field within the air cavity, although the cylindrical geometry should average out an effect and measurements made during the trials confirmed that any effect was negligible.

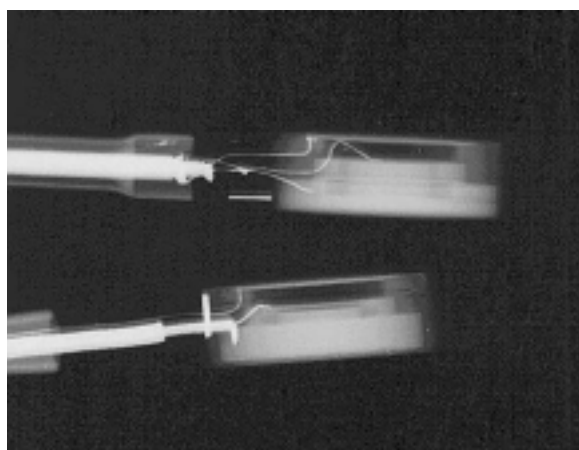


Figure 2. Radiographs of NACP chambers. Top - Dosetek chamber; bottom - Scanditronix

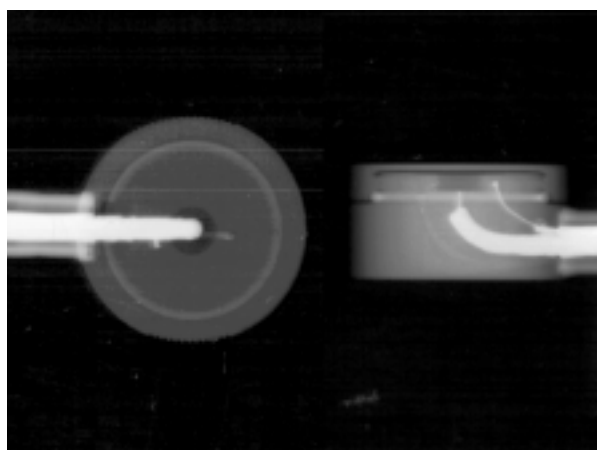


Figure 3. Radiographs (front and side views) of Markus chamber

2.6 Analysis

Since three of the four components in Equation (1) have been previously determined, the analysis required to determine chamber calibration factors is fairly simple. As described above, NPL maintains a set of NACP reference chambers and their individual values of $N_{ref,g}$ are shown in Table 1. The differences between chambers can be interpreted as differences in the effective volume of each chamber. However, rather than rely on one chamber to obtain the user chamber calibration factor, the mean response of all four reference chambers was taken for the value for $M_{ref,w}$ in Equation (1). Since only initial results were available from the calculations to obtain the ratio of perturbation factors, it was decided to use the best value from the literature - a value of unity - although this may need to be revised once the calculations at NPL have been completed. The stopping power ratio values used are given in Table 2.

Table 1. Graphite calibration factors for NPL reference chambers

E_{nom} (MeV)	$N_{ref,g}$ (Gy/ μ C)			
	N30-09	N37-01	N37-02	N41-07
4	140.09	125.70	122.74	122.08
6	139.57	125.20	122.23	121.62
8	138.20	124.03	121.10	120.45
10	137.48	123.36	120.46	119.81
12	136.58	122.43	119.53	119.00
16	134.79	120.95	118.04	117.52
19	133.96	120.18	117.37	116.76

Table 2. Stopping power ratio at the reference depth used for each electron energy

E_{nom} (MeV)	$R_{50,D}$ (g/cm ²)	$s_{w/air}/s_{g/air}$
4	1.23	1.1466
6	1.97	1.1459
8	2.75	1.1452
10	3.48	1.1445
12	4.23	1.1437
16	5.72	1.1423
19	6.60	1.1412

2.7 Uncertainty

The various components of equation (1) contribute to the overall uncertainty in the calibration of a user chamber in terms of absorbed dose to water. The uncertainties for all energies (quoted as standard uncertainties according to NIS 3003 (1995)) are given in Table 3.

Table 3. Uncertainties in the calibration of an ion chamber in terms of absorbed dose to water

Source	Standard Uncertainty ($\pm$ %)
Graphite calibration factor for NPL chambers	0.35
Ratio of chamber measurements	0.1
Ratio of stopping powers	0.5
Ratio of perturbation factors	0.35
Recombination correction	0.17
Electrometer calibration	0.05

This gives an overall uncertainty in $N_{user,w}$ of $\pm 1.5\%$ at the 95% confidence level. Work is still in progress on the ratio of stopping powers, perturbation factors, and calorimeter performance. It is hoped that, once this work is finished, the overall uncertainty will be around $\pm 1\%$ at the 95% confidence level.

3 RESULTS AND DISCUSSION OF MEASUREMENTS MADE AT NPL

3.1 Calibration factors

Examples of calibration factors for all four types of chamber are shown in Table 4.

Table 4. Typical calibration data for the various chamber types

E_{nom} (MeV)	$R_{50,D}$ (cm)	$d_{ref,w}$ (cm)	$N_{w,u}$ (NACP) (Gy/ μ C)	$N_{w,u}$ (Markus) (Gy/ μ C)	$N_{w,u}$ (Roos) (Gy/ μ C)	$N_{w,u}$ (Farmer) (Gy/ μ C)
4	1.23	0.64	141.76	501.93	79.86	---
6	1.97	1.08	142.52	498.67	---	---
8	2.75	1.55	141.55	495.89	79.23	---
10	3.48	1.99	140.81	493.23	---	---
12	4.23	2.44	138.93	491.56	78.01	41.39
16	5.72	3.33	138.64	489.19	76.86	41.24
19	6.60	3.86	137.48	485.61	76.33	41.11

3.2 Chamber construction

3.2.1 NACP chambers

Figure 4 effectively shows the relative volume of each NACP chamber compared to N30-09 in a 6 MeV electron beam. Assuming that serial numbers are chronological, there is a definite change (of some 15%) between chambers N29-05 and N31-04. Radiographs have also shown a difference in the design of the polystyrene backing to the collector between these two chambers; therefore, it can be reasonably assumed that this volume change is due to a design change. Measurements made to date indicate that it is not necessary to consider these two designs as separate chamber types. Also shown in Figure 4 is a comparison of the chambers obtained from ^{90}Sr check-source measurements. As can be seen, there is a good correlation between the linac and ^{90}Sr results, except for one chamber (N41-03), for which there is no obvious explanation. In a broad electron beam as in the linac, the chamber volume is defined by the chamber diameter and plate separation. However, in the ^{90}Sr measurements, the source diameter is much smaller than the cavity diameter and therefore the measurement volume is much less dependent on the chamber diameter. One possibility therefore is that for N41-03, the cavity volume is the same as other NACP chambers, but the plate separation is larger. Recombination measurements could be used to test this hypothesis, since the recombination correction is directly dependent on the plate separation. Such a difference is not likely to affect the chamber's performance in an electron beam.

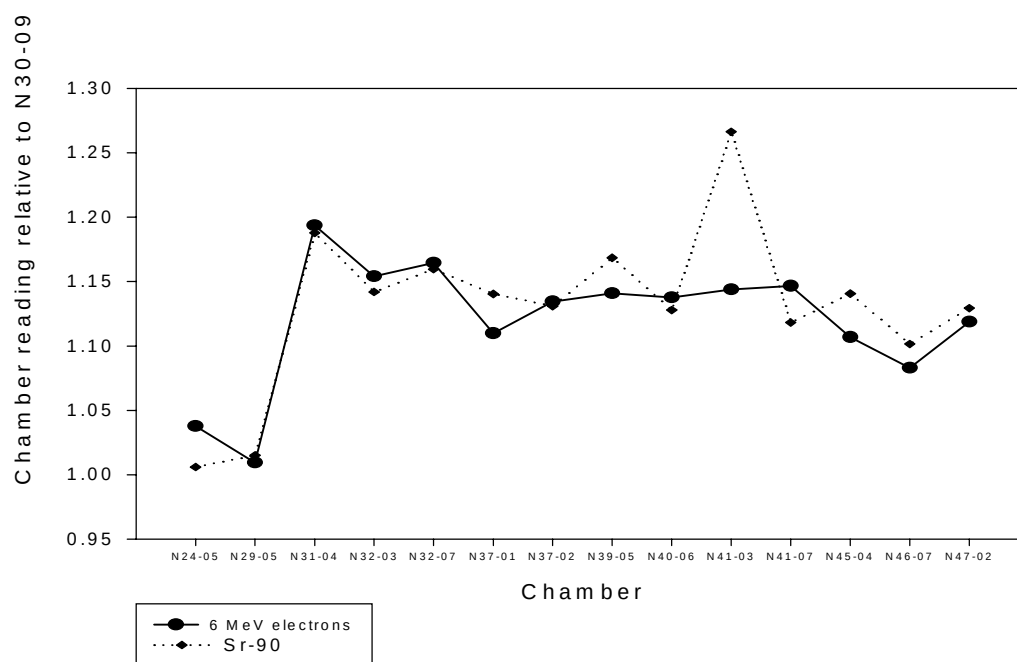


Figure 4. Response of user NACP chambers relative to NPL chamber ser. no. 30-09.
Data is shown for Sr-90 check source measurements and 6 MeV electrons.

3.2.2 Markus chambers

Figure 5 shows equivalent data for Markus chambers and, in comparison, there is no obvious trend with serial number (again assuming chronological numbering) and the spread is smaller than for NACP chambers. Differences in chamber volume may be an indicator of manufacturing tolerances and thus chamber-to-chamber variations, although this is somewhat speculative. It is interesting that the ^{90}Sr results are more constant than the 6 MeV results. The difference may be due to scatter effects of the chamber body in a broad electron beam.

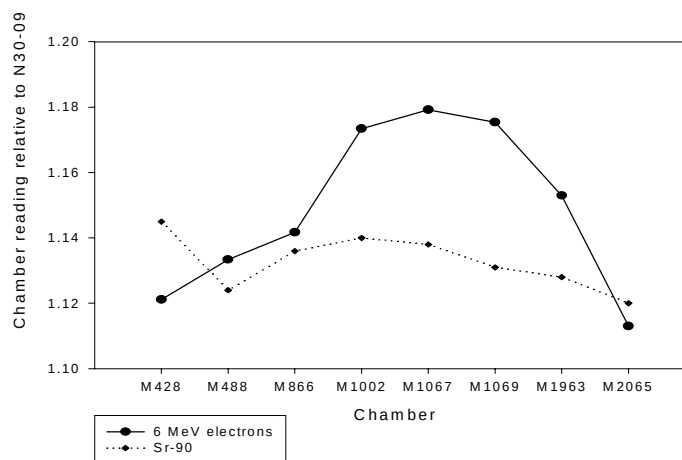


Figure 5. Response of user Markus chambers relative to NPL chamber ser. no. 30-09. Data is shown for Sr-90 check source measurements and 6 MeV electrons.

3.2.3 Farmer chambers

One of the Farmer chambers (F1623) calibrated was a type NE2505/3, rather than a type NE2571. The NE2505/3 is the design prior to the NE2571 and the only difference between the chamber versions is a slightly different internal guarding arrangement. The stem of the NE2571 is guarded to within 26 mm of the air volume, whereas the NE2505/3 has less of the stem guarded. Figure 6 shows the ratio of each NE2571 chamber to the NE2505/3. As can be seen there is a slight difference in the energy response between the chamber versions - 0.15% over the range 12-19 MeV. Also, the effective volume of F1623 is approximately 2.5% greater than the NE2571 chambers. It is not thought that these differences are significant and, as production of the NE2505/3 ended in 1979, it is not likely that the proposed calibration service will involve many such chambers.

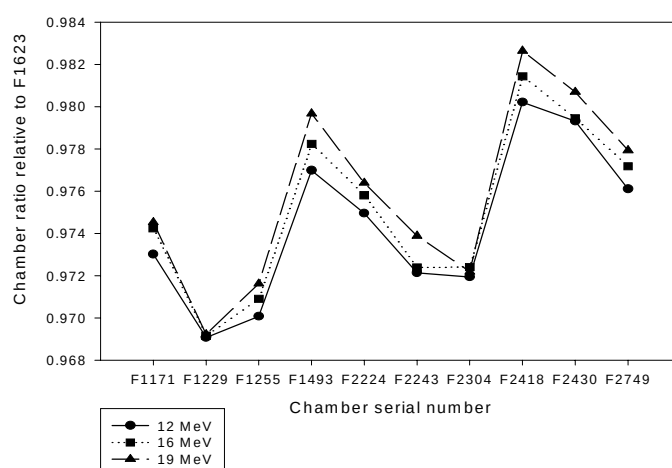


Figure 6. Response of NE2571 chambers relative to NE2505/3 chamber (S/N F1623) at three electron energies.

Since the chambers are all of the same type from the same manufacturer one can assume that serial numbers are chronological. Figure 6 therefore seems to indicate a trend of increasing chamber volume over time, although the change is only 0.8% from the earliest to the latest and there are chamber-to-chamber differences of a similar magnitude. This indicates good manufacturing tolerances and is probably the reason for the close agreement of the calibration factors for these chambers. The equivalent ^{90}Sr data showed a much larger spread in the chamber ratios relative to F1623 ($\sim 2.5\%$), which is most likely to be due to the design of the check source.

3.3 Chamber performance

Measurements with the NPL reference chambers were made at the beginning and end of each day. Reproducibility was of the order of $\pm 0.1\%$, with no trend with electron energy, indicating accurate repositioning of the chambers in the holder and phantom, and little drift in the linac output. One concern was that chamber repositioning was not precise enough in water at low electron energies for accurate calibrations. Solid phantoms (as recommended in the IPEMB Code) give more robust chamber positioning but have other problems and water is the material of first choice. These measurements confirm the validity of the present calibration process.

Figure 7 shows how the various chamber type readings “settle” with time. With pressures on measurement time it is useful to know when chambers have reached equilibrium. As can be seen, the NACP chamber shows a much smoother curve. Equilibrium is typically reached in 6 minutes although the chamber reading is within 0.05% of the final value after two minutes. By comparison, the Markus chamber is much noisier and takes longer to settle. This may be due to the difference in the air cavity volume - 0.16 cm^3 for the NACP, 0.05 cm^3 for Markus - or perhaps the poor guarding arrangement of the Markus chamber. The Farmer and Roos chambers exhibited settling times similar to the NACP chambers. Noticeably, both have larger chamber volumes of 0.6 cm^3 and 0.35 cm^3 respectively.

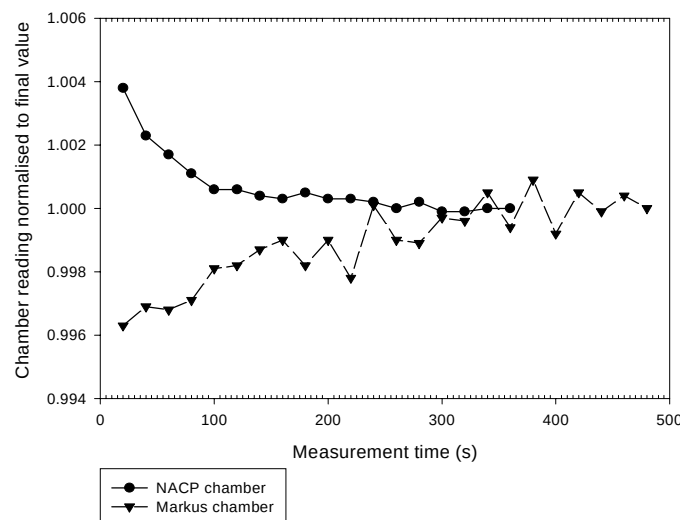


Figure 7. Time taken for chambers to reach equilibrium. Each point represents a 20 second acquisition.

Taking the data for each NACP chamber relative to one reference chamber (N30-09) and normalising for volume yields the relative deviation in energy response for that chamber, as in Figure 8. As can be seen, some chambers show better agreement with N30-09 than others. Assuming that serial numbers are chronological, it would seem that newer chambers (e.g. N46-07, N47-02) are more variable than older ones (e.g. N24-05, N29-05). However, this is not confirmed by the second trial, indicating that deviations in energy response are random or due to

experimental setup. These variations, which can be up to $\pm 0.4\%$, are perhaps larger than one would like for reference chambers and may be an indication of the inherent stability of the NACP design. The NACP chambers that were recalibrated in the second trial showed changes of the order of $\pm 0.2\%$ from the previous year, which are consistent with results from the NPL reference chambers. The two Roos chambers calibrated in the second trial showed almost identical responses (within $\pm 0.05\%$), which is better than any other chamber type, with a deviation around the energy response of N30-09 at the $\pm 0.1\%$ level. Whether this is representative of all Roos chambers or just a coincidence remains to be seen.

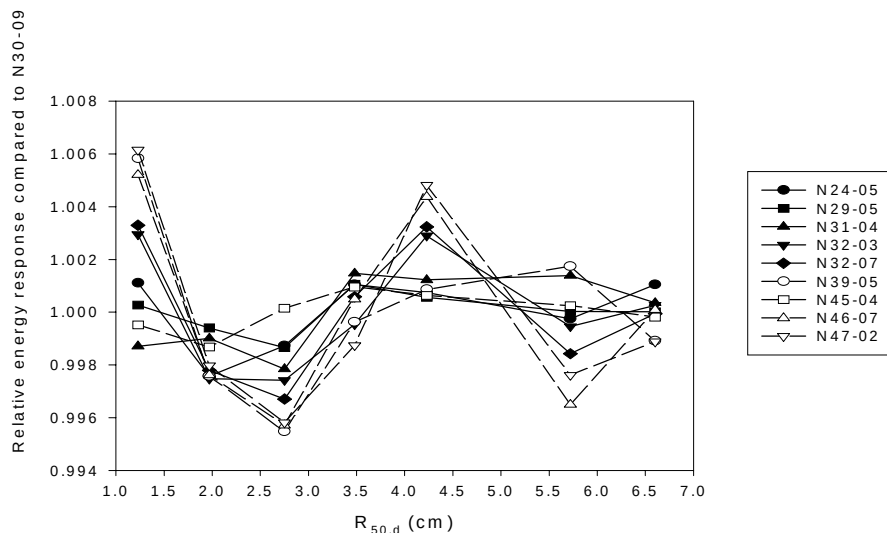


Figure 8. Energy response of NACP chambers relative to N30-09

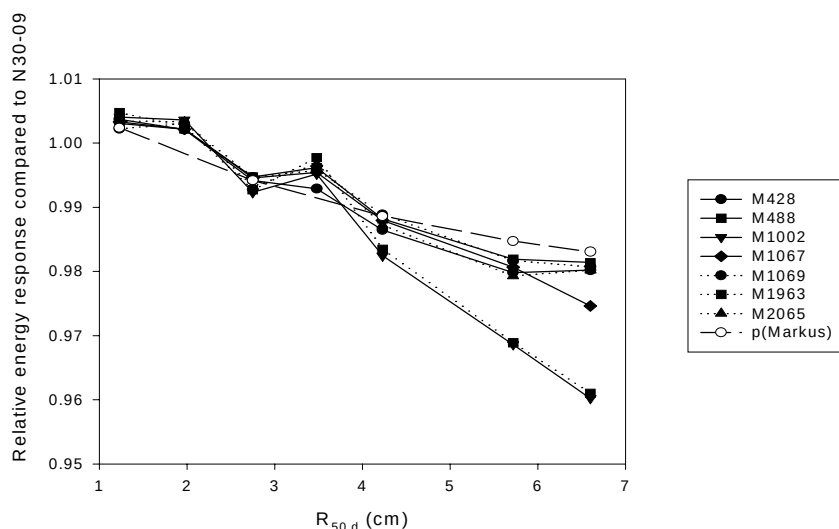


Figure 9. Energy response of Markus chambers relative to N30-09.

$p(\text{Markus})$ is the perturbation correction for the Markus chamber as given in the IPEMB Code

Figure 9 shows equivalent data for the Markus chambers. What is immediately obvious from this graph is that two chambers - M1002 and M1963 - exhibit very different characteristics from the others. There is no explanation for

this at present. It is also worth noting that the Markus chambers, apart from these “strange” two, show a smaller spread at each energy compared to the NACP chambers. A comparison between the Markus calibrations in the first and second trials show very good agreement, indicating good repeatability of the calibration procedure, as well as good chamber stability. The anomalous behaviour of chamber M1963 from the first trial was confirmed one year later.

It was believed, from the literature and measurements on NPL chambers, that Farmer chambers were very stable and reproducible in their response. This design of chamber has been around for some time and there is a large degree of confidence in the design. The results of this trial, as shown in Figure 10, confirm this view on repeatability. As in the case of the other chamber types, the data is normalised to remove the chamber volume and therefore shows the energy response of each chamber relative to N30-09. As can be seen, all eleven chambers calibrated show the same energy response within $\pm 0.15\%$. No particular orientation of the Farmer chambers was used and Figure 10 suggests that this is not an issue in the response of these chambers in electron beams. As stated earlier, radiographs of NPL Farmer chambers have showed that the central electrode was not always straight, and this would affect the electric field within the air cavity and possibly the effective point of measurement. Since no rotational dependence was observed, the effect of a non-straight central electrode must be small.

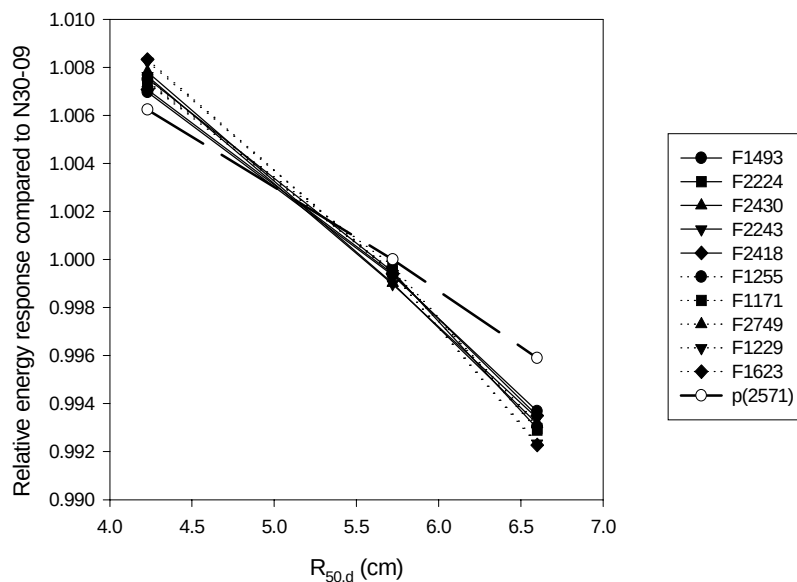


Figure 10. Energy response of Farmer chambers relative to N30-09.
p(2571) is the perturbation correction for the NE2571 chamber as given in the IPEMB Code

3.4 Chamber perturbation

As noted above, a number of measurements were made to investigate the perturbation correction for each chamber type. Perhaps of greatest significance is the possibility of a perturbation correction for the NACP reference chambers in graphite. Any perturbation in water would be the same for the calibration service and IPEMB Code and would therefore cancel, whereas a perturbation in graphite is specific to the NPL service. Since it is not possible to measure a perturbation correction directly, one must look at ratios of materials or chambers for indirect evidence.

The ratio of each NPL reference chamber to one particular chamber, N30-09 in water, was obtained and compared to the ratios obtained in a graphite phantom. The graphite ratios were obtained during calibration of the reference chambers against the calorimeter. The ratio in water and graphite should be the same, assuming the same chamber construction and perturbation effect. The three reference chambers tested showed a systematic difference in the water and graphite ratios of the order of 0.25%, as shown in Table 5. The difference seen may just be due to the uncertainty in the chamber measurements, although the fact that all three chambers show a difference in the same direction may indicate that there are real differences in the perturbation effect for each NPL reference chamber. This effect may be related to the design change in the NACP backing noted earlier - chamber N30-09 is different from the other NPL reference chambers. Further Monte-Carlo simulations, modelling small but reasonable changes in chamber construction may resolve this.

Table 5. NACP chambers in water and graphite

Chamber	Ratio / N30-09 in water	Ratio / N30-09 in graphite	Ratio water / graphite
N37-01	1.1099	1.1126	0.9976
N37-02	1.1352	1.1388	0.9968
N41-07	1.1443	1.1460	0.9985

The next step is to extend these measurements to different versions of the NACP design. Table 6 shows the results of measuring the ratio $p_{ref,w} / p_{ref,g}$ for a number of chambers with respect to chamber N30-09 at nominal energies 12 and 19 MeV. As can be seen, the Scanditronix chambers appear to be equivalent but there is a significant difference in the ratio for the Dosetek chamber. The perturbation correction can be expressed as the product of two components - the effect due to the air cavity effect and the effect due to materials from which the chamber is constructed (the wall effect). One might expect to see a difference between the 01 and 02 designs considering the significant constructional differences in these chambers. The NACP-01 design encapsulates the graphite chamber components in a large PMMA body. The fact that we do not see any effect suggests that the wall effect is determined by the material close to the air cavity, where the chambers designs are the same. Conversely, one would expect the Scanditronix and Dosetek NACP-02 chambers to have the same perturbation since their constructions are nominally identical. The most likely reason, as noted above, is that the Dosetek chamber was found to have a fault in the routing of the collector wire through the air cavity. This could significantly affect the electric field within the chamber, and the chamber may not be guarded correctly.

Table 6. Relative perturbation corrections

Chamber type	Serial number	Ratio of water/graphite perturbation correction relative to chamber N30-09	
		12 MeV	19 MeV
NACP-01 (Scanditronix)	N08-06	1.0008	0.9993
NACP-02 (Scanditronix)	N37-01	1.0011	1.0003
NACP-02 (Dosetek)	C1136	1.0036	1.0060

The results from the perturbation measurements made with the Roos chamber were interesting. At all energies there was a small, but significant difference between the measurements made with and without the graphite backing. The result was as follows:

$$\frac{M_{\text{water behind}}}{M_{\text{graphite behind}}} = 1.0010 \pm 0.0002$$

with M being the chamber reading (corrected for temperature and pressure). There was no energy dependence over the range 4-16 MeV. One would expect the reading with graphite to be less since the backscatter contribution for graphite is less than that for water. Although this is not a definitive measurement of the perturbation correction of the NACP chamber it does suggest that the effect of the graphite backing is not as large as suggested by Klevenhagen (1991). This measurement suggests an upper limit on the backscatter effect of 0.2%, which is closer to the result reported by Nilsson *et al* (1996). It is more difficult to measure the perturbation effect of the air cavity although unpublished measurements by Roos (1993) in developing that chamber have indicated that a well guarded parallel-plate chamber (such as the Roos and NACP designs) has a negligible cavity perturbation. This measurement of the backscatter effect is somewhat at odds to the water/graphite ratios obtained for the reference chambers.

As stated earlier, Monte Carlo calculations are in progress at NPL to determine the total perturbation correction of the NACP chamber and initial results are described by Williams *et al* (1998). His calculations showed that the effect of the air cavity in both water and graphite was small and could not be distinguished from unity within the uncertainties. An accurate determination of the wall effect was not possible due to the large errors in simulating backscatter using the EGS4 code used. It is hoped that the physical modelling within EGS4 will soon be improved which will allow a more accurate calculation of the wall perturbation correction to be made.

Also shown in Figure 9 of the measured Markus energy response relative to a NACP chamber is the Markus perturbation correction as given in the IPEMB Code of Practice (1996). This is derived from the work of Van der Plaetsen *et al* (1994) and, as can be seen, the majority of chambers follow the expected curve (within ~ 0.3%) except for the two anomalous chambers (M1002 and M1963). It is well known that the Markus chambers have a significant perturbation effect (due, mainly, to the narrow guard ring) but it has been assumed that the perturbation correction has been accurately determined. This data indicates that this may not be true. There have been a number investigations into the Markus perturbation correction relative to the NACP chamber, e.g. Wittkamper *et al* (1991), Van der Plaetsen *et al* (1994). Although these authors report reasonable consistency it may be that a large enough sample of chambers have not been measured previously. It is also possible that the different values that are reported for the Markus perturbation by various authors are due to real chamber-to-chamber variations. It therefore follows that one should, if possible, compare the response of a Markus chamber with that of a NACP chamber to ensure that it behaves as one would expect.

Similarly, the perturbation correction for the Farmer chamber, as given in the IPEMB Code of Practice is plotted in Figure 10 of the Farmer energy response. There is a difference between this published correction and the "correction" as derived by comparison with the NACP chamber of approximately 0.25%. Although this difference is small, it is larger than the difference between chambers. One explanation may be that perturbation correction is derived at the peak of the depth dose curve, which doesn't correspond exactly with the measurement depth used here. Different depths will give different electron spectra and thus different perturbations. Further work is required to resolve this difference, although it does not significantly affect the calibration or measurement of absorbed dose.

3.5 Recombination and polarity

Measurements on the NPL reference chambers have shown that the recombination correction at a particular polarising voltage is independent of electron energy, depending only on dose per pulse. By obtaining $1/I$ vs $1/V$ plots at a number of values of dose per pulse it is possible to obtain a general equation for a chamber, giving the ion recombination at a particular polarising voltage as a function of dose per pulse. As noted above, this information

for the NPL reference chambers is incorporated into the measurement system, allowing on-line recombination corrections.

Figure 11 shows $1/I$ vs $1/V$ plots for a number of parallel-plate chambers. As can be seen, apart from chamber M1963, all chambers exhibit similar responses. M1963 is one of the chambers exhibiting an anomalous perturbation effect, and it is likely, that the two effects - different perturbation response and different recombination correction - are correlated. However, all chambers, including M1963, show a linear relation between recombination correction and dose per pulse. The corrections for the NACP and “normal” Markus chambers are the same (to $\pm 0.2\%$), which is to be expected since the determining factor is electric field strength, and the plate separation for these chambers is the same. Ideally, one would like to assign a mean recombination response to each chamber type, but the recombination measurements shown here confirm the need for characterising individual chambers rather than relying on a mean response. The Roos chamber is only recommended for use at a polarizing voltage of 100 V and below, which is in line with the recommendations of Burns and McEwen (1998). However, this may be a problem for certain electrometers with fixed values of the polarizing voltage.

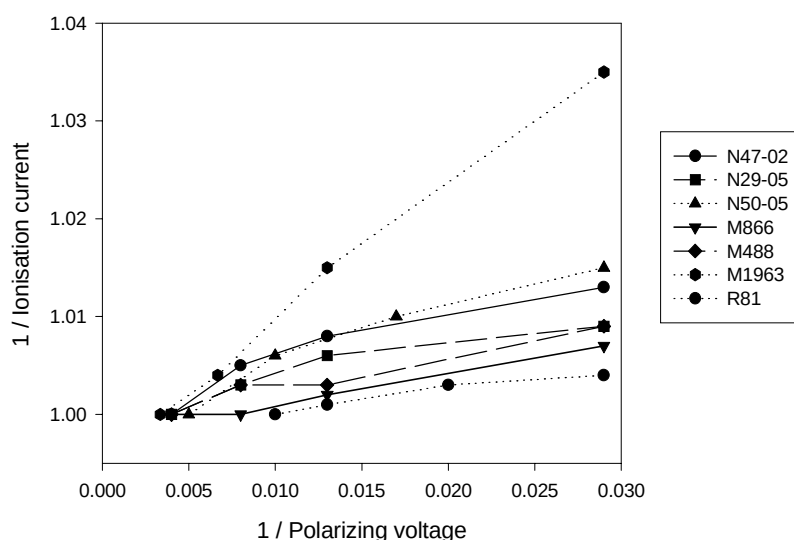


Figure 11. Recombination curves for NACP, Markus and Roos chambers at a dose rate of 0.005 cGy per pulse. Results for each chamber are normalised to the reading at the highest polarizing voltage

The recombination measurements for the Farmer chambers were as consistent as the measurements relative to the reference chambers, as shown in Figure 12. Although a number of chambers appear to show a slight curvature the effect on the recombination correction is less than 0.05%, and there is no problem with operating these chambers at higher values of the polarizing voltage.

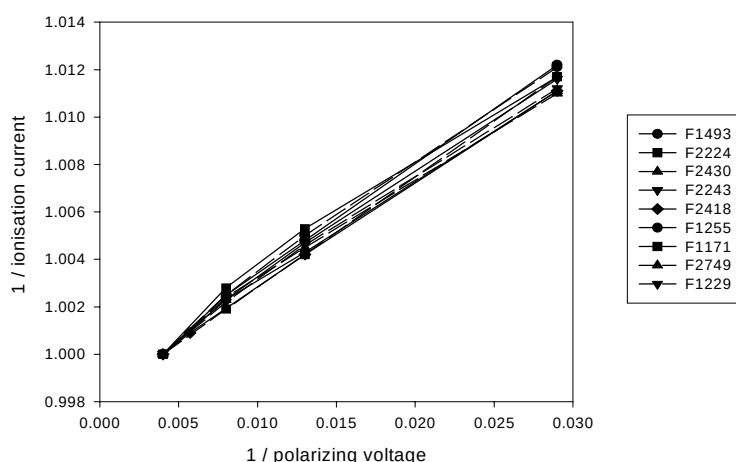


Figure 12. Recombination measurements for Farmer chambers at 0.004 cGy/pulse. Results for each chamber are normalised to the reading at the highest polarizing voltage.

The results from the polarity measurements, shown in Table 7, were somewhat surprising. It was possible to assign a mean response to all the Scanditronix chambers tested, and the Farmer chambers also showed a small, repeatable polarity correction. Although there were only two Roos chambers they were very similar in their behaviour, which is perhaps to be expected from their performance in other areas (energy response, recombination). However, it was not possible to assign any mean response to Markus chambers - there were large variations in the polarity correction from chamber to chamber. Since polarity is related to charge storage effects one might expect the Markus chamber to show the largest effect since it has the largest amount of material behind the collector of any of the parallel-plate chambers. As stated above, the calibration service uses a fixed polarity, with the assumption that a particular chamber has a fixed polarity correction for a given beam quality. This appears to be a valid assumption for NACP, Roos and Farmer chambers, but not so for Markus chambers. Further work is required to investigate the Markus polarity response, if such chambers are to be included in the calibration service. It may also be necessary to revise the calibration procedure to include polarity measurements.

Table 7. Comparison of polarity corrections for various chamber types. The correction is to the reading taken with negative polarizing voltage.

Enom (MeV)	NACP-02 Scanditronix	Roos	Markus	NE2571 (Farmer)
4	0.9992	0.9987	0.9926 - 0.9994	
8	1.0005	0.9996		
10	1.0007			
12	1.0004	1.0002		0.9982
16	1.0007		0.999 - 1.009	0.9983
19	1.0007	1.0003	0.999	0.9998

3.6 Electrometer performance

Figure 13 shows the results of calibrating a number of NE2570 electrometers, which appear to be the “standard” type of electrometer used with electron chambers in hospitals. Other electrometer types showed similar behaviour. As can be seen from Figure 13, the NE2570 electrometers show very good linearity. Each NE2570 was calibrated on several ranges and on ‘hi’ and ‘lo’ settings. Agreement between ‘hi’ and ‘lo’ settings was of the order of 0.2% or less. The other types of electrometers show similar performance - no single type of electrometer stood out as the “best”. Because of the lack of any defined secondary standard, there was some concern about the quality of electrometers used for electron dosimetry in hospitals but there doesn’t appear to be a problem. The two trials have now involved the calibration of nine types of electrometer, indicating the wide variety in use in UK hospitals. One may question the validity of calibrating the chamber and electrometer separately, since they will be used together. One good reason for separate calibrations is that, often, one electrometer is used with a number of chambers, so it would be inconvenient to calibrate it with every chamber. Also, the linac irradiations would take much longer if one used each electrometer rather than the NPL computer-controlled system. The majority of electrometers in use in UK radiotherapy centres cannot be controlled by a computer, and the ones that do tend to operate in very different ways. Another concern is the calibration technique, which assumes that all the electrometers work on the same principal of collecting charge. It is known that some types of electrometer (e.g. the new NE2670 Farmer dosemeter) measure ionisation current rather than charge and the calibration method would need to be changed for such electrometers. Unfortunately, it is not always clear how an electrometer operates, which could lead to errors as to which calibration method is used. An IPEM Working Party is presently looking at recommendations for electrometers with the aim of producing a specification for a Secondary Standard instrument.

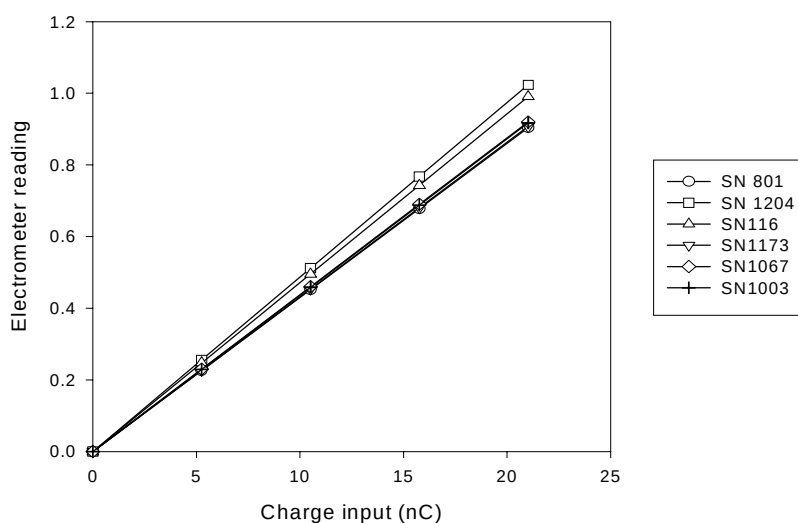


Figure 13. Calibration of type NE2570 electrometers

3.7 Performance in ^{60}Co

The 1985 HPA Code of Practice (and IPSM Addendum, 1992) recommended a comparison of all electron chambers with a secondary standard NE2561 chamber in a Cobalt-60 beam. In the 1996 IPEMB Code which replaced this code, it is recommended that only the NE2571 chamber is used in Cobalt-60 and that parallel-plate chambers are then compared with the Farmer chamber in high energy electrons. The reason given for this was that a number of authors (Andreo et al 1992; Rogers 1992) have raised the possibility that the perturbation correction for a parallel-

plate chamber in ^{60}Co could be dependent on the individual chamber. Measurements were carried out at NPL to compare the response of a number of chambers in ^{60}Co with their response in electron beams. The ^{60}Co measurements were made in a $15\text{ cm} \times 15\text{ cm}$ graphite phantom at depth of 6.4 gcm^{-2} (equivalent to 5 cm water) with a field size of $10\text{ cm} \times 10\text{ cm}$ and an SSD of approximately 900 mm. The measurements in an electron beam were made at a nominal energy of 16 MeV (13.7 MeV at the phantom surface) in the same graphite phantom at a depth of 1.4 gcm^{-2} (on the build up portion of the depth-dose curve) with a field size of $15\text{ cm} \times 15\text{ cm}$ at an SSD of 2000 mm. The shallow depth was used to minimise the perturbation correction of the Markus chamber. The results of each chambers response is shown in Table 8 relative to chamber N30-09. The uncertainty on the measurements is estimated to be $\pm 0.3\%$ at the 95% confidence level.

Table 8. Response of NACP chambers in ^{60}Co and electron beams

Chamber	Cobalt-60	16 MeV electrons ($E_z = 10.4\text{ MeV}$)	Ratio $^{60}\text{Co}/e^-$
N37-01	1.113	1.113	1.000
N37-02	1.138	1.140	0.998
N41-07	1.145	1.146	0.999
N46-07	1.073	1.069	1.004
R133	2.053	2.042	1.005
M2225	0.3177	0.3159	1.006

For the Scanditronix NACP chambers, there is no systematic difference in the chamber ratios between ^{60}Co and high energy electrons, indicating that these chambers have the same perturbation in ^{60}Co . However, this is a relatively small sample so does not rule out the possibility of chamber-to-chamber variations. The Roos and Markus chambers both indicate a difference in chamber response between ^{60}Co and electrons of approximately 0.5%. Although nothing can be said about variability between chambers of the same type it is reassuring that this difference is small. It would appear from these measurements that the use of parallel-plate chambers in ^{60}Co is possible without introducing large uncertainties. However, since the absorbed dose calibration service makes direct measurements in electron beams, any problem with chamber performance in ^{60}Co is circumvented.

4 PROCEDURE FOR COMPARING NPL CALIBRATION WITH IPEMB CODE OF PRACTICE IN CENTRES

Each centre received the calibration data for their chamber together with a brief procedure to derive absorbed dose measurements, as shown in Appendix A. One significant difference from the IPEMB Code of Practice is in the definition of reference depth. As stated above, the NPL procedure adopts equation (2). This was first proposed by Burns *et al* (1996) and provides a simple, robust depth specifier. By comparison the IPEMB code defines the reference depth as d_{max} or $0.5R_{50}$, whichever is the greater. This difference in d_{ref} means that centres must correct from one depth to another to compare the absorbed dose calibration with the IPEMB code. By using measured depth-dose curves, the uncertainty in this correction should not be significant.

The main obstacle in obtaining measurements in radiotherapy centres has been time. In UK clinics, there tend to be very few opportunities to make the large number of measurements required to give an accurate comparison of the NPL and IPEMB methods. In addition, medical physicists have just had to come to terms with the introduction of the IPEMB Code of Practice. This has meant that only half of the participating centres have returned results so

far and therefore, the results presented here should not be regarded as conclusive. However, it was felt important to report these initial results rather than wait for all the clinics to complete measurements.

5 RESULTS AND DISCUSSION OF MEASUREMENTS MADE BY CENTRES

Comparisons of the NPL calibration and the IPEMB Code of Practice for NACP and Markus chambers are given in Figure 14, and for Farmer chambers in Figure 15. The results are expressed as $\text{Dose(NPL)}/\text{Dose(IPEMB)}$. The various centres are not identified, to prevent bias in interpreting the results.

It is fairly simple to compare the calibration measurements made at NPL, since the only variable is the chamber and everything else (electron spectra, measuring assembly, operator *etc*) stays the same. The results from clinics are somewhat harder to analyse since they involve a large number of people carrying out two very different procedures to realise absorbed dose to water.

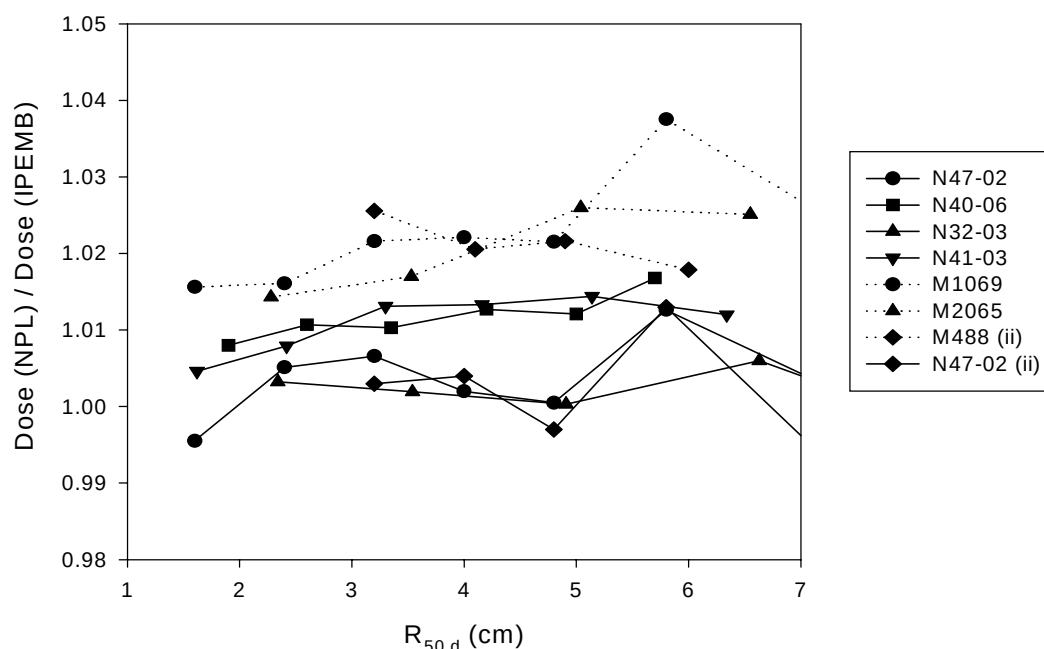


Figure 14. Comparison of doses derived using the NPL calibration factor and the IPEMB Code Of Practice for parallel-plate chambers, expressed as NPL/IPEMB . Solid lines are NACP chambers, dashed lines are Markus chambers. Results from the second trial are indicated by the suffix (ii).

Considering the NACP data first in Figure 14, the agreement looks promising. The ratio NPL/IPEMB is within $\pm 1\%$ of unity and there is little indication of a trend with energy. One would expect agreement for NACP chambers since they are the same as the NPL reference chambers and are of a well-guarded design. The results for the Markus chambers are not so encouraging, showing a NPL/IPEMB ratio not equal to unity and with a possible slight trend with energy. The size of the discrepancy, of the order of 2.5%, is larger than one would have expected. The results of the comparison for Farmer chambers, as shown in Figure 15, indicate agreement at the $\pm 1\%$ level, although the results are somewhat variable. One potential problem that became apparent is the difference in reference depths for

the calibration service and IPEMB Code. If one does not correct for depth one can introduce an error of the order of 1-2% at high energies. The agreement for the Farmer chambers is satisfying since it gives a direct comparison back to the air-kerma calibration of the NPL-designed secondary standard NE2561 chamber. Chambers F2418, N47-02 and M1069 are from the same centre, and the fact that the NACP and Farmer give agreement between the NPL calibration and the code, while the Markus does not, indicates a problem with the calibration or use of the Markus chambers, rather than an implicit error in the formalism of either the Code of Practice or the NPL procedure. The spread on the Farmer results is larger than for the parallel-plate chambers, which is slightly surprising since they all exhibited very similar behaviour at NPL.

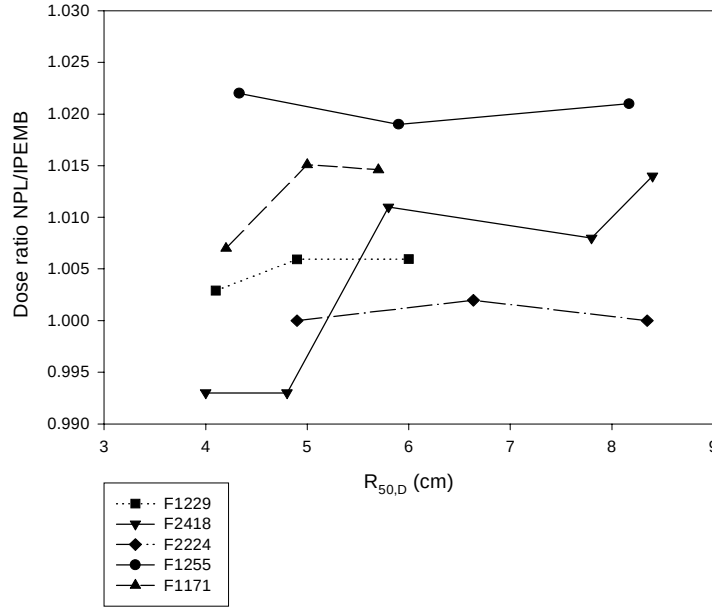


Figure 15. Comparison of doses derived using the NPL calibration factor and the IPEMB Code Of Practice for Farmer chambers, expressed as NPL/IPEMB.

Although there is not space here for a full analysis, a brief review of the IPEMB Code may indicate the reason for the Markus discrepancy. The first stage is to compare a NE2571 chamber against a NE2561 chamber in ^{60}Co , which yields the absorbed dose to air calibration factor, $N_{D,air}$ for the Farmer chamber. The value of $N_{D,air}$ for a parallel-plate chamber is obtained by comparison with the NE2571 chamber in a high energy electron beam. This two-staged process is used because of the potential problem of using parallel-plate chambers in ^{60}Co (see above). The absorbed dose at the reference depth at any electron energy is then given by:

$$D_w = M_u N_{D,air} p_u(E_z) s_{w:air}(E_z) \quad (5)$$

where M_u is the chamber reading, corrected for temperature, pressure, recombination and polarity; $p_u(E_z)$ is the chamber perturbation factor and $s_{w:air}(E_z)$ is the stopping power ratio, water-to-air, evaluated at the reference depth. The comparison with the NE2571 is carried out at high energy to ensure that the chamber perturbation factor is close to unity. For two chambers of different types, the only energy dependence is due to different perturbation factors or the chamber reading, since the stopping power ratio will cancel. The anomalous behaviour of chambers M1002 and M1963 indicates a different perturbation from the other Markus chambers, and therefore there is the

possibility that the discrepancy seen is due to an incorrect Markus perturbation correction. Nisbet *et al* (1998) carried out a comparison of the IPEMB Code with other air kerma-based codes and found agreement at the 1.5% level. However, this is somewhat to be expected, since the formalisms of the various codes are basically the same and all use the same basic data for stopping powers *etc*. A similar analysis of the calibration service shows that the only place any relative energy dependence can arise is in the chamber measurements themselves.

Although the data is not conclusive, it would appear that the NPL/IPEMB discrepancy for the Markus chambers is larger at the higher energies, where the perturbation correction for the Markus approaches unity. As mentioned above, a number of measurements of the Markus perturbation correction have been made, with a spread of around 1%. Unless the perturbation correction is very chamber specific (i.e. different for the chambers calibrated here from those previously measured), the uncertainty in the perturbation correction is not large enough to explain the discrepancy seen here. This would therefore indicate that the problem is one of experimental procedure, either at NPL or within the centres. A related possibility is that it is a polarity effect. The NPL protocol assumes that if R_{50} is used as the beam quality specifier then any polarity effect will cancel in electron beams of the same quality. However, as noted above, Markus chambers can have very different polarity corrections in the same electron beam and therefore this assumption should be questioned. Further measurements are required, both at NPL and within the participating centres, to resolve this discrepancy.

Nisbet and Thwaites (1997) carried out an extensive dosimetry comparison of radiotherapy centres in the UK and found that measurement practice was equivalent at the $\pm 2\%$ level, using the HPA (1985) Code of Practice. It must be noted that the IPEMB Code of Practice was only introduced from January 1997 with the result that centres have little experience of using it. However, the results reported here yield a similar value for the consistency of measurement which, despite the Markus discrepancy, is reassuring. .

6 CONCLUSION

The trial calibration was a success, as far as completing the measurements and analysis at NPL. All chambers were calibrated at all beam qualities in the time permitted. In addition, recombination measurements were made on a number of chambers indicating that not all chambers of the same type exhibit the same behaviour. The results of the measurements made in the centres are somewhat unexpected, giving agreement for NACP and Farmer chambers but not for Markus chambers. There is no obvious reason for this discrepancy and further measurements are required to identify the source of the problem.

NPL has introduced an absorbed dose to water calibration service for IPEMB-designated electron chambers during 1998. The service will be based on the electron beam calorimeter and will use a set of reference NACP chambers calibrated at NPL against the graphite calorimeter. The measurements described above confirm the suitability of the NACP chambers as reference chambers. The calibration factor for a user electron chamber will be derived from the reference chambers by direct comparison at NPL in a water phantom. Beam quality both in the NPL calibration beam and in the user beam will be specified in terms of the measured half-value $R_{50,w}$ in water, thus circumventing the need to estimate the mean energy E_d at the calibration depth.

The calibration service provides a significant improvement in accuracy over the present air kerma-based protocol together with a simpler procedure in the clinic. A direct calibration in an electron beam also means that there is no longer any dependence on ^{60}Co at a time when the number of Cobalt units in the UK is diminishing. This service directly tests each chamber so there is no dependence on some defined mean response for a chamber type. Finally, a calorimetric-based calibration service should provide a more stable long-term basis since it will not be affected by changes in air kerma parameters (such as the energy required to produce an ion pair), as seen in recent years.

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9 CHAMBER MANUFACTURERS AND SUPPLIERS

NE TECHNOLOGY Ltd	Bath Rd, Beenham, Reading, UK, RG7 5PR
PTW-FREIBURG	Loerracher Str. 7, D-79115 Freiburg, Germany
UK Supplier	GOTHIC CRELLON Ltd 3 The Business Centre, Molly Millars Lane, Wokingham, RG41 2EY
SCANDITRONIX MEDICAL AB	Stålgatan 14, S-754 50 Uppsala, Sweden
UK Supplier	QADOS Ltd Unit 9, Compton Place, Surrey Avenue, Camberley, GU15 3DX
WELFHÖFER DOSIMETRIE	Bahnhofstrasse 5, D-90592 Schwarzenbruck, Germany
UK Supplier	VERTEC SCIENTIFIC 5 Comet House, Calleva Park, Aldermaston, RG7 8JA

Appendix A Information sent with chamber / electrometer calibration

(References to tables should be ignored)

1 General Information

1.1 Status

This document describes the results of a trial calibration. No charges were involved and no certificate will be issued. The numbers given herein do not indicate NPL policy and should not be quoted. This document is not for general distribution and should not be cited as a reference. It must not be used as a basis for patient treatment.

1.2 Ion Chamber Calibration

1.2.1 Specification of beam quality and reference depths

The electron beam calibration service characterises beam quality in terms of the half-value depth R_{50} derived from the depth-ionisation distribution measured in water using a plane-parallel ion chamber. These measurements should be carried out for a fixed phantom distance of approximately 100 cm (not less than 70 cm or greater than 130 cm) and for a field size not less than 10 cm by 10 cm. No inverse-square correction is necessary. The bremsstrahlung background should not be subtracted (in line with the existing definition of $R_{50,I}$). The effective point of measurement of the chamber is taken as the position of the inside of the front face.

Since the reference depth in water for each quality is specified as a function of $R_{50,D}$, a conversion is required between $R_{50,I}$ and $R_{50,D}$. This is given by Ding et al in Med Phys 22 (1995) p489:

$$R_{50,D} = 1.029 R_{50,I} - 0.063 \quad (cm)$$

and is valid for $R_{50,I} < 10$ cm. The reference depth is then given by:

$$d_{ref,w} = 0.60 R_{50,D} - 0.10 \quad (cm)$$

All measurements are in cm. Note that $d_{ref,w}$ is the depth (in cm) at which the effective point of measurement of the chamber should be positioned (consistent with the measurement of $R_{50,I}$).

1.2.2 Calibration procedure at NPL

For each beam quality (characterised by the $R_{50,D}$) the user electron chamber u was positioned at the reference depth $d_{ref,w}$ in a water phantom and connected to the NPL measurement assembly (using the NPL interconnecting cable). An absorbed dose to water calibration factor $N_{w,u}$ for the user chamber was derived by direct comparison with three NPL reference NACP-02 chambers, each having a history of comparisons against the primary standard graphite calorimeter. All chamber readings were corrected to standard ambient conditions of 20°C and 101.33 kPa and no correction was made for humidity. The results are summarised in Table 2. The Farmer chambers were all irradiated in the same waterproof, perspex sleeve. At high energies the use of a different sleeve in the user beam should not have a significant effect. The quoted nominal energy E_{nom} is that set on the NPL accelerator and is given for

reference purposes only. It is not to be taken as a measure of the beam quality; quality is only specified in terms of $R_{50,D}$ as discussed above.

1.2.3 Correction for ion recombination

As a result of ion recombination, the response of an ion chamber at a particular dose rate (specifically dose-per-pulse) is dependent upon the polarising voltage and a correction must always be applied for this effect. A problem arises because the current response I of the chamber to changes in the polarising voltage V does not behave linearly as $1/I$ against $1/V$ for voltages in excess of around ± 125 V for many plane parallel chambers. NPL uses a value of 100 V for all its NACP reference chambers, but this is not an option for all users, since it depends on the type of electrometer being used. If the $1/I$ vs $1/V$ plot is not linear then the 2-voltage technique will give different corrections if different pairs of voltages are used. As part of this trial, recombination measurements were made on all chambers at a number of doserates. From these measurements one can derive the recombination correction at any dose per pulse at a fixed polarizing potential:

$$p_{ion} = c + md$$

where d is the dose per pulse in cGy. The parameters c and m are given in Table 1 together with the polarizing potential used in the calibration. The calibration factors $N_{w,u}$ given in Table 2 are corrected for ion recombination.

1.2.4 Polarity effect

It is known that the response of an ion chamber depends not only on the magnitude of the polarising voltage but also on the sign. No polarity correction has been applied. So long as the chamber is used with a negative polarity (as calibrated), no polarity correction should be applied in the clinic as this is implicitly included in the calibration factor.

1.2.5 Uncertainty on chamber calibration and realisation in the clinic

When the full service is established, it is anticipated that the uncertainty in $N_{w,u}$ will be around $\pm 1.0\%$ at the 95% confidence level. However, not all the Monte Carlo simulations have been completed, and the present reliance on published data increases the estimated uncertainty to around $\pm 1.5\%$ at the 95% confidence level.

In addition, some estimate must be made of the error introduced by the inexact matching of the NPL and clinical beam qualities. There is mounting evidence that for a typical clinical machine used under the standard conditions noted in Section 1.2.1, the error is not likely to be greater than 0.2-0.3%.

1.3 Electrometer Calibration

The user electrometer (if supplied) was calibrated using a NPL voltage standard in conjunction with a 500 pF standard capacitor. The calibration covered a range of meter readings and measurements were made on various ranges, as detailed in Table 3. A linear fit of the data gave a mean calibration factor in terms of μC per unit meter reading M_u . The uncertainty on this calibration factor is estimated to be better than $\pm 0.1\%$ at the 95% confidence level.

1.4 Using the chamber / electrometer calibration in the clinic

The procedure which should be used to realise the chamber / electrometer calibration in the clinical environment is outlined in the example below.

1. Set the required beam quality and choose a field size not less than 10 cm by 10 cm and a fixed source-to-phantom distance in the range 70-130 cm.
2. Using a plane-parallel ionisation chamber, measure the depth-ionisation $R_{50,I}$ in water (the effective point of measurement is taken to be the position of the inside of the front face). To convert from ionisation to dose use $R_{50,D} = 1.029 R_{50,I} - 0.063$ (cm).
3. Position the chamber with its effective point of measurement at the depth (in cm) given by $d_{ref,w} = 0.6 R_{50,D} - 0.1$ (cm)
4. Interpolate from the data in Table 2 to give the appropriate calibration factor, $N_{w,u}$, for the $R_{50,D}$.
5. Select the correct range and setting on the electrometer.
6. For the polarising voltage as specified in Table 1 measure the chamber / electrometer response for your standard calibration MU setting. Let the electrometer reading, corrected for temperature and pressure in the usual way, be M_u .
7. Determine the recombination correction for the user ($p_{ion,u}$) beam qualities from the data given in Table 1. No polarity correction need be applied, as this is implicitly included in the calibration factor.
8. From Table 3 obtain the electrometer calibration factor, E_u , for the range / setting used. The dose to water at the reference depth $d_{ref,w}$ is given by

$$D_w(d_{ref,w}) = M_u \times p_{ion,u} \times E_u \times N_{w,u} \quad \text{for the number of MU set}$$