PROTECTION-LEVEL BETA PARTICLE SOURCE & INSTRUMENT CALIBRATIONS

1. Purpose and Scope

This document describes procedures used at NIST to calibrate protection-level beta-particle sources and laboratory–standard transfer instruments. Between 1982 and 1985, the National Bureau of Standards (NBS) as it was then known, with partial support from the U.S. Nuclear Regulatory Commission, developed a facility suited to establish a service for calibrating certain user-owned encapsulated beta-particle sources and certain laboratory–standard transfer instruments for application in radiation protection (Pruitt et al. 1988). This work was undertaken in response to the need of the radiation-protection community for better calibrations of beta-particle survey instruments and dosimeters. This task was ably performed by J.S. Pruitt who was also responsible for the first wave of automation of the extrapolation chamber and data acquisition. In 1988 the author took over this service upon the retirement of Dr. Pruitt. He has been aided in further efforts to automate the system by Dr. M.G. Mitch, who is responsible for the LabView code now used for data acquisition and control. The methods and corrections as developed by Pruitt were applied until 2000, when the methods and corrections of ISO 6980-2 (ISO 6980-2, 2003) were implemented.

1.1. Quantity for Reporting Calibration Results

The physical quantity of interest in radiation protection is the absorbed dose (rate)[1] to tissue, from which the effective dose equivalent (rate) and the pertinent practical dose-equivalent (rate) quantity (or quantities) may be derived. For the application in radiation protection, absorbed dose (rate) to tissue may be set equal to absorbed dose (rate) in water. Therefore, source-calibration results are reported by NIST in terms of absorbed-dose rate to water at a fixed source-to-detector distance, and instrument-calibration results are reported as calibration coefficients, the quotients of absorbed-dose (rate) to water and the corresponding instrument reading ("scale indication"). Throughout this document, water is considered to be equivalent to tissue.

1.2. Sources and Instruments Accepted for Calibration

The following beta-particle sources and instruments are accepted:

1) Encapsulated sources of ^{90}Sr+^{90}Y, ^{204}Tl, ^{85}Kr, and ^{147}Pm, with activities leading to absorbed-dose rates to water ranging from a few tenths of one μGy/s to a few mGy/s, for calibration in terms of absorbed-dose rate to water at fixed distances in air (corresponding to conditions specified in ISO 6980) (ISO 6980-1, 2003) at a reference depth of 0.07 mm.
2) Thin-window parallel-plate ionization chambers suited for use as transfer instruments for the calibration of beta-particle sources in terms of absorbed-dose rate to water. (see also Section 2.5)

1.3 Procedures for Calibration and Internal Quality Control

[1] Throughout this document, when a statement is made that can refer either to a particular radiation quantity or to its rate, the name of the quantity is followed by the word "rate" in parentheses.

Calibrations are performed at fixed source-to-detector distances. If a beam-flattening filter is to be used with the submitted source (see Section 2.3), it is to be supplied with the source. The calibration uncertainty (for a coverage factor of k=2) for ^{90}Sr+^{90}Y is reported as 2.2 %, for ^{204}Tl and ^{85}Kr sources as 2.4 %, for ^{147}Pm sources as 3.2 %, and for thin-window parallel plate ionization chambers as 2.2 % when calibrated with ^{90}Sr+^{90}Y, 2.4 % when calibrated with ^{204}Tl and ^{85}Kr, or 3.2 % when calibrated with a ^{147}Pm source (see Section 3.7). Consistency of calibration results is ensured through internal quality-control procedures comprising (a) the calibration in terms of absorbed-dose rate to water of a NIST beta-particle source of known absorbed-dose rate along with the submitted unknown source incorporating the same radionuclide, or (b) the calibration of a NIST extrapolation chamber along with the chamber submitted in at least one of the calibration beams. Calibration data on the submitted source or chamber are considered acceptable if the data obtained (when corrected for decay) for the NIST source or instrument agree to within the statistical uncertainty (type A uncertainty) stated in Tables 5 and 6 of Section 4.7.

1.4 International Comparisons of the Determination of Absorbed-Dose Rate to Water

Absorbed-dose rate to water were determined for the four Buchler beta-particle secondary standard sources (BSS1, described in Section 2.3) at the reference distances from measurements of ionization currents in the extrapolation ionization chamber. The methods used for this initial comparison were those applicable to calibrations performed before 2000 (Pruitt et al. 1988). The results are shown in Table 1. Since the sources had been initially calibrated at the Physikalisch-Technische Bundesanstalt (PTB), it was possible to compare the NIST calibrations with those obtained at the PTB in a similar geometry at the same reference distances. Table 1 shows a comparison for absorbed-dose rates to water at the surface. The results agree to 1 % or better for the ^{90}Sr+^{90}Y sources and to 2 % for ^{204}Tl. A 4 % disagreement for ^{147}Pm is not surprising, considering the size of the overall uncertainty in the measurement of the ionization current (see Table 5, section 4.7) and the relatively strong dependence of the measurement results on the calibration geometry, as well as the difference in calculation methods of some of the corrections applied to the measured currents.

One of the aims of the ISO Working Group 2, Sub Group 0 on reference radiations for beta particles was to harmonize the methods used to calculate the correction factors. The fruits of this effort are evident in the latest comparison between PTB and NIST, performed when the BSS2 set of sources was obtained. The results of this comparison are shown in Table 2, where now it is seen that these is agreement to better than 2 % for all sources and distances. In this comparison, both parties used the methods specified in ISO 6980-2 for the calculation of correction factors for the measured currents.

2. Equipment

2.1 Rationale for Facility Choice and for Preliminary Studies

One of the reasons why protection measurements for beta particles are considerably more difficult than for photons is the beta particles' vastly greater interaction in the media

intervening between the source and the point of measurement ("reference point"). And the resulting greater change in the beta-particle spectrum with the change of measurement configuration – and consequently in most instances also in detector-response characteristics. As a consequence, calibrations of radiation-protection instruments in beta-particle beams can be considered strictly valid only for the particular configuration in which they are performed and are applicable to field measurements in similar configurations only. Conversely, knowledge of the degree to which changes in measurement configuration may produce changes in beam characteristics and therefore in calibration results is of considerable importance. Therefore, prior to establishing the calibration service, the influence on spectral characteristics of beam-flattening filters and other absorbing materials in the beta-particle beams, and the influence of changes in source-to-detector distance, were investigated (Pruitt et al. 1988). Changes in absorbed dose rates with elevation above sea level were given special attention (Pruitt 1985).

2.2 Facility Design

The NIST facility for carrying out beta-particle measurements for radiation-protection purposes is located in Building 245, Room B003 and consists of:

1) a set of well-characterized beta-particle sources covering a wide energy and dose-rate range;
2) an extrapolation ionization chamber suited for the determination of absorbed-dose rates to water at distances from the beta-particle sources appropriate for the study of radiation-protection instruments;
3) an electrical interlock system causing the source shutter to close automatically when the safety perimeter (established by an infrared beam) is penetrated; and
4) measurement and control equipment capable of changing the air gap, proper biasing and measuring current produced in the extrapolation chamber, and for the determination of necessary corrections. The rest of Section 2 deals with a more detailed description of these systems and with their use.

2.3 The Beta-Particle Sources

NIST purchased its first complete Buchler beta-particle secondary standard source setup in 1982, referred to in the following as BSS1, and a second, modernized setup was obtained from AEA Technologies in 1998, referred to as BSS2. Both sets of sources were initially standardized by the PTB (see Section 1.4). BSS1 consists of four encapsulated beta-particle sources, a source holder on a stand equipped with a shutter, separate beam-flattening filters for each type of source and associated electrical circuitry for shutter operation and timing. The beam flattening filters are those specified in ISO 6980: plastic discs, thicker in the center than on the periphery for ^{90}Sr+^{90}Y and ^{204}Tl, and with a central circular opening for ^{147}Pm. When installed perpendicular to the beams and concentric with the beam axis at a pre-set distance from the sources, they filter the beams selectively so as to achieve beam cross sections of relatively constant absorbed-dose rate over an area sufficient for instrument calibration (see also Sections 2.4.1 and 4.11), and consistent with the requirements of ISO 6980 for Series 1 reference radiation fields. Figure 1 shows a picture of BSS1 and the extrapolation chamber. BSS2 is of similar design to BSS1

except that there are only three sources, and ^{204}Tl is replaced by the longer lived and higher activity ^{85}Kr. This system is also safer, since each source now resides in its own holder which contains a shutter. The system is also more automated and contains sensors to verify that the correct distance and filter have been set. Irradiations at non-perpendicular angles are also facilitated, as well as operation of the system in a vertical beam geometry. Figure 2 shows pictures of BSS2 as well as the source capsules. Information on the properties of the beta-emitting nuclides employed and on source structure and nominal activity is given in Table 3. Figure 3 shows the approximate theoretical beta-particle spectra of the four radionuclides, covering a range of average energies from 0.06 to 0.8 MeV.

2.4 The Extrapolation Ionization Chamber

2.4.1 Description

The extrapolation ionization chamber is a device designed to achieve a continuously variable air volume. This volume is defined by two electrodes and an insulating ring which separates the collecting region from the guard region. A potential is placed between the two electrodes which causes ionization products to be swept out (collected) of the defined volume. The radiation enters the chamber through a thin (0.006 mm thick) carbonized polyethylene terephthalate (PET) window which also serves as the "high voltage" electrode by having a voltage placed upon it. The radiation passes through the air in the gap between the electrodes, striking the other (collecting) electrode which is held at ground potential. The sign of the voltage placed on the high voltage electrode determines the sign of the ionization products collected by the collecting electrode. Since the beta particles are also stopped in the collecting electrode material, there is always a negative current being measured and recourse must be made to measurements at both polarities in order to remove this unwanted "parasitic" current from the desired ionization current. Figure 1 is a picture of the arrangement for producing the beta-particle fields with BSS1 and for determining absorbed-dose rates to water in these fields by means of measurements with an extrapolation chamber. The beta-particle sources fit into the shuttered source holder. Different beam flattening filters are employed with the different radionuclide sources. The extrapolation chamber (shown before the stepping motor was added to the end to control the air gap remotely) on the left was designed by the PTB and built for NIST by Pychlau Technical Works (PTW). The body of the chamber is made of polymethyl methacrylate (PMMA). Its diameter is 140 mm – which makes it large enough to simulate a phantom of infinite size. The plate separation is variable and can be accurately determined by means of a micrometer measurement (see screw on the end of the chamber at left). The thin entrance window for the beta particles is constructed of carbonized polyethylene terephthalate (PET). The source shutters on both BSS1 and BSS2 are electrically interlocked with an infrared beam and photocell defining a safety perimeter as long as the shutter is open. Figure 2 shows a similar view of BSS2, with the extrapolation chamber absent.

The chamber is mounted in a stand that can be moved from side to side across the table, for investigating beam uniformity in the calibration plane (which is the plane

perpendicular to the beam axis at the calibration distance). The reference distances have been chosen in accordance with ISO 6980 to be 20 cm for ^{147}Pm, and 30 cm for ^{90}Sr+^{90}Y, ^{204}Tl and ^{85}Kr. Variations in dose rate from BSS1 with reference distance can be studied by moving the chamber cart along the tracks.

2.4.2 Chamber Construction

Figure 4 shows a schematic cross-section through the front end of the extrapolation chamber, which was originally designed by Böhm [1984]. The high-voltage electrode through which the incident beta particles enter the extrapolation chamber is a 0.67 mg/cm2 graphite-coated PET foil. The collecting electrode and the guard electrode are both graphite coatings on the acrylic piston. The plate separation, d, is changed by moving the piston using a stepping motor attached to a micrometer screw (not shown).

The ionization-chamber volume is taken to be the product of the area of the collecting area of the electrode, $A = (\pi/4)\bullet(\text{effective diameter})^2$, and the plate separation (air gap), d, of the electrodes. The effective diameter and consequently the area A can be measured accurately with a traveling microscope. Accurate determination of d is usually more difficult but can be readily accomplished by extrapolation measurements.

In the current version of the NIST extrapolation chamber, all motions and the data collection are computer controlled. A single stepping motor is used to drive a rotating stage to move the collecting electrode towards the entrance window. Data is collected from the electrometer, and, since ionization chamber measurements must be corrected to reference conditions of temperature and pressure, from a thermometer and a barometer. The polarity and magnitude of the voltage applied to the entrance window is also under computer control.

2.4.3 Principle of Use

The following is a guide to the use of the extrapolation chamber for determining absorbed-dose rate to water at the points of interest in the beta-particle beams. Covered are steps leading from the initial ionization measurements to the fully corrected absorbed-dose rates, including a description of the required corrections.

2.4.3.1 Measurement of Ionization Current as a Function of Chamber Depth

The ionization current is obtained from a measurement with a high-impedance electrometer of the charge accumulated on a calibrated capacitor after irradiation of the extrapolation chamber over a measured period of time. Figure 5 shows the results of current measurements as a function of air gap with three types of sources, after application of certain corrections. These corrections are introduced in Eq. 4 below and are separately discussed in detail. The corrected currents vary linearly with chamber depth to a good approximation. Linearity is important since the slopes of the curves are used in the computation of absorbed-dose rate, as seen in Eq. 9, Section 4.5. The average of the absolute values of the deviations from the lines drawn, as determined from least-squares computations, are too small to be shown in the figure.

The net measured current, I, is given by

$$I = (I_+ + |I_-|)/2, \quad (1)$$

where

$$I_{+,-} = C(U_2-U_1)/t, \quad (2)$$

and C is the external feedback capacitance, U_1 and U_2 are the initial and final voltages on the feedback capacitor and t is the integration time. An associated quantity, known as the parasitic current, I_B, is given by

$$I_B = (I_+ + I_-)/2. \quad (3)$$

This quantity represents the current in the collecting electrode due to incident beta particles stopping on the collecting electrode. It is only slightly dependent on chamber depth, increasing with decreasing chamber depth. It serves as a useful monitor of the measurement stability and should be recorded with the net current.

The measured currents are small to moderate, on the order of 100s of fA for most of the sources used and thus an extremely sensitive electrometer is required. The high voltage supply must be bipolar since measurements are made at both positive and negative polarities. The voltage gradient used is moderate, 10 V/mm, however the recommended air gaps are very small ($\leq$ 2.5 mm), so only modest voltages are required.

2.4.3.2 Correcting the Net Measured Ionization Current
The corrected net ionization current, I_c, is given by

$$I_c = I \Pi_i k_i \Pi_j k'_j, \quad (4)$$

where k_i are corrections which may vary during the measurement of the extrapolation curve and k'_j are corrections that are constant during the measurement. The following is a discussion of these correction factors. Note that correction factors in ISO 6980-2 which have the value of unity for all sources are not discussed.

a) k'_{ba}, the backscatter correction, takes into account the difference in backscatter from water and backscatter from PMMA, the collecting electrode material. Values for k'_{ba} (taken from ISO 6980-2) are shown in Table 4.

b) k'_{br}, the bremsstrahlung correction, takes into account the contributions to the ionization current due to photons from material intervening between the source and the chamber air volume (chamber window plus added filtration, if any). Values for k'_{br} (taken from ISO 6980-2) are shown in Table 4.

The rest of the corrections discussed vary with the chamber depth.

c) k_{ad}, the correction for air density changes inside the chamber, arises because of temperature and pressure variations of the ambient air, since the chamber is of a type which is open to the atmosphere. It corrects to the reference temperature and pressure using the relationship,

$$\rho_a = \rho_{a0}\left[\frac{p}{100.726} - \frac{r}{114.2}\left(\frac{T}{T_0}\right)^{17.97}\right]\frac{T_0}{T} \quad (5)$$

where

T is the absolute temperature in K of the air in the collecting volume;

p is the air pressure in kPa;

r is the relative humidity of the air, expressed as a fraction;

ρ_{a0} is the air density for the reference conditions which are defined for the following parameters:

T_0 = 293.15 K,

p_0 = 101.325 kPa,

r_0 = 0.65. For these conditions,

ρ_{a0} = 1.19740 kg m^{-3}

Eq. 5 is valid only for standard test conditions. The correction factor for the variations of the air density within the collection volume, k_{ad}, is then given by

$k_{ad} = \rho_{a0}/\rho_a$.

d) k_{abs}, the correction for variations in the attenuation and scattering of beta particles between the source ant the collecting volume due to variations from reference conditions, is calculated using the functions and coefficients given in ISO 6980-2.

e) k_{ac}, the correction for the attenuation of beta particles within the chamber air gap, is calculated using the functions and coefficients given in ISO 6980-2.

f) k_{di}, the beam divergence correction, is necessary because of the relatively short source-detector distance and the point-like nature of the source. Assuming inverse-square law

dependence over the short distances involved in the change in air gaps in the extrapolation chamber measurement, it is calculated from

$$k_{di} = 1+d/y_0, \quad (6)$$

where y_0 is the source to chamber surface distance.

g) k_{pe}, the sidescatter correction, takes into account the perturbation of the of the beta particle flux by the side walls of the extrapolation chamber. It is calculated using the functions and coefficients given in ISO 6980-2.

h) k_{sat}, the correction for ion recombination and diffusion in the air inside the chamber, is usually quite small for protection level measurements. It only becomes appreciable for large ion currents and/or small voltages. It is calculated by means of published relationships [Böhm 1976] as

$$k_{sat} = ([1- 5.05 \times 10^{13}\ Id^3 / aU^2][1- 4.4\ d/ U][1- 17.24 \times 10^{-5}\ T / U])^{-1} \quad (7)$$

where d is the chamber depth in m, I is the measured current in A, U is the biasing voltage in V, a is collector area in m^2 and T is the ambient temperature in K.

i) k_{de}, the correction for source decay, can be taken into account by the correction factor

$$k_{de} = \exp[(t_m - t_0)\ln(2)/t_{1/2}] \quad (8)$$

where $t_{1/2}$ is the half life of the radionuclide, t_m is the time at which the measurement is made, and t_0 is the time to which the measurement is being corrected to, which is the reference time for the measurement. For the measurement of an extrapolation curve, the reference time is usually taken as the beginning of the measurement. Table 3a shows values of half lives for the beta-particle emitting nuclides used in this service.

3. Health & Safety

While the absorbed dose rates involved with protection level measurements are generally low, the principle of As Low As Reasonably Achievable (ALARA) shall be followed. To this end, unshielded sources are only handled using the tool described in Section 4.12. The interlock system described in Section 2.2 shall be employed to prevent accidental exposure to the calibration beams. The entrance to the back part of Room B003 where the calibration fields are located is very narrow and shall be roped off when radiation fields are expected to be present. In addition, the area shall be posted as a Radiation Area and red lights turned on when the shutters are opened.

4. Procedures

4.1 Source Acceptance

Once a customer has contacted NIST and indicated that a source is being shipped for calibration, a NIST 364 form must be completed and submitted to Gaithersburg Radiation Safety Division (GRSD). The source is then assigned an RS# which will be used in future source inventories. Ideally the source will be removed from inventory when it is returned to the customer. (See Section 4.8).

4.2 Chamber acceptance

Chambers need only be inspected for damage. Note that PTW extrapolation chambers should be shipped with the micrometer screw locked in place. This is accomplished by moving the micrometer to a setting of about 10 mm, which exposes a 5 mm Allen screw which is screwed out to lock the piston and screwed in to free the piston. This is to protect the window from the piston during shipment. The window should also be protected from the outside by a covering of thick plastic which is screwed into place on the face of the chamber. Check for damage to the window before proceeding with the calibration.

4.3 Opening a test folder

Once a customer completes the required online purchase using the E-Commerce system, an order number is generated for the calibration request.

4.4 Source leak testing

Prior to being released by GRSD, the source will have been checked for removable radioactive contamination. Since this test usually takes the form of swiping the inside and outside of the Type A container, and the outside of the shielded source container, it is prudent to also perform a visual inspection of the source prior to use. This is done with the source behind plastic shield. Things to look for are a smooth, shiny surface with no corrosion spots or foil kinks. If there is any doubt about how the source looks, a thorough leak test should be performed by rubbing a swipe with the source surface and having GRSD count it. Any oddities about the source capsule should be noted by at least a sketch.

4.5 Initial information to be logged in the Data Book

In the data book prior the start of the calibration the following information shall be recorded:

1) customer name, address and phone number
2) source RS#, assigned by GRSD
3) source maker, model and serial number (located usually on a flat on the handle)
3) customer purchase order number (PO#), from customer
5) NIST order number (O#), assigned by E-Commerce system
6) NIST Report of Calibration number (DG#), assigned by Group or Division secretary

4.6 Generation of Report

Once the measurements have been completed and analyzed (see Sections 4.11 through 4.16), a Word template is used to generate the final calibration report. Be careful in generating this report that the appropriate fields are changed, such as the DG number, RS# and dates in the footer, the customer and source information on the front page, the source ID and measurement data tables. A sample report for an instrument calibration is shown in Appendix A.

In addition, a copy of all pertinent raw and analyzed data results listed in the final calibration report is to be included in the order number for the review process. These values should be highlighted for the reviewer to facilitate comparison with the final reported values. This will further the accuracy check of reports and ensure no mistakes were accidentally made when inputting values into final report templates.

4.7 Uncertainty of Calibration

The method of uncertainty assessment used here follows the recommendation of NIST 1260 (Taylor and Kuyatt 1994). Evaluation of the uncertainty estimates are of two kinds. Conventional statistical estimates of random uncertainties are given as standard deviations of the mean, designated "Type A", which can be considered to be objective estimates. All other uncertainty estimates, designated "Type B", are subjective estimates, based on the extensive experience of the calibration staff. The Type B uncertainties are estimated so as to have roughly the character of standard deviations. The estimates of each type are combined in quadrature, and then the two results are combined in quadrature to give a combined uncertainty. The combined uncertainty in turn is multiplied by two, to give an expanded, overall uncertainty at a confidence level of 95 %.

Table 5 gives a breakdown of the uncertainties in the determination of absorbed-dose rate to water at the 7 mg/cm^2 depth of interest from the ionization current measured with the extrapolation chamber. The data in this table are based on the detailed presentation of corrections presented in Section 2.4.3 and measurement procedures in Sections 4.11 through 4.16. Many of these components are common to ionization chamber measurements and should be consistent with those of other Radiation Physics Division calibration service uncertainty budgets. A few, however, are peculiar to this service. The uncertainty in the determination of absorbed dose rate to water and known influence of measurement geometry on source calibration then are used in Table 6 to arrive at combined uncertainties in the calibration of beta particle sources and transfer ionization chambers submitted to NIST. The overall uncertainty is quoted as two times the combined uncertainty.

4.8 Source Shipment

When the calibration has been completed satisfactorily, the source is repacked in the Type A package in which it arrived along with the final signed calibration report. In cases where there is a delay in obtaining the required signatures on the report and the customer has an urgent need for the source to be returned, the source may be shipped with only a

draft, not fully signed report to be used by the customer in the interim until the final report is ready. In this case it shall be clearly indicated in a note attached to the report that the report is a draft and that the final report will be sent separately. Shipping Radioactive Material (RAM) may be performed only by personnel trained every two years. The shipper shall fill out the NIST Form 796a, Shipper's Declaration of Hazardous Materials and submit the packed source to GRSD for checking, measuring of exposure rates and proper labeling.

4.9 Instrument Shipment

Instruments are packed securely inside the container in which they were received. Note the precautions to be taken to prepare PTW extrapolation chambers for shipment given in Section 4.2.

4.10 Mounting Extrapolation Chambers in BSS1 and BSS2

Extrapolation chamber mounting and proper positioning is very similar in the two source ranges. In both cases the extrapolation chamber is attached at its base to its support rod which is in turn attached to the aluminum stand shown in Figure 1. A distance rod is supplied with each set. In the BSS1 set there are 2 rods, one for 20 cm and one for 30 cm; BSS2 contains only a single rod for 30 cm. In both cases the rods go into the source stand exactly as sources do (see Section 4.12). Remove any flattening filters before installation of the distance rod and **be very careful not to poke out the window of the chamber with a distance rod!** Changing windows on a PTW extrapolation chamber should not be a routine occurrence (see Section 5.2); they are expensive and not easy to change. It is prudent to set chambers up with some sort of covering over the window, even if it's only the 7 mg/cm^2 cowl. A better covering is the plastic protective piece which goes over the chamber for shipping. It is also convenient if the chamber center is marked on the covering used, although this is not crucial as the beams are fairly uniform and rigorous centering is not essential for good results. Small adjustments in the height of the chamber are possible by loosening the nut at the chamber base and screwing the support rod in or out. The face of the chamber is made parallel to the calibration plane by measuring the distance with a meter stick between the arms of the source support stand ("cross") on all four sides of the chamber face. Adjustments can then be made to the position of the table, turning it slightly and/or shimming the front or back legs. The last adjustment is to bring the chamber forward carefully until the distance rod just touches the window surface. This must be done with the cowl removed for the most accurate positioning. Unlike the centering, placing the chamber surface at the proper distance is crucial to good measurement results because the distances are relatively small and consequently the dose rate gradients appreciable. Once a chamber has been set up properly on a range, remove the distance rod and carefully place the proper cowl over the front face of the extrapolation chamber. The cowl is designed to add material at the chamber front to bring the measurement depth to the equivalent of 7 mg/cm^2 (0.07 mm) in water or unit density tissue. For the currently installed window of the NIST chamber, which is 0.67 mg/cm^2,

the cowl plastic added thickness is 6.87 mg/cm^2 making a total thickness of 7.54 mg/cm^2 which for PET is equivalent to 7.03 mg/cm^2 of water or unit density tissue (ISO 6980-2). The remaining small difference from the reference depth of 7 mg/cm^2 is accounted for in the correction k_{abs} (seen Section 2.4.3.2). If BSS1 is being used at 20 cm or 30 cm and the appropriate distance rod was used, then the chamber is at the proper distance and source installation can proceed (see Section 4.12). If measurements are to be made at 50 cm with the unfiltered 1850 MBq ^{90}Sr+^{90}Y source, then the chamber must be rolled back to this distance, as determined by measurements with a meter stick. If using BSS2 at distances other than 30 cm, unlock the positioning lock on the optical bench and slide the source support stand to the required position (11, 20, or 50 cm) and relock the stand.

4.11 Mounting Sources in BSS1 and BSS2

Mounting sources in BSS1 must be done carefully since the sources are not shielded when out of their storage pig. The first thing to remember is to close the shutter manually on the source holder stand after removing the distance rod. Sources are removed from the storage pig using the shielded source manipulation tool, which has a spring loaded mechanism for attaching to the back of the source and removing it from the pig. With the tool attached to the back of the source, unscrew it from the pig and take it to the source stand, being careful to keep the front of the source pointed away from yourself or anyone else in the lab. Insert the front of the source carefully into the source stand and screw it hand tight into position. It should be tight enough so that the source manipulation tool can be removed without losing the source. Install the appropriate flattening filter, for ^{147}Pm, ^{204}Tl or the 74 MBq ^{90}Sr+^{90}Y source used at 30 cm. Flattening filters are installed with the lettering on the filter out and the mark on the peripheral pointing up. For multi component filters this should results in the smaller components facing away from the source.

Mounting sources on BSS2 is much easier and safer than BSS1, but still precautions must be taken. To install a source, take it from its storage pig and place it shutter first into the source stand. When it is all the way in, lock it in place using the lever at the back of the stand. Be careful not to open the shutter of the source capsule during manipulation; it's difficult but not impossible to so. Each source is keyed differently and the system can recognize which source has been installed. Finally install the appropriate flattening filter, for ^{147}Pm, ^{204}Tl or the ^{90}Sr+^{90}Y source used at 30 cm. Each filter is also keyed differently and the system can recognize which filter has been installed. The filter supports are sized such that the filter will only go on the supports one way.

4.12 Current Measurements

The basic measurement performed by all the data acquisition programs controlling the extrapolation chamber is the net current. In the present operating scheme this is obtained from charge measurements across an external capacitor using a Keithley 642 electrometer in the external feedback capacitor mode. Measurements at both positive and negative polarities are made. The time base of the controlling computer and software (LabView) is used for timing over the user specified integration period for each reading. Since there are

limitations in the analog-digital converter used to read the output of the electrometer as well as the range of charge the electrometer is capable of reading, Table 7 is given as a guide for the selection of appropriate integration times for the system. The net (uncorrected) current is obtained from the average of the magnitudes of the currents at the two polarities.

4.13 Extrapolation Measurements using the LabView Extrapolation Chamber Control Programs

Data acquisition and control are accomplished using a suite of LabView programs. To initiate the measurement process, execute the program Extrapolation ControlMGM.vi, for which there is a shortcut on the desktop of the host computer. This will bring up the initial window allowing selection of the control mode. Choose Constant Time Extrapolation (the default) and then run the program by clicking on the arrow at the upper right. This brings up the PreExtReading page on which initial information about the measurement can be entered in as much or as little detail as desired. The main use of this information is for descriptive headers and production of input files for the PTB program BETA, which can be used for data analysis as an alternative to the Excel spreadsheet described in Section 4.15. When this page has been filled out to the user's satisfaction, click the Boolean switch. This puts one on the Extrapolation Chamber with setsMGM page, which is the main control page. Expect a small delay to first access this page (10 s of seconds on a 550 MHz Pentium). This is the most important page for the actual measurement as all the critical parameters controlling the measurement are entered here. First one chooses the number of readings per set. Choose six here to get five current measurements. Then choose the number of sets, a set being a series of measurements at both positive and negative polarities. Choose two here, to match the parameters given in Table 7. Next choose the integration time, the value being governed by the expected absorbed dose rate, the total measurement time, and the limits of the current measurement system (see Section 4.13). Next enter the current micrometer reading on the barrel of the extrapolation chamber itself. This is the actual reading, which is about 0.06 mm less than the actual estimated air gap. Note that when "reading" is used it refers to the actual micrometer indication and when "air gap" is used it refers to the estimated actual air gap, which is the reading + 0.06 mm. Indicate which direction the air gap changes should go, either decreasing or increasing. If small currents (<20 fA), it is a good idea to try to have these measured out-of-hours; therefore, if starting in the afternoon, choose decreasing so that smaller air gaps will run in the middle of the night. If starting first thing in the morning, choose increasing air gaps to get the small air gaps done before most people arrive and start putting more load on the building’s electrical systems. Next choose the initial gap, 0.25 mm for increasing gap measurements and 2.5 mm for decreasing gap measurements. Next choose the gap increment, which should be 0.125 mm. Finally choose the number of air gaps, which will be 19 for the conditions specified. Check that everything on this page is correct and then click the Boolean switch; this will bring up a smaller window on which the initial gap and the current reading are displayed. Make sure that these values are correct and then hit the Boolean switch. The extrapolation chamber should be moved to the initial gap. When the chamber has stopped moving, check that the

reading in the initial gap is less than 0.06 mm. Now the source and filter (if used) can be mounted if not already done so, and the area roped off and red lights turned on. Reset the interlocks and open the shutter of the range being used. Remember to set an exposure time for the range longer than the anticipated measurement time as given in Table 7 so that the shutter does not close during the measurement. When the measurement is complete there is a prompt to save the measured data. The first file is saved with the name PB#### (no extension) where #### is the measurement sequence number. This file contains all the data necessary for the absorbed dose measurement with the Excel file as described in Section 4.15. The other two files that can be saved are used by the BETA program for absorbed dose rate measurement.

4.14 Calculation of absorbed dose rate

Absorbed dose rate to water, calculated from, $\dot{D}_w$, is given by the Bragg-Gray relationship

$$\dot{D}_w = \frac{(\overline{W}/e)s_{w,air}}{\rho_0 a}(\Delta I_c/\Delta d)_{d\to 0}\ , \qquad (9)$$

where $\overline{W}/e$ is the average energy in joules needed to produce one coulomb of charge of either sign in air at 65 % relative humidity (33. 83 ± 0.06 JC^{-1}), $s_{w,}^{air}$ is the ratio of the mean mass-collision stopping power of water to that of air, ρ_0 is the density of air at the reference temperature and pressure (T_0, p_0), a is the effective area of the collecting electrode, and $(\Delta I_c/\Delta d)_{d\to 0}$ is the rate of change of the corrected current with extrapolation chamber air-gap width as the width approaches zero. The values used for $s_{w,}^{air}$ for each source are given in Table 4. The value for the effective collecting area, a, is determined to be the collector diameter given by the manufacturer. For the NIST PTW chamber in Table 9, the value is 7.0827 x 10^{-4} m^2.

Excel templates are used to perform final calculations of the absorbed dose rate for the calibration report. The raw data from the extrapolation chamber control program are pasted into the template at the proper location. Current versus air gap curves are produced, as well as a plot of current per unit air gap as a function of corrected air gap. This latter curve is useful to assess any curvature in the current versus air gap function as well as the smoothness of the data since neither of these features are apparent in the current versus air gap plot. This plot is inserted in the data book as well as the final dose rate calculation, which is done in the Excel template, which shows all corrections applied to the data. The absorbed dose rate is quoted at a depth of 7 mg/cm^2 and represents an average over the central 30 mm diameter of the radiation field.

4.15 Acceptance of Results

Reference values for the sources used are given in Table 8. Quality assurance measurements are considered valid if the results obtained match those in Table 8 (after suitable decay correction) to within the uncertainties given in Table 5: that is 1.6 % for

^{147}Pm, and 1.2 % for the other sources. The same criteria apply when a NIST reference chamber is calibrated for measurement assurance of a customer reference chamber.

5. Maintenance

5.1 List of critical equipment

A list of the critical equipment used in this calibration service is given in Table 9. Calibrations were initially performed on each piece of equipment when it was brought into service by comparison against local standards. Calibration frequency is as needed, based on control charts. Measurements using the extrapolation chamber are performed in Building 245, Room B003. All equipment is located in Building 245.

None of the devices receive routine calibration. The uncertainties of the measurements are such (see Table 5) that small corrections introduced by routine recalibrations would not influence the overall results. Furthermore, the consistency of the measurement system as a whole is routinely monitored via measurements with the reference sources.

5.2 Changing Entrance Foils/HV Electrodes

Although this is a rare occurrence, entrance foils should be replaced when they show any sign of wear, such as tears, stretch marks or clear areas where the carbonization has been removed. To replace the foil the window mounting ring is the removed from the chamber by removing the four plastic screws which attach it. Take the mounting ring to a desk or other smooth work surface and remove the four screws which attach the window mounting plate to the mounting ring. Set the mounting ring aside, and remove the eight small screws which hold the tension ring in place and remove the old entrance window. Take a fresh window (obtainable from PTW) from the stock supply, making sure it contains no creases or other flaws. Place the PET with the carbonized side downward, which will put it on the inside of the chamber. The side which is carbonized is somewhat less shiny than the uncarbonized side but if uncertain, check conductivity with a portable ohmmeter; the carbonized side is conducting, the other side not. Now use pieces of adhesive tape to stretch the window over the mounting place and hold it in place; taping in 8 places is sufficient to remove all wrinkles in the foil. While doing this, it is prudent to use a finger to press in the foil over a hole in which one of the eight screws holding the tension ring, making a circular mark on the foil to make it easier to properly orient the tension ring during mounting. Mount the tension ring, which stretches the foil tight; use a sharp object to punch holes in the foul where the tension ring mounting screws will go, and attach the screws, working in a 180° pattern and keeping pressure on the tension ring until it has been securely attached. Use a knife or scalpel to cut the foil around the outer edge of the tension ring. The finished product should be mirror-like with no wrinkles evident. Reattach the window mounting plate to the holding ring with the four metal screws, and then attach the holding ring to the extrapolation chamber with the plastic screws, being sure to remember to put the insulating ring on the holding ring before fastening down. Care should be taken in all the screw tightening not to slip and punch a hole in the window

5.3 Troubleshooting the Protection-Level Beta-Particle Measurements

Measurements in protection level beta-particle fields are relatively free from problems because of the relatively large distances employed. Problems usually occur only at very low signal levels, on the order of 20 fA or less. One precaution is to be sure that all sources in the measurement ate stored in their Pb containers prior to any low level measurements, such as with ^{147}Pm. A ^{90}Sr+^{90}Y source left in a calibration stand during measurement of a low level source will produce sufficient bremsstrahlung in the room so that the measurement is impossible. This is evident when the parasitic currents are examined. The bremsstrahlung produces a signal in the extrapolation chamber which will more than cancel out the parasitic current and leave an apparently positive parasitic current.

Indication of problems is most often evident in signal drifting or noisy signals. Problems also seem to be associated with conditions of low humidity. The acceptable range of ambient conditions under which calibrations may be performed are humidity between 20 and 70 % and temperatures between 20 and 24 °C. There are no restrictions on barometric pressure. In addition, temperature changes must be limited to less than 1 °C/hr. One of the most common problems is the absence of polarizing voltage on the high voltage electrode. Always make sure that the high voltage supply is switched on as it has a tendency to switch itself off occasionally. Also make sure that the electrometer is set up in the EXT (external feed capacitor) mode.

There are also some known problems with long exposure times using the BSS2 range, specifically premature shutter closing. There is no known cure for this, the only expedient is the placement of a shim under the shutter plunger on the front of the unit to prevent the shutter from closing. This must be done carefully to prevent radiation exposure to the extremities.

Finally, there are sometimes problems with the interlock system which will prevent the shutters from being opened. Check that the beam is aligned with the receptor by observing the LED on the receptor.

6 References

Behrens, R., *et al* "International comparison EUROMET.RI(I)-S2 of extrapolation chamber measurements of the absorbed dose rate in tissue for beta radiation" (EUROMET project No 739): Final report. *Metrologia* **44** (2007).

Böhm, J., "Saturation corrections for plane-parallel ionization chambers," Phys. Med. Biol. **21**, 754-759 (1976).

Böhm, J., "Standardization and calibration in beta dosimetry," Proceedings of the International Beta Dosimetry Symposium; 1983 February; Washington, DC, US Nuclear Regulatory Commission NUREG/CP-0050, 73-97 (1984).

Boutillon, M. and Perroche-Roux, A.M., "Re-evaluation of the W value for electrons in dry air," Phys. Med. Biol. **32**, 213-219 (1987).

ISO 6980-1: 2003, *Reference beta particle radiations – Part 1: Methods of Production*. (draft).

ISO 6980-2:2003, *Reference beta particle radiations – Part 2: Calibration fundamentals related to basic quantities characterizing the radiation field*. (draft).

Pruitt, J.S., "The effect of altitude on beta-ray source calibrations," Pad. Prot. Dosim. **11**, 151-157 (1985).

Pruitt, J. S., C. G. Soares and M. Ehrlich, *Calibration of Beta-Particle Radiation Instrumentation and Sources*, NBS Special Publication 250-21 (1988).

Taylor, B.N. and Kuyatt, C.E., *Guidelines for Evaluating and Expressing Uncertainty of NIST Measurements*, NIST Technical Note 1297 (1994).

7. Uncertainty Analysis
See Tables 5 & 6.

8. Records
Descriptions of all measurements performed are recorded in an official NIST laboratory notebook that is stored in 456/A105E. Printouts of the Excel spreadsheets that contain the results of all extrapolation chamber measurements along with all plots used to determine dose-rates are also kept in a folder in 456/A105E.

9. Definitions
Absorbed dose to water: defined as the energy from ionizing radiation absorbed by a given mass of water, 1 J/kg = 1 Gy.

Beta particle: electron (unit negative charge) or positron (unit positive charge) spontaneously emitted by certain unstable atomic nuclei in the radioactive disintegration process of beta decay.

10. Filing and Retention
The RPD Quality Manager shall maintain the original and all past versions of this RPD ProcedureAppendix A. Sample Calibration Report for an Instrument

National Institute of Standards and Technology

REPORT OF CALIBRATION

OF

PTW Extrapolation Ionization Chamber (Model: xxxxxx)
S/N -###

SP250 Service ID# 47036C

FOR

####
####

Calibration was performed by Jason S. Walia
on XXX XX, XXXX

Report reviewed by Ronaldo Minniti

Report approved by

Michael G. Mitch, Leader
Dosimetry Group

For the Director
National Institute of Standards and Technology
by

James M. Adams, Chief
Radiation Physics Division
Physical Measurement Laboratory

Information on technical aspects of this report may be obtained from Jason S. Walia, NIST, 100 Bureau Drive Stop 8460, Gaithersburg, MD 20899, 301-975-5592

Report format revised 11/19

NIST National Institute of Standards and Technology U.S. Department of Commerce

REFERENCE DG ######/##
NIST DB ###/###
ORDER #: 682.02/O- #######-##
Date: xxxx, xxxx

Extrapolation ionization chambers are calibrated by means of measurements in a reference beta-particle field. The readings obtained are compared to readings of a standard extrapolation chamber used to establish the absorbed-dose rate to tissue of the reference beta-particle field. Absorbed-dose rate to tissue in Gy/s is given by

$$\dot{D} = \frac{(\overline{W}/e)\, S_{air}^{tissue}}{\rho_0 A} \left(\frac{\Delta I_c}{\Delta d}\right) \qquad \text{Eq. 1}$$

where $\dot{D}$ is the absorbed-dose rate to tissue, $\overline{W}/e$ is the average energy required to produce an ion pair in air (33.83 J/C), S_{air}^{tissue} is the ratio of the average mass stopping power of tissue to air, ρ_0 is the density of dry air at the reference conditions of 22 °C and 760 Torr (1.197 kg/m^3), A is the area of the collecting electrode and $(\Delta I_c/\Delta d)$ is the fitted slope in A/mm. Values for the stopping power ratio are given in Table 1. For the chamber submitted, a calibration was performed in a reference ^{90}Sr+^{90}Y beta-particle field at a distance of xx cm. Calibrations of radiation-protection instruments in beta particle fields can be considered valid only for the particular geometry and configuration in which they are performed. In this field, currents were measured with both the submitted extrapolation chamber and the reference extrapolation chamber at 19 air gaps ranging from 0.25 mm to 2.5 mm. The geometrical properties of each of the extrapolation chambers are given in Table #. For each chamber, a thickness of 6.87 mg/cm^2 of polyethylene terephthalate (PTP) was added to make the total window thickness equivalent to 7 mg/cm^2 of tissue; all measured dose rates are reported at this depth. Currents were determined by voltage readings across a capacitor of known value for a known period of time. Because of the high signal levels available through the use of the NIST ^{90}Sr+^{90}Y source, no corrections for non-source-induced currents, I_B, were made. It was verified that these currents are below 1 fA, and could be safely ignored. The corrected current I_c is given by

$$I_c = \left(\frac{VC}{t}\right) k_{sat}\, k_{di}\, k_{ac}\, k_{pe} k_{abs}\, k_{br}\, k_{ba}\, k_{ad}\, k_{de} \qquad \text{Eq. 2}$$

where V is the measured voltage, C is the capacitance (100.22 pF), and t is the integration time (XX s). The raw currents are also corrected for ion recombination (k_{sat}), beam divergence (k_{di}), attenuation in the chamber air gap (k_{ac}), scatter from the chamber side walls (k_{pe}), the effect of the air path between source and detector (k_{abs}), photon contribution (k_{br}), difference in backscatter between tissue and polymethyl methacrylate collecting electrode material (k_{ba}), temperature and pressure (k_{ad}) and decay between the measurement date and the reference date (k_{de}). The first four corrections are functions of the air gap, and they are given in Table #. The other corrections, or coefficients used in determining them, are shown in Table 1. Explanation of all the corrections used is given in NIST Special Publication 250-21 which is available upon request.

The realization of the radiation quantity absorbed dose-rate done at NIST establishes the National Standard. This can in turn be transferred to other measurement facilities through a suitable measuring instrument, thus enabling traceability to the National Standard. Calibration results are reported as calibration coefficients, the quotients of absorbed-dose (rate) to water and the corresponding instrument reading.

For the day on which the calibration of the customer chamber was performed (xxxx ##, ####), ambient laboratory conditions were a temperature range of ##.# °C to ##.# °C, a pressure range of ###.# mm Hg to ###.# mm Hg, and a relative humidity range of ## % to ## %.

The corrected currents measured at each polarity at each air gap are shown in Tables # and #. Each current value shown in this table is the average of ten measurements at each polarity. The uncertainty shown represents a single standard deviation about this average. The sets of nominal air gap versus corrected net current data for both the customer and the NIST chambers shown in Tables # and # were least-squares fit to a straight line. The results of these fits are shown in Table #. The value shown for the X intercept is the correction necessary for the micrometer reading used to set the air gap. The absorbed-dose rate, corrected to the reference date of xxxx ##, ####, at a depth of 7 mg/cm^2 in tissue is calculated from Equation 1 using the fitted slope and the constants shown in Tables # and #. The last column shows the ratio of absorbed-dose rate measured with the submitted extrapolation chamber and with the NIST reference extrapolation chamber along with the associated standard deviation. Type B uncertainties associated with the various correction factors shown in Tables # and # cancel since a ratio has been formed. However, observed variations in the NIST measurements of these radiation fields (0.7 % at 1 standard deviation) must be considered. Therefore, the standard deviations of the fitted slopes have been combined in quadrature with the NIST measurement uncertainty and the resulting ratio and uncertainty are shown in Tables # through #; the latter represents a single standard deviation. From the values of the ratio we concluded that no corrections to the quoted collecting electrode are shown in Table # were necessary.

Table 1. Source-Dependent Correction Factors or Coefficients

Correction Factor or Coefficient	^{90}Sr+^{90}Y
Decay constant, λ, d^{-1}	6.587 x 10^{-5}
k_{ba}	1.010
k_{br}	1.000
K_{hu}	1.000
Stopping power ratio, S_{air}^{tissue}	1.110

Table #. Extrapolation Chamber Characteristics

Chamber	Stated Window Thickness (mg/cm^2)	Collecting Electrode	
		Diameter (mm)	Area, A (mm^2)
Customer	#.##	##.##	###.##
NIST	0.67	30.03	708.27

Table #: Air-Gap Dependent Correction Factors for $^{90}Sr+^{90}Y$ at ## cm

Source	Air Gap, d (mm)	k_{abs}	k_{ac}	k_{ad}	k_{di}	k_{pe}	k_{sat}
$^{90}Sr+^{90}Y$ at ## cm with no flattening filter, at depth of 7.6 mg/cm^2	0.250						
	0.375						
	0.500						
	0.625						
	0.750						
	0.875						
	1.000						
	1.125						
	1.250						
	1.375						
	1.500						
	1.625						
	1.750						
	1.875						
	2.000						
	2.125						
	2.250						
	2.375						
	2.500						

Table #. Measured Currents (± 1 σ) for the Customer Extrapolation Chamber at 7 mg/cm^2 Depth Using the ^{90}Sr+^{90}Y Source at ## cm SSD with No Flattening Filter

Nominal Air Gap, ***d*** (mm)	Corrected Current Using Positive Polarity (fA)	Corrected Current Using Negative Polarity (fA)	Corrected Net Current (fA)
0.250			
0.375			
0.500			
0.625			
0.750			
0.875			
1.000			
1.125			
1.250			
1.375			
1.500			
1.625			
1.750			
1.875			
2.000			
2.125			
2.250			
2.375			
2.500			

PROTECTION-LEVEL BETA PARTICLE SOURCE & INSTRUMENT CALIBRATIONS

Table #. Measured Currents (± 1 σ) for the NIST Extrapolation Chamber at 7 mg/cm^2 Depth Using the ^{90}Sr+^{90}Y Source at ## cm SSD with No Flattening Filter

Nominal Air Gap, ***d*** (mm)	Corrected Current Using Positive Polarity (fA)	Corrected Current Using Negative Polarity (fA)	Corrected Net Current (fA)
0.250			
0.375			
0.500			
0.625			
0.750			
0.875			
1.000			
1.125			
1.250			
1.375			
1.500			
1.625			
1.750			
1.875			
2.000			
2.125			
2.250			
2.375			
2.500			

Table #: Dose-Rate Calculations from Least-Squares Fit Results

Source	Chamber	Y Intercept (fA)	X Intercept (mm)	Slope, $(\Delta I_c/\Delta d)$ (fA/mm)	Dose Rate, (μGy/s)	Ratio, customer/ NIST
$^{90}Sr+^{90}Y$ at xx cm SSD	customer					
	NIST					

Appendix B. Sample Calibration Report for a Source

National Institute of Standards and Technology

REPORT OF CALIBRATION

OF

AEA Technology Beta-particle Secondary Standard Sources
^{85}Kr Model XXXXX, S/N XXXX
^{90}Sr/Y Model XXXXX, S/N XXXX

SP250 Service ID# **47035C**
FOR

XXXXXXXXXXXXXXX
XXXXXX
XXXXX

Calibration was performed by Jason S. Walia
Reference Date: XXXX **##, ####**

Report reviewed by Ronaldo Minniti

Report approved by Michael G. Mitch, Leader
Dosimetry Group

For the Director
National Institute of Standards and Technology
by

James M. Adams, Chief
Radiation Physics Division
Physical Measurement Laboratory

Information on technical aspects of this report may be obtained from Jason S. Walia, NIST, 100 Bureau Drive Stop 8460, Gaithersburg, MD 20899, 301-975-5592

Report format revised 11/19

National Institute of Standards and Technology
U.S. Department of Commerce

REFERENCE DG #####/##
NIST DB #####/##
ORDER #: 682.02/O-#######-##
Date: xxxx, xxxx

Version	Date	Author	Approval	Pages	Filename
3.20	12/6/19	JSW	JMA	25 of 41	Procedure10v320

Beta particle sources are calibrated by means of measurements with a standard extrapolation chamber, in terms of absorbed-dose rate to tissue. This is determined from current measurements at a range of air gaps. The absorbed-dose rate to tissue in Gy/s is given by:

$$\dot{D} = \frac{(\overline{W}/e)\, S_{air}^{tissue}}{\rho_0 A}\left(\frac{\Delta I_c}{\Delta d}\right) \qquad \text{Eq. 1}$$

where $\mathbf{D}$ is the absorbed-dose rate to tissue, $\overline{W}/e$ is the average energy required to produce an ion pair in air at reference conditions of temperature, pressure and humidity (33.83 J/C), S_{air}^{tissue} is the ratio of the average mass stopping power of tissue to air, ρ_0 is the density of air at the reference conditions of 293.15 K (20 °C), 101.325 kPa (760 Torr) and 65 % relative humidity (1.1974 kg/m^3), A is the area of the collecting electrode and $(\Delta I_c/\Delta d)$ is the fitted slope in A/m. Calibrations of radiation-protection instruments in beta particle fields can be considered valid only for the particular geometry and configuration in which they are performed. Values for the measured absorbed dose rates are given in Table 1 for each of the geometries used. For each geometry, currents were measured with the reference extrapolation chamber at 19 air gaps ranging between 0.25 mm and 2.5 mm. The reference extrapolation chamber is equipped with an entrance window that is 0.67 mg/cm^2 thick, and a polymethyl methacrylate (PMMA) collecting electrode with an area, A, of 708.27 mm^2. A thickness of 6.9 mg/cm^2 of polyethylene terephthalate (PTP) was added to make the total window thickness equivalent to 7 mg/cm^2 of tissue; measured dose rates are reported at this depth. Currents were determined by voltage readings across a capacitor of known value for a known period of time. The corrected current I_c is given by:

$$I_c = \left(\frac{VC}{t}\right) k_{ba} k_{br} k_{hu} k_{abs} k_{ac} k_{ad} k_{de} k_{di} k_{pe} k_{sat} \qquad \text{Eq. 2}$$

where V is the measured voltage, C is the capacitance (100.22 pF), and t is the integration time. As indicated in Eq. 2, the raw currents are corrected for difference in backscatter between tissue and PMMA (k_{ba}), photon contribution (k_{br}), the effect of relative humidity (k_{hu}), the effect of the air path between source and detector (k_{abs}), attenuation in the chamber air gap (k_{ac}), temperature and pressure (k_{ad}), decay between the measurement date and the reference date (k_{de}), beam divergence (k_{di}), scatter from the chamber side walls (k_{pe}), and ion recombination (k_{sat}). Explanation of all the corrections used is given in ISO 6980-2, "Reference beta-particle radiation – Part 2: Calibration fundamentals related to basic quantities characterizing the radiation field," (2004), which is available upon request.

The realization of the radiation quantity absorbed dose-rate done at NIST establishes the National Standard. This can in turn be transferred to other measurement facilities through a suitable measuring instrument, thus enabling traceability to the National Standard. Source calibration results are reported in terms of absorbed dose-rate to water at a fixed source-to-detector distance.

For the days on which the calibrations were performed, ambient laboratory conditions were at a temperature range of ####.## K to ###.## K, a pressure range of ##.## kPa to ##.## kPa and a relative humidity range of ## % to ## %. The corrected current measured at each air gap was the average of ten measurements at each polarity. Integration times ranged from **## s** for the highest dose rate to **## s** for the lowest dose rate. The nominal air gap versus corrected net current data were least-squares fit to the functions recommended in ISO 6980-2. The terminal slopes determined from these fits were used in Eq. 1 to calculate the absorbed-dose rate at the reference depth of 7 mg/cm^2, which is shown in Table 1. The expanded, combined uncertainty in these measurements is also given in Table 1. The Type A uncertainty components are calculated as standard deviations of the mean of replicate readings; other components are estimated using the values recommended in ISO 6980-2, and can be assumed to have the approximate character of standard deviations. The expanded, combined uncertainties are two times the square root of the quadratic sum of all the component uncertainties; they are considered to have the approximate significance of 95 % confidence limits.

Table 1. Calibration results

Source	Distance, cm	Geometry	Tissue Depth, mg/cm^2	Reference date	Absorbed Dose Rate in tissue, μGy/s
^{85}Kr	##	xxx	7	xxx ##, ####	**### +/- ###**
^{90}Sr/Y	##	xxx	7	xxx ##, ####	**### +/- ###**
^{90}Sr/Y	##	xxx	7	xxx ##, ####	**### +/- ###**

List of Tables

List of Figures

Table 1. Comparison of absorbed-dose rates for the original BSS1 sources, at the surface, obtained by NIST and PTB; and absorbed-dose rates to water at the depth of interest in radiation protection for three of the NIST sources

Source		Source-to-detector distance (cm)	Flattening Filter used?	Absorbed-Dose Rate[a] to water, at the surface			to water at a depth of 7 mg/cm^2 (μGy/s)
Type	Nominal activity (mCi)			NIST (μGy/s)	PTB (μGy/s)	Ratio NIST/PTB	
^{147}Pm	14	20	yes	0.267	0.257	1.04	0.06
^{204}Tl	0.5	30	yes	0.341	0.333	1.02	0.33
^{90}Sr+^{90}Y	2	30	yes	1.93	1.90	1.01	2.01
"	50	11	no	513	506	1.01	-
"	"	30	no	70.6	69.9	1.01	-
"	"	50	no	25.2	25.1	1.00	-

[a]Referred to January 1, 1983 and 20 °C at 1 standard atmosphere (101.325 kPa).

Table 2. Comparison of absorbed-dose rates for the BSS2 sources, at a depth of 7 mg/cm^2, obtained by NIST and PTB

Source		Source-to-detector distance (cm)	Flattening Filter used?	Absorbed-Dose Rate[a] to water at a depth of 7 mg/cm^2			
Type	Nominal activity (mCi)			NIST (μGy/s)	PTB (μGy/s)	Ratio NIST/PTB	Reference date
^{147}Pm	100	20	yes	2.97	3.00	0.990	5-Mar-98
^{85}Kr	100	30	yes	50.3	50.2	1.002	6-Mar-98
^{90}Sr+^{90}Y	25	30	yes	10.3	10.2	1.010	9-Mar-98
"	"	11	no	118.2	116.4	1.015	20-Mar-98
"	"	20	no	36.4	35.9	1.014	18-Mar-98
		30	no	16.3	16.0	1.019	13-Mar-98
"	"	50	no	5.70	5.66	1.007	4-Mar-98

[a]Referred to 20 °C at 1 standard atmosphere (101.325 kPa).

Table 3. Characteristics of NIST Beta-Particle Sources

a) Radionuclide data

Radionuclide	Half life (days)	Maximum energy emitted, E_{max} (MeV)	Photon radiations
^{147}Pm	958.2	0.225	γ: 0.121 MeV (0.01%) Sm X-rays: 5.6 to 7.2 and 39.5 to 46.6 keV
^{85}Kr	3915	0.687	γ: 0.514 MeV (0.4%)
^{204}Tl	1381	0.763	Hg X-rays: 9.9 to 13.8 and 68.9 to 82.5 keV
^{90}Sr + ^{90}Y	10523	2.274	None

b) Source Structure and activity

Radionuclide	Source Set	Structure	Window mass per unit area	Activity (MBq) and reference date
^{147}Pm	BSS1[a]	^{147}Pm carbonate pressed into Ag foil	5 mg/cm^2 Ag	518 on 16-Dec-82
^{147}Pm	BSS2	^{147}Pm carbonate pressed into Ag foil	2 mg/cm^2 Ti	3700 on 5-Mar-98
^{204}Tl	BSS1[a]	^{204}Tl chromate pressed into Ag foil	20 mg/cm^2 Ag	18.5 on 16-Dec-82
^{204}Tl	BSS1[b]	not specified	not specified	1850 on 14-Aug-95
^{85}Kr	BSS2	gaseous	22 mg/cm^2 Ti	3700 on 6-Mar-98
^{90}Sr + ^{90}Y	BSS1	^{90}Sr carbonate pressed into Ag foil	50 mg/cm^2 Ag + 0.1 mm (77 mg/cm^2) steel	74 on 16-Dec-82
^{90}Sr + ^{90}Y	BSS1	^{90}Sr carbonate pressed into Ag foil	50 mg/cm^2 Ag + 0.1 mm (77 mg/cm^2) steel	1850 on 24-May-82
^{90}Sr + ^{90}Y	BSS2	^{90}Sr carbonate pressed into Ag foil	80 mg/cm^2 stainless steel	460 on 20-Mar-98

[a]Source has decayed too much to be now used and has not been replaced.
[b]Source has developed corrosion problem and is now no longer used.

Table 4. Source Dependent Correction Factors and Constants for Extrapolation Chamber Measurements Which are Independent of Chamber Depth

Factor	Description	$^{90}Sr+^{90}Y$	^{85}Kr, ^{204}Tl	^{147}Pm
k'_{ba}	backscatter correction	1.01	1.01	1.00
k'_{br}	bremsstrahlung correction	1.000	1.000	0.990
$s_{w,air}$	stopping-power ratio	1.110	1.121	1.124

Table 5. – Uncertainties in the Determination of Absorbed-Dose Rate to Water from Measurements with the Extrapolation Ionization Chamber

a) Corrected Ionization Current (Extrapolation Chamber)

		Percent Uncertainty					
		Type A			Type B		
Parameter	Symbol	^{147}Pm	^{204}Tl, ^{85}Kr	$^{90}Sr+^{90}Y$	^{147}Pm	^{204}Tl, ^{85}Kr	$^{90}Sr+^{90}Y$
current	I	0.4	0.3	0.1	0.1	0.1	0.1
backscatter	k'_{ba}				0.4	0.3	0.3
bremsst-rahlung	k'_{br}				0.2	0.2	0.2
air density	k_{ad}				0.6	0.6	0.6
absorption	k_{abs}				0.6	0.2	0.3
attenuation	k_{ac}				0.1	0.05	0.05
divergence	k_{di}				0.1	0.1	0.1
sidescatter	k_{pe}				0.1	0.1	0.1
recom-bination	k_{sat}				0.2	0.2	0.2
decay	k_{de}				0.02	0.01	0.01
Corrected ionization current	I_c	0.4	0.3	0.1	1	0.8	0.8

b) Absorbed –Dose Rate to Water at a Depth of 7 mg/cm^2

		Percent Uncertainty					
		Type A			Type B		
Parameter	Symbol	^{147}Pm	^{204}Tl, ^{85}Kr	$^{90}Sr+^{90}Y$	^{147}Pm	^{204}Tl, ^{85}Kr	$^{90}Sr+^{90}Y$

slope	$(\Delta I_c/\Delta d)_{d\to 0}$	0.4	0.3	0.1	1	0.8	0.8
Air density	ρ_{ao}				0.04	0.04	0.04
area	a				0.1	0.1	0.1
Energy per ion pair	$\overline{W}/e$				0.2	0.2	0.2
Stopping power ratio	$s_{w,air}$				0.7	0.7	0.7
Absorbed dose rate to water at 7 mg/cm^2	$\dot{D}_w$	0.4	0.3	0.1	1.2	1.1	1.1

Table 6. Uncertainty in the Calibration of Beta-Particle Sources and Transfer Ionization Chambers Submitted to NIST

a) Source Calibration

Parameter	Percent Uncertainty					
	Type A			Type B		
	^{147}Pm	^{204}Tl, ^{85}Kr	^{90}Sr+^{90}Y	^{147}Pm	^{204}Tl, ^{85}Kr	^{90}Sr+^{90}Y
Positioning of extrapolation chamber and sources				1	0.2	0.2
Absorbed dose rate to water at 7 mg/cm^2	0.4	0.3	0.1	1.2	1.1	1.1

Overall Uncertainty	^{147}Pm	^{204}Tl, ^{85}Kr	^{90}Sr+^{90}Y
Combined uncertainty	1.6	1.2	1.1
Expanded uncertainty (k=2)	3.2	2.4	2.2

b) Calibration of Transfer-Ionization Chamber

Parameter	Percent Uncertainty					
	Type A			Type B		
	^{147}Pm	^{204}Tl, ^{85}Kr	^{90}Sr+^{90}Y	^{147}Pm	^{204}Tl, ^{85}Kr	^{90}Sr+^{90}Y
Positioning of transfer chamber and sources				1	0.2	0.2

Absorbed dose rate to water at 7 mg/cm^2	0.4	0.3	0.1	1.2	1.1	1.1
Measured ionization current				0.1	0.1	0.1
Source decay correction				0.05	0.05	0.05

Overall Uncertainty	^{147}Pm	^{204}Tl, ^{85}Kr	^{90}Sr+^{90}Y
Combined uncertainty	1.6	1.2	1.1
Expanded uncertainty (k=2)	3.2	2.4	2.2

Table 7. Integration Time Selection Table
Measurement limitations of the data collection system which uses a 12-bit (4096 level) digitization of a ± 5 V signal and a capacitance of 100.22 pF

Integ-ration time,s	Current to produce 1 digital unit of 2.44 mV I, fA	Max I for 6 reads, fA	Time for 19 gap, 2 set measurement min	hours	days	Dose rate µGy/s	Slope fA/m	0.25 mm I, fA	2.5 mm I, fA	Limiting Integration times Mini-mum s	Maxi-mum s
10	24.45	8351.67	92	1.54	0.064	0.005	0.11	0.03	0.28	878	299838
20	12.23	4175.83	168	2.81	0.117	0.01	0.22	0.06	0.56	439	149919
30	8.15	2783.89	244	4.07	0.170	0.02	0.45	0.11	1.11	219	74960
40	6.11	2087.92	320	5.34	0.223	0.05	1.11	0.28	2.79	88	29984
50	4.89	1670.33	396	6.61	0.275	0.1	2.23	0.56	5.57	44	14992
60	4.08	1391.94	472	7.87	0.328	0.2	4.46	1.11	11.14	22	7496
90	2.72	927.96	700	11.67	0.486	0.5	11.14	2.79	27.85	9	2998
120	2.04	695.97	928	15.47	0.645	1	22.28	5.57	55.71	4	1499
180	1.36	463.98	1384	23.07	0.961	2	44.57	11.14	111.4	2	750
240	1.02	347.99	1840	30.67	1.278	5	111.4	27.85	278.5	1	300
300	0.82	278.39	2296	38.27	1.595	10	222.8	55.71	557.1	0	150
360	0.68	231.99	2752	45.87	1.911	20	445.7	111.4	1114	0	75
420	0.58	198.85	3208	53.47	2.228	50	1114	278.5	2785	0	30
480	0.51	173.99	3664	61.07	2.545	100	2228	557.1	5571	0	15
600	0.41	139.19	4576	76.27	3.178	200	4457	1114	11142	0	7
900	0.27	92.80	6856	114.27	4.761	300	6685	1671	16712	0	5
1200	0.20	69.60	9136	152.27	6.345	500	11142	2785	27854	0	3
1800	0.14	46.40	13696	228.27	9.511	1000	22283	5571	55708	0	1

PROTECTION-LEVEL BETA PARTICLE SOURCE & INSTRUMENT CALIBRATIONS

Rules:
1. The integration time must be such that at least 10 digital units of current are measured.
2. The integration time must be such that less than 5 V is accumulated on the capacitor in 6 integration periods.

Table 8. Reference dose rates for the sources available at NIST

Protection level dose rates for:				**1/1/2004**			On 1/1/2004	
BSS.1 Dose rates					Reference values for Dose Rate 7mg/cm^2	Reference Date	Dose Rate 7mg/cm^2	
Isotope	S/N	Distance	Geometry	Halflife, d	µGy/s		µGy/s	mGy/min
90Sr/Y	#36-2mCi	30 cm	filter	10523	1.36	9/3/1999	1.23	0.07
90Sr/Y	#36-50mCi	50 cm	no filter	10523	17.69	9/3/1999	15.9	0.96
90Sr/Y	#36-50mCi	30 cm	no filter	10523	50.18	9/3/1999	45.2	2.71
90Sr/Y	#36-50mCi	11 cm	no filter	10523	366	9/3/1999	329.8	19.79
BSS2 Dose rates								
147Pm	FU 989	20 cm	filter	958.2	3.00	3/5/1998	0.644	0.04
85Kr	5828 BX	30 cm	filter	3915	50.2	3/6/1998	34.45	2.07
90Sr/Y	FU 991	30 cm	filter	10523	10.2	3/9/1998	8.87	0.53
90Sr/Y	FU 991	50 cm	no filter	10523	5.66	3/4/1998	4.92	0.30
90Sr/Y	FU 991	30 cm	no filter	10523	16.0	3/13/1998	13.91	0.83
90Sr/Y	FU 991	20 cm	no filter	10523	35.9	3/18/1998	31.2	1.87
90Sr/Y	FU 991	11 cm	no filter	10523	116.4	3/20/1998	101.3	6.08

Table 9. List of critical equipment

Device	Manufacturer	Model	S/N	NIST #	Location
BSS1	Buchler		36	529252	B003
BSS2	AEA Technology		001	586972	B003
Extrapolation chamber*	PTW		24670		B003
Electrometer[§]	Keithley	642		516889	B003
Thermometer	Digitec	8810		188816	B003
Barometer	Setra	350A	10200	531034	B003
Humidity gauge	General Eastern	400D			B003
External Capacitor	General Radio	1403-0	6421		B003

* Includes motorized chamber air gap setting and cowls to add the window thickness to bring to 7 mg/cm^2 water equivalent thickness
[§]Operated in the external feedback capacitance mode

Figure 1. BSS1 Beta-Calibration Facility. The source support stand is shown at the right, the extrapolation ionization chamber (in its pre-automation condition) at the left, and a beam flattening filter supported by wires in-between, The pictured flattening filter is for the ^{147}Pm source, and is designed for use at the pictured source-to-chamber distance of 20 cm. The source shutter is shown in the open position. The chamber is mounted on a stand that can be moved from side to side across the table, which in turn is mounted on a cart, with wheels running on tracks shown at the bottom.

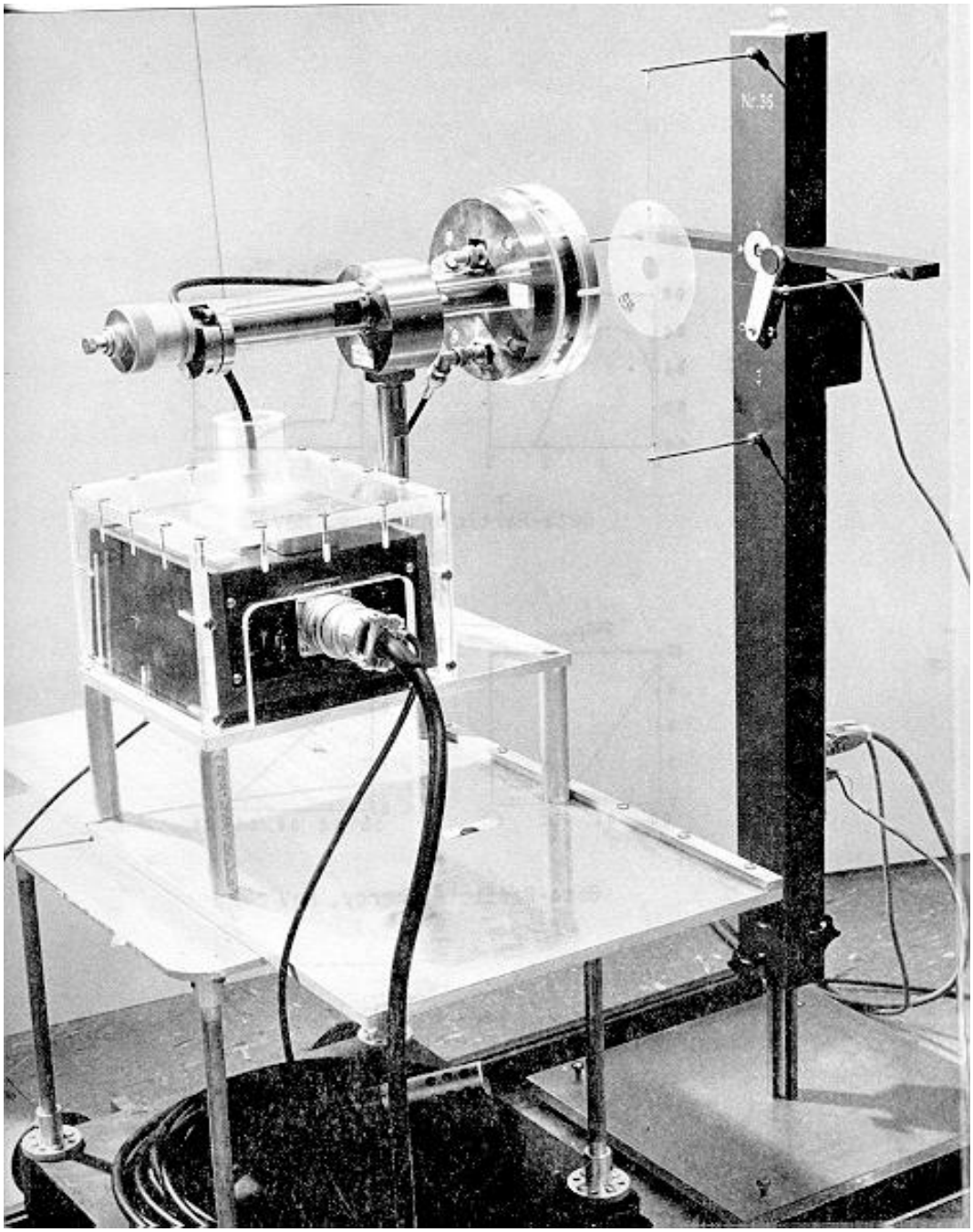

Figure 2. BSS2 with Source Holders. The source holder support stand is shown at the left, and examples of the source holder with its shutter at the right. A flattening filter is shown mounted in the system. The extrapolation is mounted in the same table as shown in Figure 1, and sits on a platform which is attached to the round goniometer stand shown at the bottom. The position of the chamber remains fixed while the source-to-chamber distance is set by sliding the source holder support stand along the attached optical bench.

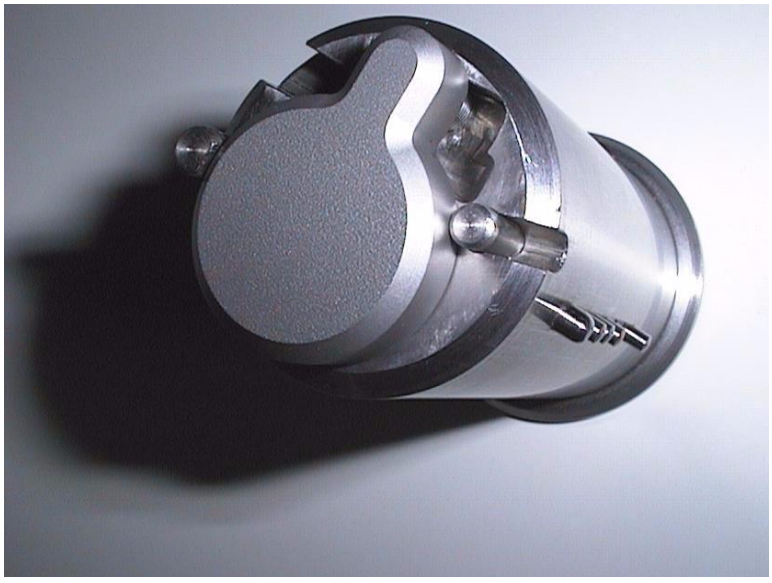

Figure 3. Theoretical Beta-Particle Spectra for the Radionuclides Employed calculated under the LOG-FT approximation. Plotted is the number of beta particles per MeV for one transition from the original state, against beta-particle energy in MeV.

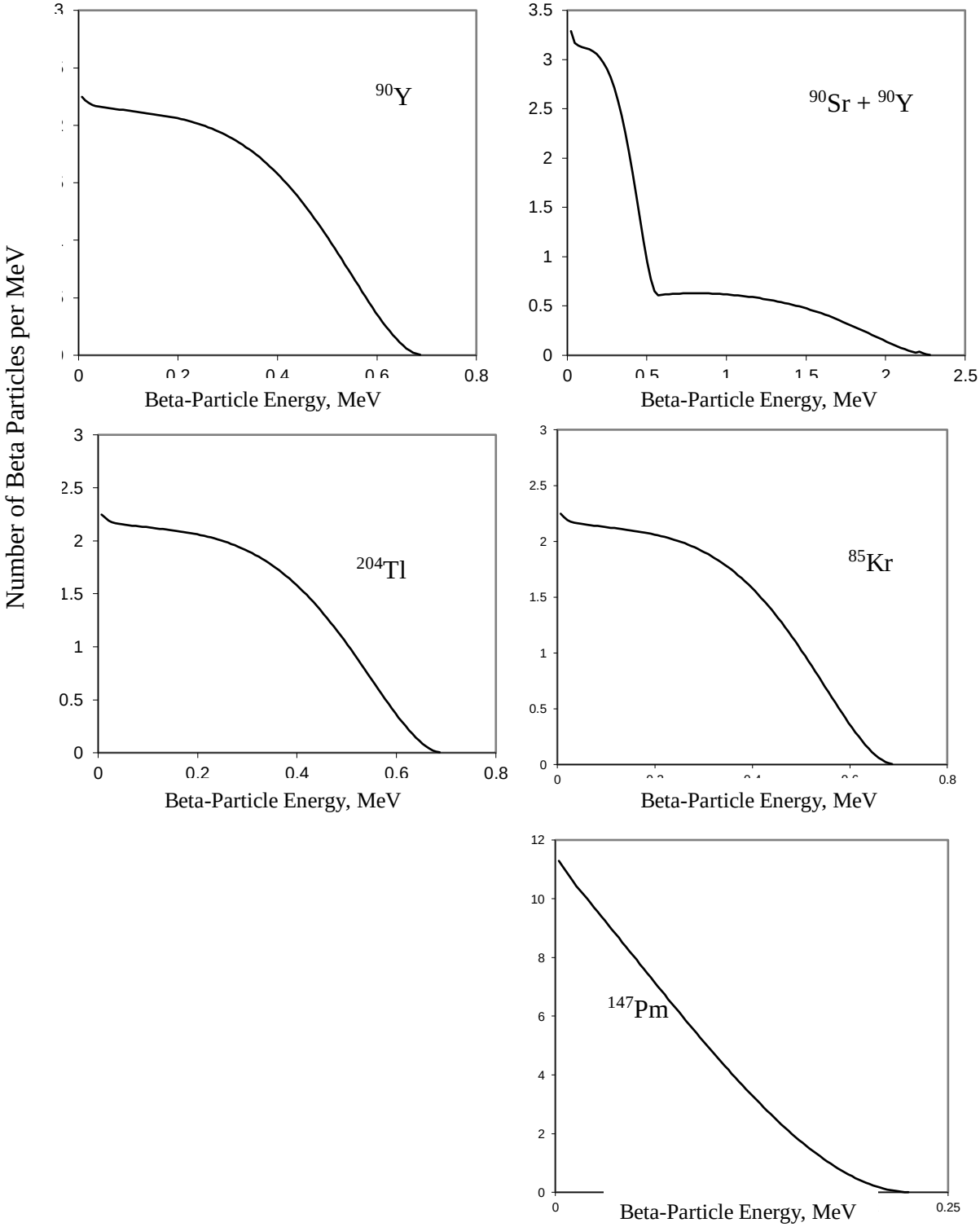

Figure 4. Extrapolation Ionization Chamber: Cross Section through Front Portion (Schematic Representation)

The collecting and guard electrodes (graphite coating on PMMA) are separated by a 0.2-mm wide circular groove (shown of exaggerated size). The distance between the midpoints of the two grooves (distance between the indicated dashed lines) defines the effective diameter of the collecting volume. In this particular instrument, the diameter is 30 mm. The entrance window is a 0.67 mg/cm^2 carbonized PET foil. For the measurements, the plate separation, *d*, (also referred to as air gap or chamber depth) is usually varied between 0.25 mm and 2.5 mm. During any experiment, the voltage gradient across the chamber is kept constant at 10 V/mm.

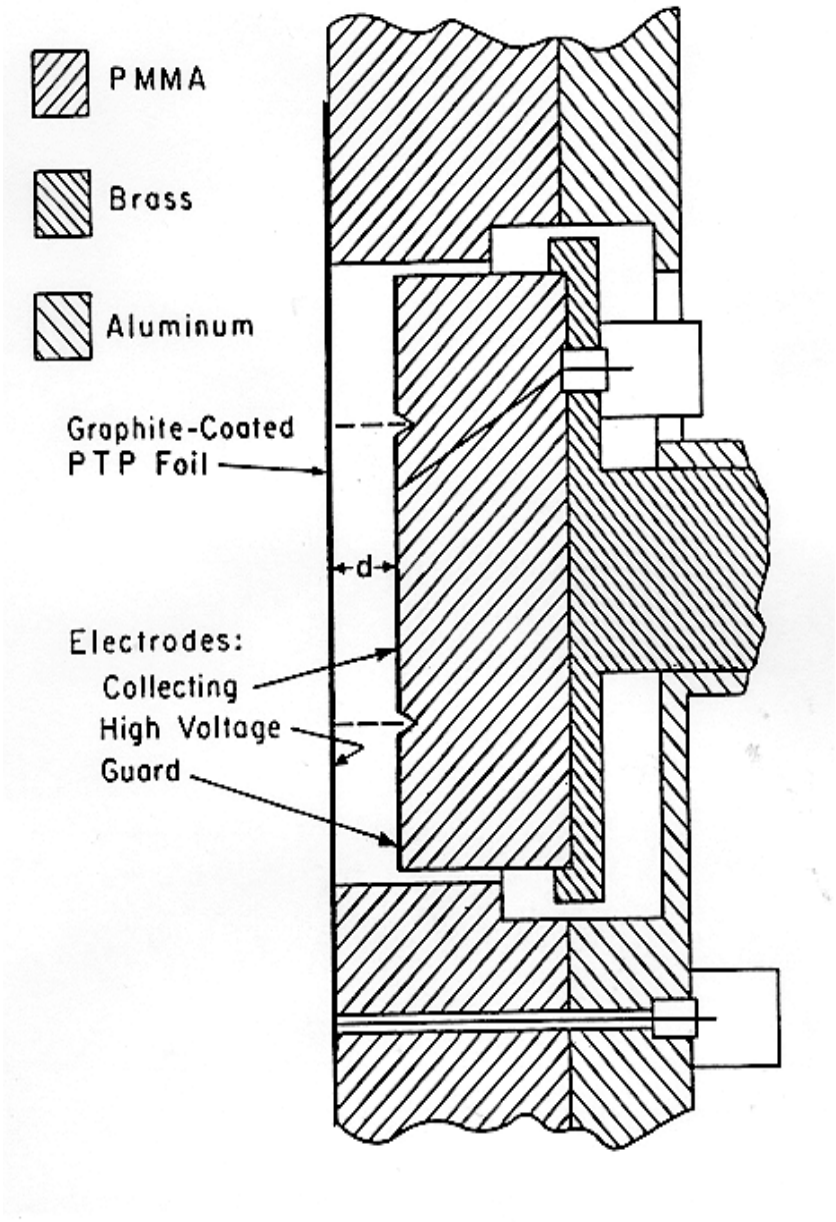
PMMA
Brass
Aluminum
Graphite-Coated
PTP Foil
d
Electrodes:
Collecting
High Voltage
Guard

Figure 5. Current measurements with the extrapolation chamber. Lines represent linear least-squares fits to the data shown.