NRC Activities and Publications, 2005-2007
Report to the CCRI(I) Meeting, BIPM
May 2007

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1 Introduction

The Ionizing Radiation Standards (IRS) Group at NRC is part of the Institute for National Measurement Standards (INMS), which is Canada's national metrology institute. The group has 13 full-time staff members, 1 term appointment, 2 former staff members who work part-time, one graduate student and one visiting worker.

The group is responsible for Canadian calibration services in the field of ionizing radiation. A listing of the calibration services offered can be found at: http://inms-ienm.nrc-cnrc.gc.ca/calserv/ionizing_radiation_e.html

A searchable database of INMS publications is available at: http://serpent.cisti.nrc.ca/DBTW-WPD/textbase/inms/search_e.html.

Details on research activities related primarily to Monte Carlo modeling can be found at: http://www.irs.inms.nrc.ca/irs.html.

2 INMS Organizational Structure

The management team of INMS comprises a Director General (Jim McLaren) and two Directors, one for Metrology (Alan Steele) and one for Business and Research Support (Katalin Deczky). The Groups Leaders, each of whom is responsible for one or more areas of metrology, report to the Director of Metrology.

3 ISO 17025 Quality System

IRS underwent an internal audit in September 2006 and an external audit in December 2006. The external audit noted several issues that needed to be addressed and an appropriate action plan was prepared. A summary of our quality system, along with the results of the audits were presented to the SIM Quality System Task Force (QSTF) in February 2007. Our quality system was approved by the QSTF and the IRS CMCs are again listed in Appendix C of the MRA. After we satisfactorily address all the findings of the audits the SCC (Standards Council of Canada) will formally accredit our quality system.

4 Air kerma standards

4.1 For kV x-rays

(John McCaffrey and Ernesto Mainegra-Hing)

IRS provides kV x-ray calibrations in the energy range from 10 to 300 kV. Two free-air chambers serve as standards, one covering the low-energy range up to about 60 kV and the second covering the range from 60 to 300 kV. A second high-energy chamber is under construction. It will be used as a spare, and for exploratory studies of some of the factors that affect the response of free-air chambers.

A comparison of low-energy (10 to 50 kV) x-ray standards of the NRC and the BIPM was undertaken in March 2007. Four chambers, two of each type, were initially calibrated at the NRC and then taken to the BIPM. Initial results from the comparison are encouraging.

A detailed study of free-air chamber correction factors is underway using the EGSnrc Monte Carlo code.

4.2 For ^{60}Co and ^{137}Cs

(John McCaffrey)

^{60}Co and ^{137}Cs air kerma standards are based on a graphite cavity chamber.

A new ^{60}Co irradiator has been purchased because the manufacturer of our Eldorado 6 could no longer guarantee service support. The new unit, referred to as the Gammabeam X-200 and supplied by MDS Nordion, uses the same source geometry as the Eldorado but has sufficient shielding to accommodate a source activity of 430 TBq, thus giving a dose rate of about 2 Gy/min at 1 m, approximately twice that of Eldorado.

5 Absorbed dose standards

5.1 For ^{60}Co

(John McCaffrey, Malcolm McEwen and Carl Ross)

The absorbed dose rate to water in the ^{60}Co beam is established using a water calorimeter.

The new irradiator mentioned in Section 4.2 will also be used to maintain and disseminate our standard for the absorbed dose to water.

5.2 For MV x-rays

(Malcolm McEwen and Carl Ross)

Following from the work on water calorimetry in clinical x-ray beams, a calibration service has been developed for clinical users. Absorbed dose to water calibrations are carried out at the three x-ray energies produced by the linear accelerator maintained at the laboratory. The nominal beam energies are 6, 10 and 25 MV and the corresponding values of $\%dd(10)_x$ ($TPR_{20,10}$) are 67.4(0.681), 72.4(0.731) and 84.0(0.800). The standard for absorbed dose to water is a sealed water calorimeter, which measures the radiation-induced temperature rise at a depth of 10 cm in a water phantom (10 x 10 cm^2 beam, with the surface of the phantom at 1 m from the source). The standard dose rate at the point of measurement is 300 cGy/min. For reference-class 0.6 cc cylindrical ionization chambers the standard uncertainty in the absorbed dose calibration coefficient is typically 0.5 %. The calibration process includes polarity and recombination measurements, as required for dosimetry protocols such as AAPM TG-51.

The first customer calibrations have recently been carried out and accreditation of the service to ISO17025 is anticipated in the coming months.

6 All-glass, water-only calorimeter vessel

(Norman Klassen)

Calorimeter vessels containing water saturated with nitrogen or argon have been assumed to have the same response as a vessel containing only water. Neither dissolved nitrogen nor argon is believed to play a significant role in the radiolysis of water and, hence, do not affect the heat defect. However, it is feasible to prepare a vessel containing only liquid water and a small gas space containing only water vapour. We have prepared an all-glass, sealed vessel with a small gas space in which the liquid water contains a very low concentration (less than 1×10^{-5} M) of helium.

We chose to deaerate the water by bubbling it with helium. Helium is not very soluble in water (4×10^{-4} M at 1 atmosphere of helium) and traces of helium are not expected to influence the radiolysis of water. Following deaeration, the helium in the vessel was removed by successive expansions into a vacuum line. The glass vessel was the type that was completely sealed off, with no valves and with the thermistor housings sealed into the vessel.

Preparation of the water-only fill can be followed by referring to Figure 1. All surfaces that came into contact with liquid water were scrupulously cleaned. Bubbling with helium (99.9999 % pure with <0.1 ppm O_2) was done using a Teflon tube inserted through a glass tube that was subsequently sealed off. The apparatus was connected to a vacuum line through two stopcocks and a ground-glass joint. The vacuum line contained several pressure gauges that allowed pressure readings from 1000 to 0.001 Torr. At equilibrium, the amount of helium in the water was 6 % of the helium in the gas space above the water up to point A. Given the respective volumes of the gas space up to A and of the vacuum line (valved off from the pump), expansion into the evacuated vacuum line removed 97 % of the helium above the water. Ten expansions were carried out. In between each expansion, the water was allowed to stand and/or was agitated to assist in bringing the helium in, and above, the water, into equilibrium. The gas in the vacuum line from the tenth expansion was cooled by placing dry ice in the Styrofoam cup to freeze out the water vapour allowing the pressure of the helium only to be measured. The result indicated that the helium left in the water was less than 1×10^{-5} M. In future, a proper trap to hold liquid nitrogen will be added to the vacuum line so that the helium pressure can be measured after each expansion.

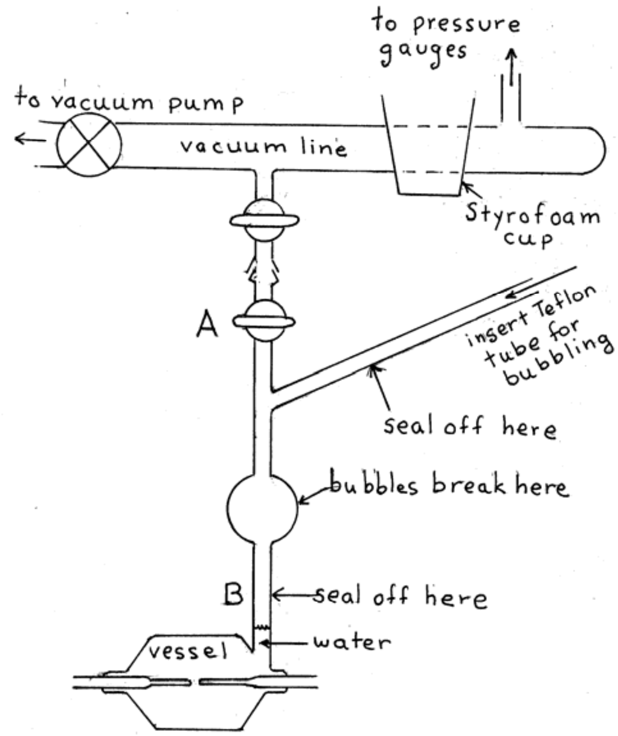

Figure 1. Diagram showing the main components used when filling the water-only vessel.

7 Electron beam calibrations

(Malcolm McEwen and Carl Ross)

This project is concerned with the direct measurement of ion chamber absorbed dose calibration coefficients in electron beams from a clinical linac. The NRC primary standard water calorimeter was used to calibrate a set of cylindrical and parallel-plate chambers (NE2571, NACP-02, PTW Roos) in the high energy electron beams from an Elekta *Precise* linac installed at NRC (12, 18 and 22 MeV). Calibration coefficients were also obtained for a 20 MeV electron beam from the Vickers research accelerator, also installed at NRC. Much effort was put into thermal modeling to correct for heat production in the glass walls and significant heat flow due to the steep depth-dose gradients of the electron beams.

The three water calorimeter vessels used in this investigation included a sealed all-glass cylindrical vessel (as used in photon beams) and two parallel-plate designs with different measurement depths (referred to as “standard’ and “angled probe”). There was very good agreement between the three vessels:

Standard parallel-plate/cylindrical = 1.0008

Standard parallel-plate/angled probe = 0.9996

The standard uncertainty on the calorimeter ratio was estimated to be approximately 0.2 %.

The $N_{D,w}$ values obtained for the two accelerators were in good agreement. The values for the 20 MeV beam were also in good agreement with previous data obtained in 2001 indicating very high stability of the primary standard water calorimeter. Initial results for one NACP chamber are shown in Table 1. The overall standard uncertainty on the calibration coefficients is estimated to be 0.4 %.

E_{nom} (MeV)	R_{50} (cm)	$N_{D,w}$ (cGy/nC)	$N_{D,w}$ / $N_{D,w,TG-51}$
12	4.8	16.2	1.010
18	7.1	15.88	1.008
22	9.0	15.78	1.013

Table 1. Absorbed dose to water calibration coefficients obtained for a NACP-02 ion chamber in comparison with the NRC primary standard water calorimeter.

These initial results show a consistent difference with the present international methods (based on a ^{60}Co calibration and calculated conversion factors) that requires further investigation. A second area for future work is in the extension to lower energies. It may not be possible to calibrate lower-energy electron beams with the present design of water calorimeter (due to the shallow reference depth for energies less that 10 MeV).

8 Wall perturbation factors for parallel-plate chambers

(Malcolm McEwen, Hugo Palmans (National Physical Laboratory) and Andrew Williams (Norfolk and Norwich University Hospital))

This project arose from a review of data required for the NPL calibration procedure for ion chambers in high-energy electron beams in terms of absorbed dose to water. An empirical model based on experimental backscatter data was developed to calculate the perturbation due to the rear wall of a well-guarded ion chamber in a high-energy electron beam. The overall uncertainty in calculating the ratio of wall perturbation factors for a chamber in two low-Z phantoms using this method is estimated to be 0.32 %, which is the lowest reported to date for an experimental method and similar to that reported for recent Monte Carlo investigations. The model reproduces measured data at the 0.1 % level or better and indicates that the NACP ion chamber has a non-zero perturbation factor in electron beams due to backscatter from the rear wall. The effect is small (<0.5 %) at high energies (E_0 > 10 MeV, R_{50} > 4 cm) but becomes large at low energies and is up to 1.4% at E_0 = 4 MeV (R_{50} = 1.2 cm). The correction at lower energies is significantly greater than the uncertainty of 0.35 % assigned by NPL in adopting a zero perturbation correction for the NACP chamber. The model indicates that there is a non-zero correction for the NACP chamber in both a graphite and water phantom and that material adjacent to the air cavity has a significant effect on the measured ionization. These values are consistent with previous measurements and Monte Carlo calculations (see Figure 2).

The model developed in this project is simple to apply and could be used in the design of ion chambers and in the estimation of corrections for non-homogeneous systems, especially in the absence of accurate Monte-Carlo simulations.

Since the data, both from experiment and Monte Carlo, appear to be conclusive regarding a significant perturbation correction for parallel-plate chambers it would seem timely to revisit electron-beam dosimetry protocols such as TG-51, TRS-398 and IPEM-2003.

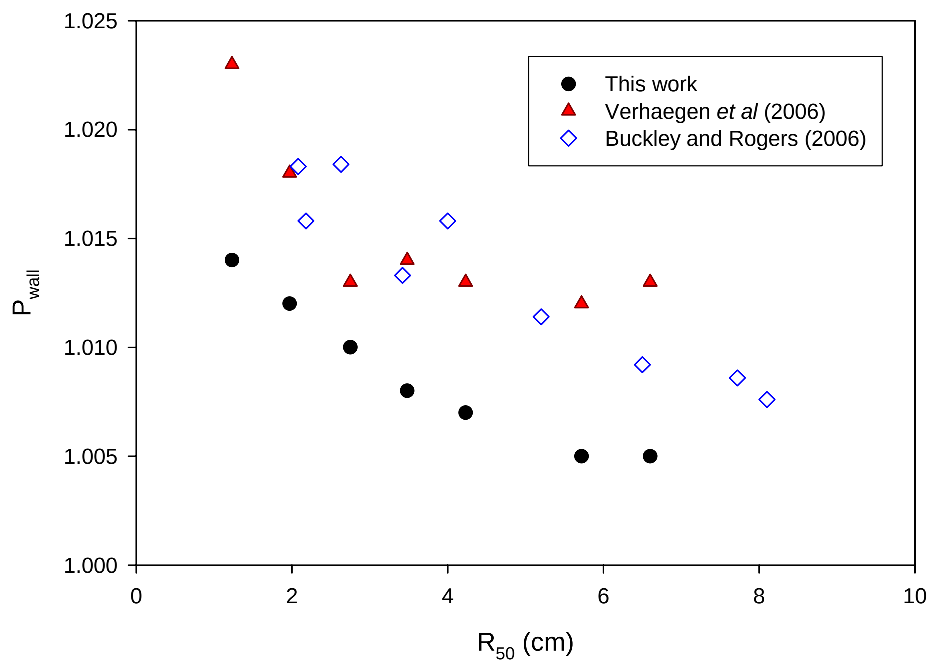

Figure 2. Comparison of recent p_{wall} determinations for the NACP chamber in a water phantom. Verhaegen *et al* and Buckley and Rogers both used the Monte Carlo system EGSnrc.

9 Effective point of measurement

(Malcolm McEwen, Carl Ross and Iwan Kawrakow)

In a recent paper Kawrakow [5] used Monte-Carlo calculations to show that the standard shift for cylindrical chambers, recommended in dosimetry protocols, of -0.6*r* (where *r* is the internal radius of the cavity) is incorrect. He showed that there is no universal recipe for defining the point-of-measurement and that the required shift depends on the details of the chamber construction.

In order to test his predictions, a precision experimental investigation of the effective point of measurement of ion chambers in megavoltage beams was carried out. A 1-D scanning phantom system was developed with an overall accuracy in the positioning of a chamber of better than 0.15 mm and it was used to measure depth-ionization curves for a wide range of cylindrical ion chambers. For each chamber the standard shift of -0.6*r* was applied and Table 2 shows the additional shift required to match each depth-ionization curve to that of an NE2571 chamber. We found that errors of up to 1.4 mm could occur for certain chamber designs (not shown in Table 2) although typical errors for common chambers were not more than 0.5 mm.

	Shift (mm)
NE2571	0
NE2581	0.18
PTW30001	0.20
PTW30013	0.10
Exradin A12	-0.06
Capintec PR-06G	0.23
NE2561/NE2611	0.33
PTW233642	-0.02
Exradin A16	-0.02

Table 2. Shift in effective point of measurement relative to NE2571 reference chamber. A positive shift indicates that the effective point of measurement must be moved downstream.

We also compared cylindrical chamber data (PTW233642) with that for parallel-plate chambers (Figure 3). Assuming the standard shift for a cylindrical chamber of -0.6*r*, we see a significant difference:

0.35 mm for 25 MV, 10 x 10 cm
0.45 mm for 25 MV, 25 x 25 cm

The cylindrical chamber plot must be shifted to greater depths by this amount, which agrees very well with the Kawrakow values of 0.42 mm (10 x 10 cm) and 0.59 mm (30 x 30 cm). These results support the perspective that the point of measurement of a parallel-plate chamber is at the inside of the front face.

Our investigations suggest that for the highest accuracy depth-dose curves in megavoltage photon beams one should use a well-guarded parallel-plate ion chamber. Three chamber designs were tested here and found to be satisfactory - the Scanditronix-Wellhofer NACP-02, PTW Roos and Exradin A11.

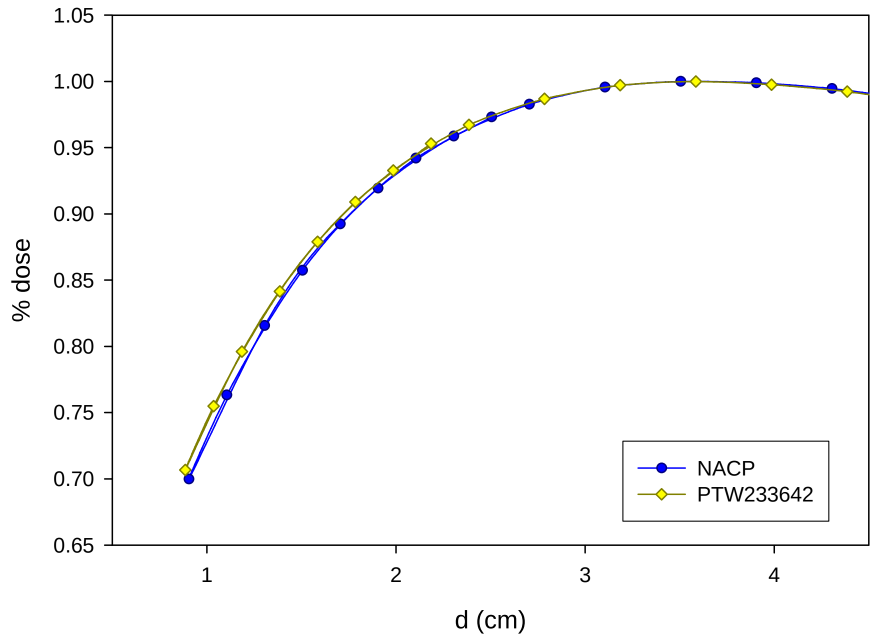

Figure 3. Comparison of depth dose curves for two types of ion chambers - cylindrical (PTW233642) and parallel- plate (NACP). For the cylindrical chamber a shift of -0.6*r* has been applied; for the NACP the effective point of measurement is taken as the inside front face (chamber entrance window scaled to a water-equivalent thickness).

10 β-ray dosimetry

10.1 Experimental work

(Patrick Saull, David Marchington and Stewart Walker)

IRS maintains a standard for absorbed dose to tissue in a β-ray field using an extrapolation chamber. This instrument has been fully integrated into an automated data-acquisition system with two PTW β-source irradiators: our original Beta Secondary Standard (BSS1) acquired in the early 1980s, and the newer BSS2 system from Isotrak acquired in 2003. Our primary standard was put to the test in 2005 using the Pm-147, Kr-85, and Sr-Y-90 sources of the BSS2 irradiator, as part of our participation in the EUROMET comparison titled "Supplementary comparison of absorbed dose rate in tissue for beta radiation" (EUROMET project No. 739, BIPM KCDB: EUROMET.R(I)-S2), which involves the participation of six European countries, as well as Canada, the US, and Japan. Although the results of this study are yet to be finalized, the preliminary draft report indicates that NRC has performed very well.

Using the BSS1/BSS2 irradiators and our well-established standard, we have recently established an independent testing facility and taken on the role of "reference calibration centre" as part of the Canadian Nuclear Safety Commission's regulatory standard on quality assurance. As of May 2006, all dosimetry service providers operating in Canada are required to undergo annual independent testing of their extremity dosimeters at NRC.

10.2 Theoretical work

(Patrick Saull, Palani Selvam, Bhabha Atomic Research Centre and Dave Rogers, Carleton University)

Following on from previous work in which we successfully modelled the response of NRC's extrapolation chamber to Sr-Y-90 beta fields using the EGSnrc/BEAMnrc Monte Carlo code system, we have applied our MC calculations to the verification of experimentally measured correction factors for dose to tissue, and have studied the possibility of establishing a MC-based approach to the standard for absorbed dose to tissue. One particularly interesting result of our work has arisen from the application of Spencer-Attix cavity theory to the derivation of theoretical dose, as compared to the more traditional Bragg-Gray approach recommended by ISO: differences of up to 2.3% have been observed between these two approaches for absorbed dose to tissue in an Sr-Y-90 field.

11 Neutron dosimetry

(Patrick Saull and Dong Tchmshkyan)

We have had an active program for the calibration of neutron survey meters for external clients at NRC for several decades. Calibrations are performed in a low-scatter area using our well-characterized AmBe neutron source. More recently we have established an independent testing facility and taken on the role of "reference calibration centre" as part of the Canadian Nuclear Safety Commission's regulatory standard on quality assurance. As of May 2006, all dosimetry service providers operating in Canada are required to undergo annual independent testing of their neutron dosimetry systems at NRC.

To further improve the characterization of our our AmBe field, as well as those of our other neutron sources, we have begun using several Monte Carlo codes (GEANT4, FLUKA, MCNP5) to simulate neutron production, transport, and detection in our low-scatter facility, from the generation of neutrons in the AmBe source itself, to the reflection and absorption of neutrons in the walls, air, and room materials, and finally the response of a given neutron detector experiencing the field (e.g., survey meter, long counter, or bubble detector). In addition, we are using Monte-Carlo simulations to help design moderated AmBe neutron fields of lower mean energy for use in the calibration of detectors having an energy-dependent response (e.g., bubble detectors). The use of three Monte Carlo codes in this work not only provides redundancy but permits a comparison of the codes, of interest to the Monte Carlo community.

12 Neutrons from low-energy accelerators

(Carl Ross, Patrick Saull and Dong Tchmshkyan)

Security concerns at ports of entry have led to an increased interest in developing techniques for rapidly screening trucks and cargo containers. The most widely used technique is to use a high-energy x-ray beam to radiograph the object. Some of these x-ray beams are generated by linacs with electron beam energies as high as 9 MeV. This work was initiated to assess the potential risk posed by neutrons produced by these low-energy linacs.

The project involved measuring the neutron production rate for several targets as a function of energy and comparing the results to Monte Carlo predictions. Once the Monte Carlo codes had been benchmarked, they were used to predict the neutron fluence rate from the commercial machines.

We used bubble detectors manufactured by Bubble Technologies Industries to measure the neutron dose-equivalent rate and this brief report will focus on the properties of these detectors which might be of general interest. Key advantages of the detectors are their ease of use and their sensitivity. Their typical sensitivity is a few bubbles per µSv so they can easily measure dose equivalent rates that are of concern for personnel safety. They are read by counting bubbles and although up to 100 bubbles per detector can be counted by eye, the process is rather tedious if many detectors are to be used. An automated reader is available which can quickly count up to 300 bubbles, but it is relatively expensive.

The manufacturer provides a calibration factor for each detector, but we found considerable disagreement between their factors and those we determined using our own sources (Figure 4). We are still investigating this discrepancy but it may be partly due to scatter from the calibration setup used by the manufacturer.

A more serious issue arises from the detector sensitivity to photons. The specifications for the detectors claim no sensitivity to photons and this is indeed the case for low-energy (e.g., ^{60}Co γ-rays). However, once the photon energy exceeds photonuclear thresholds in the detector itself, they exhibit considerable sensitivity to photons. Figure 5 shows that the detector response increases dramatically for high-energy x-ray beams as one varies the angular position of the detector with respect to the forward beam axis. Neutron emission is expected to be approximately isotropic, whereas the detector response increases by orders of magnitude as the detector is exposed to more of the forward-directed primary x-ray beam.

We have noted several examples in the recent literature where bubble detectors were used to measure the neutrons produced by medical linacs. In some cases, they show neutron production rates on the central beam axis with the collimator open. The apparent neutron dose rate is much higher than when the beam is shielded by collimation. This result is not expected because much of the neutron production is due to the x-ray beam striking the collimator, and is likely due to the fact that the authors have overlooked the response of the detectors to high-energy x-rays.

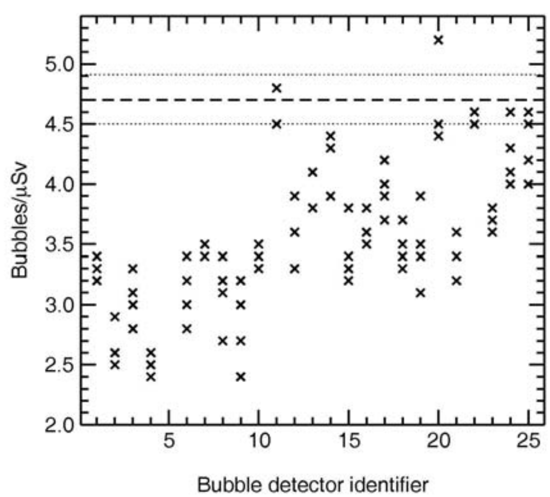

Figure 4. Measured sensitivity, corrected to 20 ºC, of various bubble detectors. The detectors are identified by an integer along the abscissa and the results of repeated calibrations are shown for each detector. The sensitivity provided by the manufacturer is shown by the horizontal dashed line.

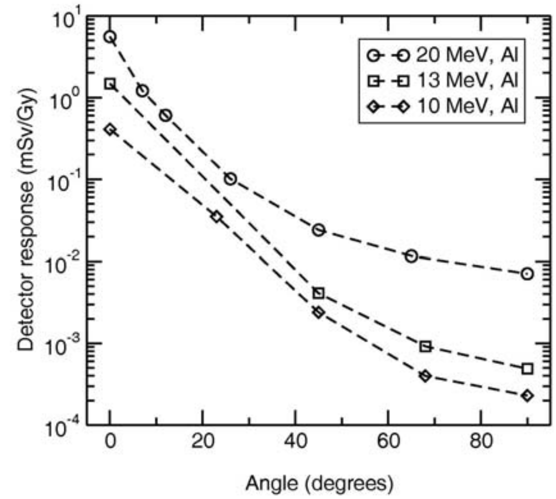

Figure 5. Measured response of bubble detectors as a function of angle for electrons incident on an Al target. Angles are measured with respect to the beam direction.

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[1] McEwen M. R., Sephton J. P. and Sharpe P. H. G. 2006 Alanine as a precision validation tool for reference dosimetry Proceedings of the PTB Workshop PTB-Dos-51 on Alanine dosimetry for clinical applications (Braunschweig: Physikalisch-Technische Bundesanstalt)

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