

# Absorbed Dose to Water for $^{60}\text{Co}$ Using the Pancake Graphite Ionization Chamber

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## Abstract

In Taiwan, the measurement of the output dose rates of medical accelerators is performed by using the ionization chamber that has been calibrated by the  $^{60}\text{Co}$  air kerma standard and the various conversion factors quoted from the AAPM TG-21 protocol (1983). The AAPM published the TG-51 protocol in 1999 which recommended medical ionization chambers to be calibrated in water with the absorbed dose to water standard in  $^{60}\text{Co}$ . This protocol makes it more convenient to measure the absorbed dose rate to water of the accelerator. To meet the domestic demands of calibrating the ionization chamber in terms of the absorbed dose to water, the Institute of Nuclear Energy Research (INER) undertook the establishment of the primary standard of the absorbed dose to water in  $^{60}\text{Co}$  according to the requirements of the AAPM TG-51 in 2000. Since M Boutillon and A-M Perroche employed the pancake ionization chamber as the absorbed dose to water in  $^{60}\text{Co}$  standard of the Bureau International Des Poids Et Mesures (BIPM) in 1992, the design and measurement technology of the standard at INER was constructed referring to the BIPM. After the measurement and evaluation for the volume, parameters and correction factors of INER's pancake chamber, the obtained expanded uncertainty ( $k = 2$ ) of the absorbed dose to water in  $^{60}\text{Co}$  was within 0.6%. At the same time, the comparison difference of INER's absorbed dose to water standard with those of ARPANSA, PTB and NIST was also within 0.8%. Thus, the Pancake chamber of INER has the capabilities to provide the calibration traceability of the absorbed dose to water in Taiwan.

## 1. Introduction

Internationally, the radiation standard dose rate measurement for photon radiation standard is performed by means of the air kerma rate and the absorbed dose to water. For now, the air kerma rate is still the mainstream of radiation standard dose rate measurement. The standard laboratory provides the standard air kerma rate and transfers it downward to applications in medicine, radiation protection and industries by the mechanism of calibration. In recent years, when operating diagnosis and treatment using high energy radiation, the standard dose rate is determined in air. This method takes profound and complicated calculations to obtain the dose rate in human body [1,2]. To improve the situation, it has been discussed to determine the standard dose rate in water. Since water occupies 70% of the weight of the human body, the medical society considers water as the human body when doing radiation dose rate measurement and this will simplify the calculation process and provide clearer clues [3].

The measurement of the absorbed dose to water could be performed with calorimeters, chemical dosimeters and ionization chambers, etc. Ionization chambers have good stability, with easy-to-measure signals, but not suitable for photon measurement above 2 MeV. In 1992, M Boutillon and A-M Perroche used a Pancake ionization chamber as the standard of Bureau International Des Poids Et Mesures (BIPM) for measuring the absorbed dose to water in  $^{60}\text{Co}$  [4]. The National Radiation Standard Laboratory (NRSL) of the Institute of Nuclear Energy Research (INER) in Taiwan referred to their design and techniques to establish the absolute measuring system of the absorbed dose to water.

## 2. Materials and Methods

The ionization chamber used as the primary standard of the absorbed dose to water in  $^{60}\text{Co}$  was built by INER referring to the design of the BIPM. Where it differed from that of the BIPM was that it was made of a whole piece of graphite except the upper lid of the chamber and the support. The central electrode board which was only about 1 mm thick including the thin and long part that extends to the support to touch with the triaxial cable were also made of a whole piece of graphite. That is, the standard ionization chamber, including the cavity and the central electrode board, was all made of graphite. The chamber cavity facing the radiation beam did not have any non-graphite material. That would avoid influence from non-graphite material. When doing the dose rate calculation, it could be taken as a pure graphite ionization chamber. The ionization chamber was made by the contractor and assembled by INER staff. The structure of the chamber is given in Fig. 1, and its basic information is given in Table 1.

According to the research of M Boutillon and A-M Perroche, the formula of measuring the absorbed dose to water with the ionization chamber is applied:

$$D_w = (Q/m) \times (W/e) \times \bar{s}_{c,a} \times K_{cav} \times [(\bar{\mu}_{en}/\rho)_w / (\bar{\mu}_{en}/\rho)_c] \times \Psi_{w,c} \times (1+\varepsilon)_{w,c} \times K_s \times K_{ps} \times K_{pf} \times K_m \times K_h \quad (1)$$

Where

$Q$  is the charge collected in the mass  $m$  of air in the cavity,

$W$  is the mean energy spent by the electrons to produce an ion pair in dry air,

$e$  is the electronic charge,

$\bar{s}_{c,a}$  is the ratio of the mean stopping powers of graphite and air averaged over the secondary electron spectrum,

$K_{cav}$  is the correction factor for the inadequacy of the chamber with the ideal Bragg-Gray cavity,

$\Psi_{w,c}$  is the ratio of the photon energy fluences at the measuring point in water and graphite,

$(\bar{\mu}_{en}/\rho)_w / (\bar{\mu}_{en}/\rho)_c$  is the ratio of the mean mass-energy transfer coefficient averaged over the photon energy spectra at the measuring point in water to that in graphite.

$(1+\varepsilon)_{w,c}$  is the ratio of the absorbed dose to kerma,

$K_s$  is the correction factor for recombination losses,

$K_{ps}$  is the correction factor for the influence of the perspex support on the chamber,

$K_{pf}$  is the correction factor for the front face of the water phantom which is not water-equivalent,

$K_m$  is the correction factor for the non-uniformity of the beam ,

$K_h$  is the correction factor for humidity,

The mass of the air ( $m$ ) can be obtained by multiplying the cavity volume ( $v$ ) with the air density,  $\rho$ .

$$m = v \times \rho \quad (2)$$

The uncertainty evaluation is performed by ISO's "Guide to the Expression of Uncertainty in Measurement" [5]. According to the law of propagation of uncertainty, the combined uncertainty  $u_c(y)$  of the system can be calculated by the following equation:

$$u_c(y) = \sqrt{\sum_{i=1}^n \left( \frac{\partial f}{\partial x_i} \right)^2 u^2(x_i)} \quad (3)$$

Where  $f$  is the function  $f(x_1, x_2, \dots)$  describing the measurement quantity.  $x_i$  and  $u(x_i)$  represent respectively the independent variable related to the measurand and its Type A or Type B standard uncertainty. The symbol  $U(y)$  represent the expanded uncertainty of the measurand  $y$ .

$$U(y) = k u_c(y) \quad (4)$$

In this paper, the coverage coefficient is 2 ( $k = 2$ ) which is at about 95% of the confidence level.

The mathematical model of the absorbed dose to water is as equation (1). According to equations (1) and (3), the expanded uncertainty  $u_{D_W}$  of the absorbed dose to water  $D_W$  is expressed as the relative uncertainty:

$$\frac{u_{D_W}}{D_W} = \sqrt{\left( \frac{u_Q}{Q} \right)^2 + \left( \frac{u_m}{m} \right)^2 + \left( \frac{u_{w/e}}{W/e} \right)^2 + \left( \frac{u_{s_{c,a}}}{s_{c,a}} \right)^2 + \left( \frac{u_{k_{cav}}}{k_{cav}} \right)^2 + \left( \frac{u_{((\mu_{en}/\rho)_w/(\mu_{en}/\rho)_c)}}{((\mu_{en}/\rho)_w/(\mu_{en}/\rho)_c)} \right)^2 + \left( \frac{u_{\Psi_{w,c}}}{\Psi_{w,c}} \right)^2 + \left( \frac{u_{(1+\varepsilon)_{w,c}}}{(1+\varepsilon)_{w,c}} \right)^2 + \left( \frac{u_{k_s}}{k_s} \right)^2 + \left( \frac{u_{k_{ps}}}{k_{ps}} \right)^2 + \left( \frac{u_{k_{pf}}}{k_{pf}} \right)^2 + \left( \frac{u_{k_{rm}}}{k_{rm}} \right)^2 + \left( \frac{u_{k_h}}{k_h} \right)^2} \quad (5)$$

Meanwhile, the determination of measurement parameters, physical constants and correction factors are described as follows.

## 2.1. Measurement parameters

### 2.1.1. Charge measurement, $Q$

The high gain electrometer [6] circuit for measuring charge is shown in Fig. 2.

In Fig. 2,

$$\Delta V_{sig} = I \times \Delta t / C_f \quad (6)$$

Where  $V_{sig}$  is the voltage between both ends of the capacitor,

$I$  is the ionization current,

$\Delta t$  is the measurement time

And  $C_f$  is the capacitance for the measurement.

Thus

$$Q=C_f \times \Delta V_{out} \quad (7)$$

Where  $Q$  is the total ionization charge and  $\Delta V_{out}$  is the voltage change obtained from the electrometer. In terms of the long-term stability of the instrument and calibration reports, the relative uncertainty of the capacitance is 0.007% and the relative uncertainty of the voltage is 0.04%. Thus, the relative uncertainty of the charge  $Q$  is  $\frac{u_Q}{Q} = 0.041\%$ .

### 2.1.2. The air mass in the chamber cavity, $m$

The air mass in the chamber cavity ( $m$ ) is obtained by multiplying the cavity volume of the chamber ( $v$ ) and the density of the dry air under standard conditions  $\rho_{air}$ . The mass in the chamber cavity is  $m_{STP} = v \times \rho_{air}$ . In general situations, the air mass in the cavity  $m = v \times \rho_{air} \times 101.325 / P \times T / 273.15$ .  $T$  is the absolute temperature in °K and  $P$  is the atmosphere in kPa.

To get the cavity volume of the chamber, INER used two different measurement methods: “taking weight by adding water method” and “geometrical measurement calculation method.” Compare the results obtained from both methods, their difference of the cavity volume of the chamber is about 0.1%. Seeing that accuracy problems occur when doing additional work by machine such as non-flat surface, radial non-uniformity, etc. It is easy to cause volume measurement errors by using mathematical geometrical calculations. The “taking weight by adding water” method can make it up for the shortage of the above problem. So, the result from the “taking weight by adding water” method is taken as the cavity volume of the chamber.

When analyzing the cavity volume “ $v$ ,” the relative uncertainty of the cavity volume  $u_v$  is 0.0075%. The air density is  $\rho_{air}$  (quoting the BIPM value), the relative uncertainty  $u_{\rho_{air}} = 0.01\%$ . For the absolute temperature and atmosphere at the time of measurement, judging from the long-term stability of the instrument and calibration reports, the relative uncertainty is 0.013% for temperature and the relative uncertainty is 0.003% for atmosphere. Thus the relative uncertainty of the mass  $m$  in the chamber cavity is  $\frac{u_m}{m} = 0.018\%$ .

## 2.2. Physical constants

The physical parameters for the measurement of the absorbed dose to water include the density of dry air  $\rho_{air}$ , the mean energy spent by the electrons to produce an ion pair in dry air  $W/e$ , the ratio of the mean stopping powers of wall material (graphite, carbon) and air in the chamber cavity,  $\frac{S_{c,a}}{S_{c,a}}$  etc.

### 2.2.1. The density of dry air, $\rho_{air}$

Under standard conditions, the density of dry air ( $\rho_{air}$ ) is 1.29299 kg/m<sup>3</sup> when referring to the BIPM quoted value [7]. Practically, the value of 1.2930 kg/m<sup>3</sup> was adopted and the difference in between was neglected. The uncertainty is included in the calculation of the air mass  $m$ .

### 2.2.2. The mean energy spent by the electrons to produce an ion pair in dry air, $W/e$

For this parameter, the CCRI(I) recommended value is 33.97 J/C (BIPM 1985). In the case of BIPM, the uncertainty should be expressed by the one that multiplying the ratio of the mean

mass-energy stopping power, and the relative uncertainty is 0.11%.

### 2.2.3. The ratio of the mean stopping powers of wall material (graphite, carbon) and air in the chamber cavity, $s_{ca}$

This parameter refers to the ionization chamber used by the BIPM, where the mean path travelled by the electrons in the air of the chamber cavity  $r = 0.42$  cm, the cut of energy is 14 keV, the  $W/e$  of the absorbed dose to water in  $^{60}\text{Co}$  is 1.0030. For the chamber used by INER,  $r = 0.52$  cm, the cut of energy is 17.5 keV, the  $W/e$  of the absorbed dose to water in  $^{60}\text{Co}$  is 1.0025.

## 2.3. Correction factors

### 2.3.1. Perturbation correction factor, $k_p$

In terms of the graphite, the introduction of the chamber cavity causes perturbation; in terms of the water phantom, the introduction of the graphite ionization chamber causes perturbation. The four items  $k_{cav}$ ,  $(\bar{\mu}_{en}/\rho)_w/(\bar{\mu}_{en}/\rho)_c$ ,  $\psi_{w,c}$  and  $(1+\varepsilon)_{w,c}$  in equation (1) are defined as perturbation correction factors,  $k_p$ .

$$k_p = k_{cav} \times [(\bar{\mu}_{en}/\rho)_w/(\bar{\mu}_{en}/\rho)_c] \times \psi_{w,c} \times (1+\varepsilon)_{w,c} \quad (8)$$

#### 2.3.1.1. The correction factor of the real chamber cavity against the Bragg-Gray ideal cavity, $K_{cav}$

In terms of graphite, the perturbation arising from the introduction of the cavity to the graphite includes the change of photon fluences, change of scattering radiation and the change of geometrical conditions. According to Boutillon's research paper [8] published in 1983, the perturbation correction factor  $K_{cav}$  from the introduction of the chamber cavity to the graphite could be obtained by means of its experimental calculation. Deduce INER's chamber conditions to the geometrical conditions of Boutillon's experiment, the  $K_{cav} = 0.9857$ . According to the experience value of BIPM, 0.9900, the calculation of  $K_{cav}$  Type A uncertainty turns out to be 0.03% and Type B uncertainty 0.04%.

#### 2.3.1.2. The ratio of the mean-energy absorption coefficients at the measuring point, $(\bar{\mu}_{en}/\rho)_w/(\bar{\mu}_{en}/\rho)_c$

Boutillon's research paper published in 1992 gave the ratio of the mean-energy absorption coefficients of the photon energy fluences at the measuring point in water and graphite at depth of  $5 \text{ g cm}^{-2}$  as 1.1122. The uncertainty, coming from Hubbell's [9] (1982) figures, was 0.14% by Type B evaluation.

#### 2.3.1.3. The ratio of the photon energy fluences at the measuring point in water and graphite, $\psi_{w,c}$

Boutillon's research paper published in 1992 gave the ratio of the photon energy fluences at the measuring point in water and graphite at depth of  $5 \text{ g cm}^{-2}$  as 1.0065. Its uncertainty is due partly to statistical fluctuations by 0.04%; on the other hand, due partly to the difference caused by quoting different figures when calculating  $\psi_{w,c}$  with  $\mu/\rho$  which turns out to be 0.06% by Type B evaluation.

#### 2.3.1.4. The absorbed dose to kerma factor at the measuring point, $(1+\varepsilon)_{w,c}$

The absorbed dose to kerma factor can be obtained by using the equation given in Boutillon's report in 1983.

$$1+\varepsilon = 1 + \alpha \times m_1 + (2/z) \times m_1 \quad (9)$$

Where  $m_1$  is the mean path travelled by the electrons before reaching the measuring point,  $\alpha$  is the proportionality coefficient that depends on  $\mu/\rho$  and  $R$ (the ratio of the energy fluences of the scattered and unscattered photons),  $z$  is the distance between the point of measurement and the source. The calculation shows that the absorbed dose to kerma factor at the measuring point at  $5 \text{ g cm}^{-2}$  is 1.0015. The uncertainty is 0.06% by Type B evaluation.

#### 2.3.2. Other correction factors

##### 2.3.2.1. Correction factor for recombination losses, $K_s$

The recombination losses are related to the strength of the irradiation field. To make them easily obtained, the method of AAPM TG-51 protocol is adopted by using the dual voltage measurement technique whose equation is as the following:

$$K_s = \frac{1 - (V_H / V_L)^2}{M_{Hav} / M_{Lav} - (V_H / V_L)^2} \quad (10)$$

$V_H$  represents normal operation voltage;  $V_L$  represents the voltage decreases at least by 50%;  $M_{Hav}$  represents the average reading under normal operation voltage;  $M_{Lav}$  represents the average reading under  $V_L$  operation voltage. The value of  $K_s$  is 1.00027. The uncertainty evaluated from experimental data is 0.0021%.

##### 2.3.2.2. Correction factor for the front face of the water phantom, $K_{pf}$

The front face of the water phantom is made of PMMA and is  $0.473 \text{ g}\cdot\text{cm}^{-2}$  in thickness. Referring to the calculations done by Boutillon and others for same purposes, the calculated PMMA thickness is  $0.476 \text{ g}\cdot\text{cm}^{-2}$ , the correction factor is  $K_{pf} = 0.9996$ . The uncertainty is 0.01% by Type B evaluation method.

##### 2.3.2.3. Correction factor for the perspex support of the chamber, $K_{ps}$

The experimental data show that the support effect which is within the statistical fluctuations is negligible ( $K_{ps}= 1$ ). The uncertainty is evaluated by Type B evaluation method. The value comes from the resolution of the electrometer (k-617), 0.0005, the midpoint of the interval is 0.00025. Assume the variation shows a rectangular distribution, the uncertainty obtained is 0.015%.

##### 2.3.2.4. Correction factor for the radial non-uniformity of the beam, $K_{rn}$

Referring to Boutillon's paper published in 1992, the radial non-uniformity correction at  $5 \text{ g cm}^{-2}$  is 1.0051. The uncertainty evaluated by Type B evaluation method is 0.03%.

##### 2.3.2.5. Correction factor for humidity, $K_h$

The dose rate measurement of the chamber is usually performed under general air conditions which means certain degree of humidity existing in the air. The air kerma is defined as

performed in dry air. Thus, it is necessary to correct the influence of humidity factor. The current measured in the general humid air is higher than that in dry air. Quoting the ICRU 31 [10] report of 1979, their correlations are shown as Fig. 8. When evaluated by Type B evaluation method, the value is 0.03%.

The correction factors of each chamber and the physical constants are given in Table 3.

### 3. Results and Discussion

#### 3.1 Comparisons with air kerma standards

To verify the conformity of the results of ionization chamber measurement, the air kerma dose rate was measured with the ionization chamber used in this paper and compared with the current national standard using a spherical chamber at INER. The measurement principles refer to the INER report “Air Kerma Rate Measurement Using the Spherical Graphite Air Ionization Chamber” [11]. The air kerma parameters for the measurement of the Pancake ionization chamber are listed in Table 4. The symbols in the table represent respectively  $k_{att}$ , the photon beam attenuation correction factor caused by the wall material;  $k_{sc}$ , the scattered correction factor of the chamber wall;  $k_{cep}$ , the mean origin of electrons correction factor;  $k_{ste}$ , the correction factor to the support effect;  $W/e$ , the mean energy spent by the electrons to produce an ion pair in dry air;  $g$ , the fraction of the bremsstrahlung radiation produced by secondary electron;  $(\mu_{en}/\rho)_{a,c}$ , the ratio of the mean energy absorption coefficient of air and wall material;  $k_h$ , air humidity correction factor,  $s_{ca}$ , the ratio of the mean stopping powers of wall material (graphite and carbon) and air,  $K_{an}$ , correction factor for the axial non-uniformity of the beam;  $K_m$ , correction factor for the radial non-uniformity of the beam.

The comparison results of the measurement of the Pancake ionization chamber in  $^{60}\text{Co}$  and the current national standard are given in Table 5. The table shows that the measurement results of the air kerma in  $^{60}\text{Co}$  by use of the Pancake chamber and the spherical chamber were in agreement.

#### 3.2. Measurement of the absorbed dose to water in $^{60}\text{Co}$

The  $^{60}\text{Co}$  irradiator is a Theratron Type 780C medical irradiator produced by Theratronics / Canada. The source is 2 cm in diameter, Type C-146, Serial No. S-4672. Its source strength on October 29, 1993 was 288.0 TBq. The employed water phantom is a 30 cm  $\times$  30 cm  $\times$  30 cm cube with a surface made of PMMA. The beam direction is from the top to the bottom and the side facing the beam is 4.00 mm in thickness which is about 4.728 of water depth. The average thickness of the other five sides are about 20 mm. When measuring the absorbed dose to water in  $^{60}\text{Co}$ , the ionization chamber is placed inside a water-proof sleeve at depth of 5 g/cm<sup>2</sup> in the water phantom. The water-proof sleeve used in the experiment should be made of PMMA and less than 1 mm thick. Measurements have been performed from April to June 2003 using equation (6) and the physical constants and correction factors given in Table 3. The results are listed in Table 6.

#### 3.3. International comparison for absorbed dose to water in $^{60}\text{Co}$

To verify the uniformity of the laboratory standard and the international standard, a transfer chamber was used to compare with PTB/Germany, NIST/USA and ARPANSA/Australia. The transfer chamber used in this comparison was an NE2571 (SN:3024) chamber which was 0.6 cm<sup>3</sup> in volume and had been calibrated by PTB, NIST and ARPANSA.

The comparison is expressed with the calibration factor. Its definition is as equation (11).

$$CF = \frac{D_w}{M \times \frac{101.325}{P} \times \frac{273.15 + T}{273.15 + 22}} \quad (11)$$

$CF$  = calibration factor (Gy/C)

$D_w$  = absorbed dose to water standard of  $^{60}\text{Co}$ (Gy)

$M$  = the reading of the calibrated ionization chamber (C)

$P$  = room pressure of the calibration (kPa)

$T$  = room temperature of the calibration ( $^{\circ}\text{C}$ )

The comparison results are listed in Table 7. The table shows that the absorbed dose to water in  $^{60}\text{Co}$  standard established by INER using the pancake chamber were in agreement with the measurement standards of other national metrology institutes (NMIs).

Through the above discussion, the Pancake ionization chamber constructed by INER has been defined for its measurement parameters and determined for its physical constants and correction factors. Thus, the absolute measurement of the absorbed dose to water can be performed. According to the ISO GUM analysis method, the expanded uncertainty is 0.54% ( $k = 2$ ). When comparing the calibration factors of the transfer chamber with those of other NMIs, the difference is between 0.17%–0.75%. In sum, this measurement system has the capabilities to provide the calibration traceability of absorbed dose to water in Taiwan.

#### 4. References

- [1] **AAPM TG-21**, *A protocol for the determination of absorbed dose from high-energy photon and electron beams*, Med. Phys. **10**, 741-771 (1983).
- [2] **IAEA**, *Absorbed dose determination in photon and electron beams and international code of practice*, Technical Reports Series No. 277 (1987).
- [3] **Almond, P.R. et al**, *AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams*, Med. Phys. **26**, 1847-1870 (1999).
- [4] **Boutillon, M. and Perroche, A-M**, *Ionometric determination of absorbed dose to water for cobalt-60 gamma rays*, Phys. Med. Biol. **38**, 439-454 (1993).
- [5] **International Organization for Standardization**, *Guide to the expression of uncertainty in measurement*, ISO/TAG 4/WG3 (1992).
- [6] **Lamperti, P. J. et al**, *Calibration of X- and gamma-ray measuring instruments at NBS* (1987).
- [7] **Boutillon, M.**, *Measuring conditions used for the calibration of ionization chambers at BIPM*, Report BIPM-01/04 (2001).
- [8] **Boutillon, M.**, *Perturbation correction for the ionometric determination of absorbed dose in a graphite phantom for  $^{60}\text{Co}$  gamma rays*, Phys. Med. Biol. **28**, 375-88 (1983).
- [9] **Hubbell, J.H.**, *Photon mass attenuation and energy-absorption coefficients from 1 keV to 20*

*keV*, Int. J. Appl. Rad. Iso. **33** (1982).

[10] **International Commission on Radiation Units and Measurements**, ICRU-31, Washington DC. (1979).

[11] **Su, S.H. et al**, *Air kerma rate measurement for  $^{137}\text{Cs}$  and  $^{60}\text{Co}$  using the spherical graphite air ionization chamber*, Institute of Nuclear Energy Research Technical Reports Series INER-2347 (2003).

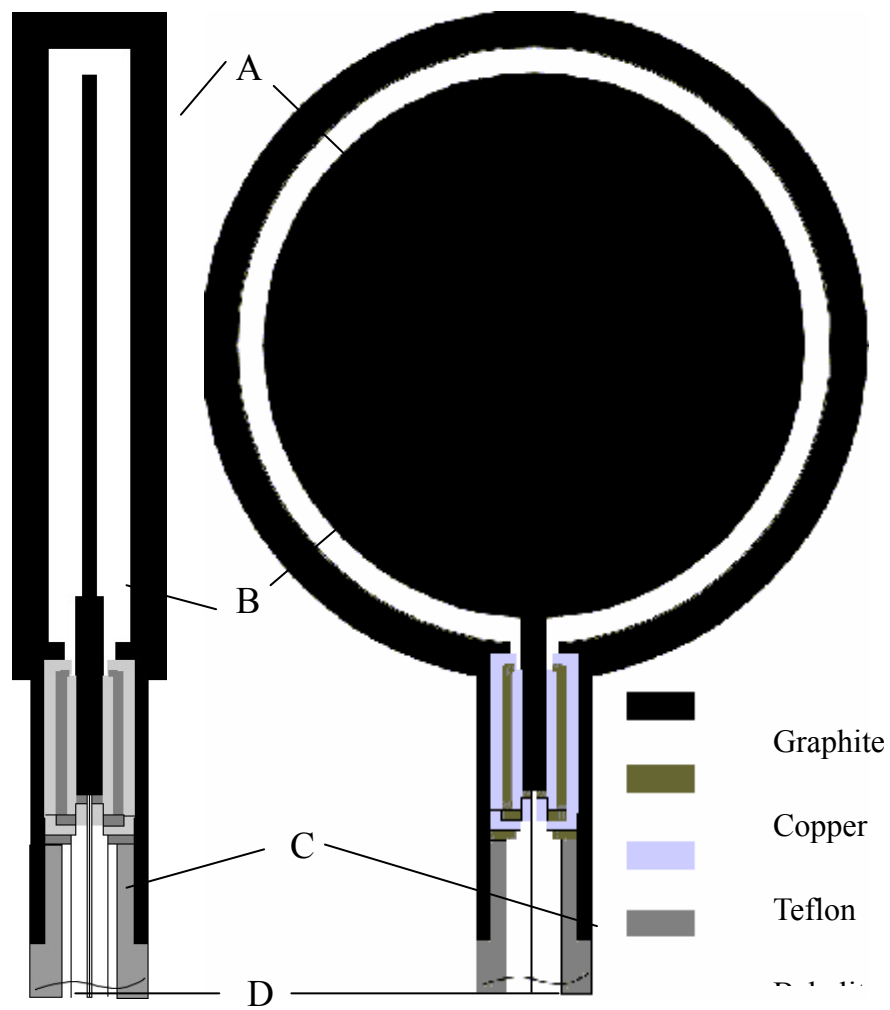


Fig. 1. Structure of the pancake ionization chamber:

- A. The chamber cavity.
- B. Central electrode board.
- C. Central conducting wire.
- D. Support of the chamber

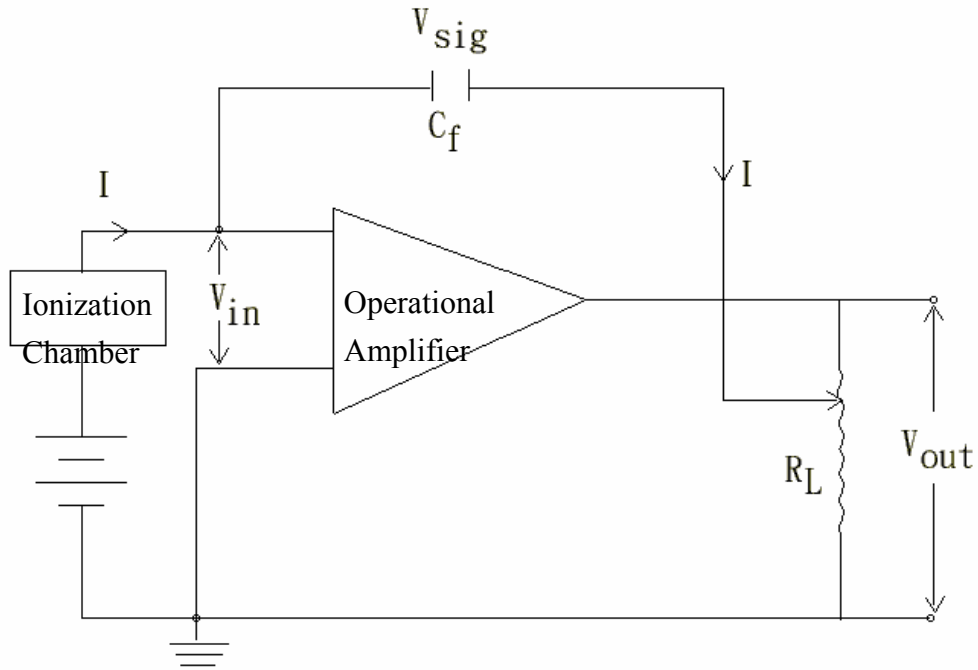


Fig. 2. The capacitor is used as the feedback element of the electrometer.

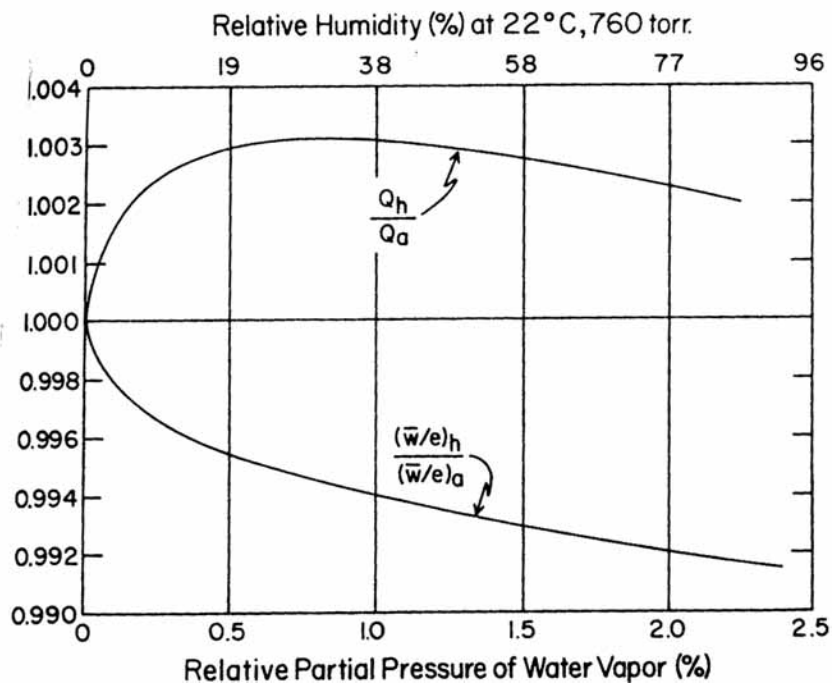


Fig. 3. The ratio relationships between the measurement value ( $Q_h$ ) under different humidity and that ( $Q_a$ ) under dry air. The lower curve indicates the ratio relationships of  $w/e$  value under different humidity and dry air.

Table 1. Basic information of the NRSL/INER pancake ionization chambers

Ionization chamber		PC3	PC4
Volume	cm <sup>3</sup>	8.4083	8.5679
Outer diameter	cm	5.005	5.005
Inner diameter	cm	4.502	4.502
Height (outer)	cm	1.140	1.140
Height(inner)	cm	0.6182	0.6182
Wall thickness(end)	cm	0.258	0.258
Wall thickness(upper lid)	cm	0.265	0.265
Electrode thickness	cm	0.1036	0.1036
Electrode diameter	cm	4.103	4.103
Density of graphite	g/cm <sup>3</sup>	1.767	1.767

Table 2. Measuring the effective cavity volume (cm<sup>3</sup>)  
by the taking weight by adding water method

Chamber no.	Cavity volume (cm <sup>3</sup> )	Effective volume of the electrode in the cavity (cm <sup>3</sup> )	Effective cavity volume (cm <sup>3</sup> )
PC3	9.7809	1.3726	8.4083
PC4	9.9273	1.3594	8.5679

Table 3. Measurement of the absorbed dose to water, various correction factors to the pancake ionization chambers and physical constants.

Ionization chamber Parameter	PC3	PC4	Uncertainty	
			Type A	Type B
<b>Mass of cavity (<math>m = v \times \rho_{\text{air}} \times 101.325 / P \times T / 273.15</math>)</b>				
$v$ (cm <sup>3</sup> )	8.4083	8.5679	0.008	---
$\rho_{\text{air}}$ (STP)	1.293	1.293	---	0.01
P	*	*	---	---
T	*	*	---	---
<b>Charge (<math>Q = C_f \times \Delta V_{\text{out}}</math>)</b>				
$\Delta V_{\text{out}}$	*	*	0.04	0.0031
$C_f$	$9.9175 \times 10^{-7}$	$9.9175 \times 10^{-7}$	---	0.007
<b>Physical constants</b>				
W/e (J C <sup>-1</sup> )	33.97	33.97	---	0.11
(S / $\rho$ ) <sub>c,a</sub>	1.0025	1.0025	---	0.11
<b>Perturbation correction factors <math>k_p</math></b>				
$K_{\text{cav}}$	0.9900	0.9900	0.03	0.04
$(\bar{\mu}_{\text{en}} / \rho)_w / (\bar{\mu}_{\text{en}} / \rho)_c$	1.1125	1.1125	0.01	0.14
$\psi_{w,c}$	1.0065	1.0065	0.04	0.06
$(1 + \varepsilon)_{w,c}$	1.0015	1.0015	---	0.06
<b>Other correction factors</b>				
$K_{\text{pf}}$	0.9996	0.9996	---	0.01
$K_{\text{ps}}$	1	1	---	0.15
$K_s$	1.00027	1.00027	---	0.0021
$K_{\text{rn}}$	1.0051	1.0051	0.01	0.03
$K_h$	0.997	0.997	---	0.03
Quadratic sum			0.066	0.255
Combined uncertainty			0.27	

Note: \* means the value depends on the figures of the measurement.

Table 4. Physical constants and correction factors of the air kerma measurement using pancake ionization chambers

Ionization chamber	PC3	PC4
Effective cavity volume (cm <sup>3</sup> )	8.4083	8.5679
<b>Physical constants</b>		
W/e (J C <sup>-1</sup> )	33.97	33.97
$\rho_{\text{air}}$ (kg m <sup>-3</sup> ) at 273.15 K, 101.325 kPa	1.293	1.293
(S / $\rho$ ) <sub>c,a</sub>	1.0005	1.0005
( $\mu_{\text{en}} / \rho$ ) <sub>a,c</sub>	0.9985	0.9985
g	0.0032	0.0032
<b>Correction factors</b>		
K <sub>at</sub>	1.0360	1.0358
K <sub>sc</sub>	0.971	0.971
K <sub>cep</sub>	0.9925	0.9925
K <sub>ste</sub>	1	1
K <sub>sa</sub>	---	---
K <sub>an</sub>	0.9963	0.9963
K <sub>rn</sub>	1.0016	1.0016
K <sub>h</sub>	0.997	0.997

Table 5. The comparison results of the measurement of the pancake ionization chamber for <sup>60</sup>Co and the current national standard

Reference date: January 1, 2003

	Irradiation field at 1 m distance (Gy / s)	This research/ Current national standard
Current national standard	6.2436×10 <sup>-3</sup>	---
This research	PC3	1.0038
	PC4	1.0008

Table 6. The measurement results of the absorbed dose to water for  $^{60}\text{Co}$  with pancake ionization chambers

Ionization chamber	Related parameters
Source	$^{60}\text{Co}$ , 288.0 TBq (Oct. 29, 1993)
Reference date	2003/1/1
Measurement date	2003/4/22-2003/6/25
Distance	100 cm
Depth	5 g cm <sup>-2</sup>
Measurement results	the absorbed dose to water: $6.3269 \times 10^{-3}$ Gy s <sup>-1</sup>
Combined uncertainty	0.27 %

Table 7. The comparison of the calibration factors of the absorbed dose to water for  $^{60}\text{Co}$  with other NMIs

NMIs	Type of ionization chamber	Serial number of ionization chamber	$N_{D,w}$ (Gy/C) At 22 °C and 101.325 kPa	Calibration date	INER / NMIs
INER	2571	3024	$4.5494 \times 10^7$	2003/05	---
NIST	2571	3024	$4.5419 \times 10^7$	2001/09	1.0017
ARPANSA	2571	3024	$4.5418 \times 10^7$	1999/11	1.0017
PTB	2571	3024	$4.5156 \times 10^7$	2000/06	1.0075

## Discussion

*Tony Aalbers* – Why did you use the pancake ionization chamber?

*Shi-Hwa Su* – That made it easier to measure the absorbed dose to water with the pancake ionization chamber.

*Hugo Palmans* – Did you employ the Monte Carlo calculation method to verify the parameters measurement of the ionization chamber?

*Shi-Hwa Su* – No. But it will be done at the next stage.

*Shi-hwa Su* – Why was the measurement uncertainty of INER smaller than that of BIPM ?

*David Webb* – The chamber volume of BIPM was measured indirectly, so the uncertainty was larger. The chamber volume of INER was measured directly, and that is why the uncertainty was smaller.