EURAMET Project 1389 SC

Bilateral Comparisons of Air Kerma and Absorbed Dose to Water standards in ^{60}Co radiation beams for radiotherapy and Air Kerma standards in ^{137}Cs radiation beams for radiation protection between BEV (Austria) and VINS (Serbia)

KCDB-Identifiers:
EURAMET.RI(I)-K1.2 / EURAMET.RI(I)-K4.2 / EURAMET.RI(I)-K5.1

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Contents

Abstract

A bilateral comparison of standards for absorbed dose to water and air kerma of the Bundesamt für Eich- und Vermessungswesen (BEV), Austria, and of the Vinca Institute of Nuclear Sciences (VINS), Serbia, has been carried out. It was performed for air kerma and for absorbed dose to water in ^{60}Co radiation beams and for air kerma in ^{137}Cs radiation beams.

Transfer standards for air kerma and absorbed dose to water were exchanged by the participants. The participants determined the calibration coefficients of the transfer standards through comparison with their national standards in their respective ^{60}Co and ^{137}Cs beams.

The ratios of the calibration coefficients for the BEV and VINS transfer standards were calculated. The results were 0.9990 for absorbed dose to water in a ^{60}Co beam at therapy level, 1.0004 for air kerma in a ^{60}Co beam at therapy level, and 0.9926 for air kerma in a ^{137}Cs beam at radiation protection level.

A connection to the key comparison data base (KCDB) is given as the results are linked to the key comparisons between the BEV and the Bureau International des Poids et Mesures (BIPM) in 2009. Detailed uncertainty budgets and graphical presentations are also included.

The project has been registered in the BIPM key Comparison Data Base (KCDB) as three different comparisons:

- EURAMET.RI(I)-K1.2: Air Kerma measured in ^{60}Co radiation beams
- EURAMET.RI(I)-K4.2: Absorbed Dose to Water measured in ^{60}Co radiation beams
- EURAMET.RI(I)-K5.1: Air Kerma measured in ^{137}Cs radiation beams

1 Introduction

The bilateral comparison between BEV (Austria) and VINS (Serbia) contained Air Kerma and for Absorbed Dose to Water, both quantities measured in ^{60}Co radiation beams and Air Kerma, measured in ^{137}Cs radiation beams. The comparison's aim was basically supporting VINS-VINCA planned calibration and measurement capabilities (CMCs) of the quantities mentioned above in the context of the CIPM - Mutual Recognition Arrangement (CIPM-MRA).

The comparison was a follow-up of a review process done by the PTB in 2014 [1].

In order to do so, transfer standards for Air Kerma and Absorbed Dose to Water were circulated among the participants. The circulating items were four ionization chambers and one dedicated electrometer.

The participants determined the calibration coefficients of the transfer standards $N_{K\mathrm{air}}$ and $N_{D\mathrm{w}}$ through comparison with their national standards in their respective ^{60}Co and ^{137}Cs beams. The calibration coefficients were corrected to reference conditions as well as for leak current and saturation. No correction for polarity effects had to be applied as the ionisation chambers were measured with a unique electrometer configuration for the polarity and the voltage level.

Detailed uncertainty budgets for the calibration coefficient determinations are given by the participants. All applied corrections to the calibration coefficient calculation are documented in written form.

The measurements are linked with the ongoing BIPM.RI(I)-K1, BIPM.RI(I)-K4 and BIPM.RI(I)-K5 comparisons through BEV [2], [3], [4].

2 Description of the scheme and time schedule

The measurement equipment was checked by BEV. Then the 1st calibration at BEV was done. The next step was the calibration at VINS-VINCA. Finally again a 2nd calibration was done at BEV including a final check of the equipment.

The official start of the project was the registration at EURAMET in March 2016. The calibration time schedule is given in Table 1.

	Participant	Measurement duration at laboratory
1	BEV	July / August /September 2016
2	VINS	October / November 2016
3	BEV	December 2016 / January 2017

Table 1 Calibration time schedule

3 Description of the measurement equipment

The circulating electrometer is a PTW UNIDOS 10002, SN 20478. The belonging ionization chambers are also from PTW.

The ionization chambers for Co-60 therapy level are not watertight. Therefore the use of a protecting PMMA-sleeve was necessary. The chambers are cylindrical (Farmer-type). Their technical data are given in Table 2. Each of these ionization chambers has its own build-up cap for the calibration in terms of Air Kerma and its own water protecting PMMA-sleeve for calibration in the water phantom in terms of Absorbed Dose to Water. Every sleeve is marked with the direction to the focus and with the position of the chamber centre.

Type, serial number	Nominal volume	Collecting Voltage	Wall material	Waterproof	Outer Diameter build-up-cap	Outer Diameter PMMA-sleeve 4322/U13
PTW T30012, SN 0026	0,6 cm^3	+400 V	Graphite	No	16,46 mm	9,26 mm
PTW T30012, SN 0027	0,6 cm^3	+400 V	Graphite	No	16,46 mm	9,26 mm

Table 2 Technical data of the cylindrical ionization chambers for Co-60 therapy level

The ionization chambers for Cs-137 radiation protection level are spherical. Their technical data are given in Table 3.

Type, serial number	Nominal volume	Collecting Voltage	Wall material	Outer Diameter
PTW 32005 30 cm^3 (TK-30), SN 000136	27,9 cm^3	+400 V	POM $(CH_2O)_N$	44,4 mm
PTW 32002 1 l, SN 000592	1000 cm^3	+400 V	POM $(CH_2O)_N$	140 mm

Table 3 Technical data of the ionization chambers for Cs-137 radiation protection level

Descriptions and technical data of the electrometer and the ionization chambers were taken from the manuals as given in [5], [6] and [7].

4 Description of the used calibration method, measurement conditions and calibration points

4.1 Object of the comparison

The calibration of two ionization chambers against the national standards of Air Kerma and of Absorbed Dose to Water in ^{60}Co beams (therapy level) and two ionization chambers against the national standards of Air Kerma in ^{137}Cs beams (radiation protection level) was carried out.

The ionisation chambers were used sequentially, each with the also circulating electrometer. The chambers were placed free in air for the Air Kerma measurements at the reference distance in the ^{60}Co and ^{137}Cs beams respectively. In the case of Absorbed Dose to Water measurements, the chambers were placed in water at the depth of 5 g/cm^2 at the reference distance in the ^{60}Co beams. The conventional true values of Air Kerma and Absorbed Dose to Water rates were established by the corresponding national standards. The calibration coefficients are calculated from the equations:

$$N_{K_\mathrm{a}} = \frac{\dot{K}_\mathrm{a}}{I_\mathrm{corr}} \quad (1)$$

$$N_{D_\mathrm{w}} = \frac{\dot{D}_\mathrm{w}}{I_\mathrm{corr}} \quad (2)$$

Meaning of the symbols:

N_{K_a} .... calibration coefficient for Air Kerma

$\dot{K}_\mathrm{a}$ .... reference Air Kerma rate

N_{D_w} .... calibration coefficient for Absorbed Dose to Water

$\dot{D}_\mathrm{w}$ .... reference Absorbed Dose to Water rate

I_corr .... measured ionisation current corrected to reference conditions as well as for leak current and saturation (recombination loss)

The circulating electrometer and the belonging ionization chambers were handled according to the manuals as given in [5], [6] and [7].

That means

- a sufficient time between switching on and the starting of the measurements
- a minimum 10 Gy pre-irradiation period for the therapy level ionization chambers.
- zero setting before measurements

According to the manual a pre-irradiation of the radiation protection level ionization chambers was not necessary. Nevertheless 10 min pre-irradiations were done.

4.2 Reference conditions

The chambers were basically placed in the usual reference configuration in the beams where the conventional true values of Air Kerma and Absorbed Dose to Water rates are established.

The calibration coefficients of the ionisation chambers N_{K_a} and N_{D_w} are given in terms of Air Kerma and Absorbed Dose to Water per unit charge in the units of Gy/C referring to reference conditions of air pressure, air or water temperature and relative humidity. These are:

$$p_0 = 101{,}325 \text{ hPa} \quad (3)$$

$$\text{T}_0 = 293{,}15 \text{ K} \quad (4)$$

$$\text{h}_0 = 50 \text{ \% rh} \quad (5)$$

Meaning of the symbols:

p_0 .... air pressure at reference conditions

T_0 .... air or water temperature at reference conditions

h_0 .... relative humidity at reference conditions

In the case of deviating conditions for air or water temperature respectively and air pressure the usual correction was applied:

$$k_{pT} = \frac{p_0}{p} \cdot \frac{T}{T_0} \quad (6)$$

Meaning of the symbols:

k_{pT} .... correction factor to correct the deviation from reference conditions for air or water temperature respectively

p .... real (measured) air pressure

T .... real (measured) air or water temperature

The relative humidity of the environment was between 20 % rh and 80 % rh, therefore no correction has been applied.

All calibrations were performed with positioning the camber centre (half outer diameter) in the reference distance (definition of the calibration reference point).

The calibration coefficients of the chambers were corrected further for saturation effects but not for polarity effects as every laboratory used the same polarity.

The saturation correction was either calculated or determined from adequate measurements according to the procedure normally used in the laboratory.

The chambers were used with the accompanying electrometer PTW UNIDOS 10002, SN 20478 in the already defined configuration for the two chambers (Collecting voltage +400 V, mode "∫ Current dt", Range LOW/MEDIUM (to be selected), integration time 60 s").

The chambers were aligned in the beam with the black line on their stem facing the radiation source and the marking on the build-up cap being on the beam axis, both markings defining together the reference point of the chamber.

Each laboratory used its own temperature, pressure and humidity measurement equipment.

4.3 Recombination correction

The saturation correction factor (recombination corrections) is calculated differently

At BEV the correction factor for losses due to ion recombination is determined following the method of Niatel as described in [8] varying the chamber high voltage and the doserate (distance from the source) in the range of the considered ionization current range. The saturation correction k_s can be expressed as

$$k_s = 1 + k_{init} + k_{vol} \cdot I \qquad (7)$$

Meaning of the symbols:

k_s .... saturation correction factor

k_{init} .... initial recombination

k_{vol} .... volume recombination factor

I .... actual ionization current

The evaluated data are given in Table 4:

Type, serial number	k_{init}	k_{vol}
PTW T30012, SN 0026	0,001 519	$2{,}936\,8 \cdot 10^5$ A^{-1}
PTW T30012, SN 0027	0,000 902	1)
PTW 32005 30 cm^3 (TK-30), SN 000136	0,001 1970	$2{,}066\,1 \cdot 10^6$ A^{-1}
PTW 32002 1 l, SN 000592	0,001 359	$5{,}341\,9 \cdot 10^5$ A^{-1}

1) For this chamber no significant volume recombination was found in the considered ionization current range. Therefore the value was set to 0 A^{-1}. In the considered ionization current range the volume recombination is very small for the 30012 chambers and makes a very small contribution to k_s (for the chamber SN 0026 $k_{vol} \cdot I$ is less than 0,0001).

Table 4 BEV data to calculate saturation correction factor

At VINS the correction factor for losses due to ion recombination is determined with the 2-voltages method which is given in IAEA TRS 398 [9]:

$$k_s = \frac{\left(\frac{U_1}{U_2}\right)^2 - 1}{\left(\frac{U_1}{U_2}\right)^2 - \frac{I_1}{I_2}} \qquad (8)$$

Meaning of the symbols:

U_1 .... standard collecting voltage (U_1 = 400 V)

U_2 .... lower collecting voltage (U_2 = 200 V)

I_1 .... ionization current at U_1

I_2 .... ionization current at U_2

4.4 General calibration procedure

1st step: Determination of the Air Kerma and Absorbed Dose to Water respectively

The national standard S was positioned in the radiation field with its reference point on the beam axis in the specified focus-detector-distance (*FDD*). The Air Kerma rate and the Absorbed Dose to Water rate respectively was determined by the standard S.

$$\dot{K}_{\mathrm{a}} = I_{\mathrm{corr,S}} \cdot N_{K_{\mathrm{a}},\mathrm{S}} \text{ respectively } \dot{D}_{\mathrm{w}} = I_{\mathrm{corr,S}} \cdot N_{D_{\mathrm{w}},\mathrm{S}} \quad (9)$$

Meaning of the symbols:

$I_{\mathrm{corr,S}}$ ....Ionization current of national standard S (corrected to reference conditions)

$N_{K_{\mathrm{a}},\mathrm{S}}$, $N_{D_{\mathrm{w}},\mathrm{S}}$ ....Calibration coefficients of national standard S (Gy/C)

2nd step: Calibration of the transfer standard

The national standard was replaced by the transfer standard T with its reference point on the beam axis in the specified *FDD*.

The calibration coefficient of the transfer standard T in Gy/C wass calculated with:

$$N_{K_{\mathrm{a}},\mathrm{T}} = \frac{\dot{K}_{\mathrm{a}}}{I_{\mathrm{corr,T}}} \text{ respectively } N_{D_{\mathrm{w}},\mathrm{T}} = \frac{\dot{D}_{\mathrm{w}}}{I_{\mathrm{corr,T}}} \quad (10)$$

Meaning of the symbols:

$N_{K_{\mathrm{a}},\mathrm{T}}$, $N_{D_{\mathrm{w}},\mathrm{T}}$ ....Calibration coefficient transfer standard T (Gy/C)

4.4.1 Calibration procedure Co-60 therapy level Air Kerma

The chambers were placed in the usual reference configuration in the ^{60}Co beams where the conventional true values of Air Kerma rates are established.

Following the BIPM reference conditions [10] the focus-detector-distance (*FDD*), i.e. the distance between the chamber reference point and the focus point of the ^{60}Co source, was 100 cm along the central beam axis. A 10 cm x 10 cm beam cross section at the reference plane perpendicular to the beam axis and specified by the photon fluence rate at the mid-point of each side of the square being 50 % of the photon fluence rate at the centre was used. For the determination of $N_{K_{\mathrm{a}}}$ the chamber was placed free in air.

4.4.2 Calibration procedure Co-60 therapy level Absorbed Dose to Water

The chambers are placed in the usual reference configuration in the ^{60}Co beams where the conventional true values of Absorbed Dose to Water rates are established.

According to IAEA TRS 398 [9] the focus-detector-distance (*FDD*), i.e. the distance between the chamber reference point and the focus point of the ^{60}Co source, was 100 cm along the central beam axis. A 10 cm x 10 cm beam cross section at the reference plane perpendicular to the beam axis and specified by the photon fluence rate at the mid-point of each side of the square being 50 % of the photon fluence rate at the centre was used. For the determination of $N_{D_{\mathrm{w}}}$ the reference point of the chamber wass placed at the depth of 5 g/cm^2 in a water phantom (30 cm x 30 cm x 30 cm).

4.4.3 Calibration procedure Cs-137 radiation protection level Air Kerma

The chambers are placed in the ^{137}Cs beams according to according to ISO 4037-3 [11] in a proper the focus-detector-distance (*FDD*), i.e. the distance between the chamber reference point and the focus point of the ^{60}Co source, where the conventional true values of Air Kerma rates are established.

The minimum focus-detector-distance (*FDD*) depends on size of the cross-sectional area of the ionization chamber. Each laboratory was responsible to ensure that the radiation field was large enough for the cross-sectional area of the ionization chamber to be calibrated.

For the determination of N_{K_a} the chamber was placed free in air.

Note:

If secondary electron equilibrium is not ensured, according to ISO 4037-3 [11] a 2 mm PMMA plate has to be positioned in front of the ionization chamber to ensure secondary electron equilibrium.

BEV used the PMMA plate for determination of conventional true value as well as for the calibration of the ionization chamber. VINS did not use a PMMA plate.

Both variations are justified for the used ionization chambers.

Measurements by BEV have shown that there is no difference between calibration procedures with or without the PMMA plate for the ionization chamber PTW 32005 30 cm^3 (TK-30) and the ionization chamber PTW 32002 1 l.

4.4.4 Determination of the conventional true value at BEV

The determination of the reference values of Air Kerma rate respectively Absorbed Dose to Water rate was done with BEV primary standards using the BEV electrometer systems

- for measurements with the Co-60 source (therapy level Air Kerma and Absorbed Dose to Water): 2-channel electrometer system with 2 electrometer Keithley 6517
- for measurements with the Cs-137 sources (radiation protection level Air Kerma): self-made 2-channel electrometer DCI.2CH

Determination of the Air Kerma Co-60 therapy level

The Air Kerma rate for Co-60 is determined with the primary standards CC01-125 and CC01-132. These primary standards are cavity ionization chambers as described in the key comparison report [2]. This report is basis for the CMC-entry of BEV.

Determination of Absorbed Dose to Water Co-60 therapy level

The absorbed dose rate for Co-60 is determined using a graphite calorimeter, which is a primary standard. It is described in [12] and [13]. The determined value of the absorbed dose rate to water was transferred to the cavity ionization chamber CC01-105 which is the basis for the current measurements. The determination of the absorbed dose rate to water is also described in the key comparison report [3]. This report is basis for the CMC-entry of BEV.

Determination of the Air Kerma Cs-137 radiation protection level

The Air Kerma rate for Cs-137 is determined with the primary standards CC01-125 and CC01-132. These primary standards are cavity ionization chambers as described in the key comparison report [4]. This report is basis for the CMC-entry of BEV.

4.4.5 Determination of the conventional true value at VINS

The determination of the reference values of Air Kerma rate and Absorbed Dose to Water rate is done with VINS secondary standards, traceable through IAEA dosimetry laboratory to primary standard of BIPM. Following secondary standards are used:

- for measurements with the Co-60 source (therapy level, Air Kerma and Absorbed Dose to Water): PTW 30012 chamber (farmer type) with PTW Unidos T10002 electrometer
- for measurements with the Cs-137 sources (radiation protection level, Air Kerma): PTW 32002 chamber (spherical litre chamber) with PTW Unidos T10002 electrometer

Determination of the Air Kerma Co-60 therapy level

The Air Kerma rate for Co-60 is determined with the secondary standard PTW 30012 with electrometer PTW Unidos T10002.

Determination of Absorbed Dose to Water Co-60 therapy level

The absorbed dose rate for Co-60 is determined with the secondary standard PTW 30012 with electrometer PTW Unidos T10002.

Determination of the Air Kerma Cs-137 radiation protection level

The Air Kerma rate for Cs-137 is determined with the secondary standard PTW 32002 with electrometer PTW Unidos T10002.

5 Presentation of the results and the uncertainty budget

The comparison of the arithmetic means of each calibration was done by calculation of the ratio of BEV-value and VINS-value.

$$R_{K_a} = \frac{N_{K_a,\text{T,VINS}}}{N_{K_a,\text{T,BEV}}} \text{ respectively } R_{D_w} = \frac{N_{D_w,\text{T,VINS}}}{N_{D_w,\text{T,BEV}}} \quad (11)$$

Meaning of the symbols:

R_{K_a} , R_{D_w} ....ratios of the calibration factor obtained by BEV and VINS

The values of VINS are linked to the KCRVs (key comparison reference values) based on the key comparisons of BEV

- BIPM.RI(I)-K1: Measurement of Air Kerma for Cobalt 60 [2]
- BIPM.RI(I)-K4: Measurement of Absorbed Dose to Water for Cobalt 60 [3]
- BIPM.RI(I)-K5: Measurement of Air Kerma for Cesium 137 [4]

and the relating CMC-entries of BEV.

Each participant delivered detailed uncertainty budgets for the calibration coefficient determinations of the transfer standards in accordance with the ISO Guide to the expression of uncertainties in measurements [14].

The model function for the 1st calibration step is:

$$\dot{K}_a = I_S \cdot N_{K_a,S} \cdot k_{pT} \cdot k_{s,S} \cdot k_{r,S} \text{ respectively } \dot{D}_w = I_S \cdot N_{D_w,S} \cdot k_{pT} \cdot k_{s,S} \cdot k_{r,S} \quad (12)$$

Meaning of the symbols:

I_S............................Uncorrected ionization current national standard S

$k_{s,S}$ ....Recombination correction factor national standard S

$k_{r,S}$ ....Correction factor to correct the deviation between the nominal *FDD* and the real *FDD* by positioning the national standard S

Usually $k_{r,S}$ = 1 is used. The possible deviation is considered by the uncertainty.

The scheme for the uncertainty budget of the 1st step is given in Table 5.

Input quantity	Symbol	$u_{i,A}$	$u_{i,B}$	$u_{i,A}^2 + u_{i,B}^2$
Calibration coefficient of the national standard S	$N_{K_a,S}$, $N_{D_w,S}$ 1)			
Ionization current of the national standard S	I_S			
Air density correction factor	k_{pT}			
Recombination correction factor national standard S	$k_{s,S}$			
Position of the national standard S	$k_{r,S}$			
Determined Air Kerma rate respectively absorbed dose rate to water	$\dot{K}_a$, $\dot{D}_w$	$u_c = \sqrt{\sum_i \left(u_{i,A}^2 + u_{i,B}^2\right)} =$		

1) The calibration coefficient of the BEV primary standards includes all corrections factors which are entering the determination of the Air Kerma respectively Absorbed Dose to Water such as wall attenuation, stem scattering scattering and uniformity. They are described in [2], [3] and [4].

Table 5 Uncertainty calculation for 1st step of the calibration procedure (determination of the Air Kerma rate respectively Absorbed Dose to Water rate)

The proposed model function for the 2nd calibration step is:

$$N_{K_a,T} = \frac{\dot{K}_a}{I_T \cdot k_{pT} \cdot k_{s,T} \cdot k_{r,T}} \text{ respectively } N_{D_w,T} = \frac{\dot{D}_W}{I_T \cdot k_{pT} \cdot k_{s,T} \cdot k_{r,T}} \quad (13)$$

Meaning of the symbols:

I_T............................ Uncorrected ionization current transfer standard T

$k_{s,T}$ .... Recombination correction factor transfer standard T

$k_{r,T}$ .... Correction factor to correct the deviation between the nominal *FDD* and the real *FDD* by positioning the transfer standard T

Usually $k_{r,T}$ = 1 is used. The possible deviation is considered by the uncertainty.

The scheme for the uncertainty budget of the 2nd step is given in Table 6.

Input quantity	Symbol	$u_{i,A}$	$u_{i,B}$	$u_{i,A}^2 + u_{i,B}^2$
Determined Air Kerma rate respectively absorbed dose rate to water	$\dot{K}_a$, $\dot{D}_w$			
Ionization current of the transfer chamber T	I_T			
Air density correction factor	k_{pT}			
Recombination correction factor transfer standard T	$k_{s,T}$			
Position of the transfer standard T	$k_{r,T}$			
Calibration coefficient of the transfer standard T	$N_{K_a,T}$, $N_{D_w,T}$	$u_c = \sqrt{\sum_i \left(u_{i,A}^2 + u_{i,B}^2\right)} =$		
			$U = 2 \cdot u_c =$	

Table 6 Uncertainty calculation for 2nd step of the calibration procedure (calibration coefficient transfer chamber)

The combined standard uncertainty of the ratio of BEV-value and VINS-value is calculated with.

$$u_{c,R_{K_a}} = \sqrt{u_{N_{K_a},T,BEV}^2 + u_{N_{K_a},T,VINS}^2 + u_{Drift}^2} \text{ respectively } u_{c,R_{D_w}} = \sqrt{u_{N_{D_w},T,BEV}^2 + u_{N_{D_w},T,VINS}^2 + u_{Drift}^2} \quad (14)$$

Meaning of the symbols:

$u_{c,R_{K_a}}$, $u_{c,R_{D_w}}$ .... combined standard uncertainty for the calibration coefficient ratio BEV and VINS

$u_{N_{K_a},T,BEV}$, $u_{N_{D_w},T,BEV}$ ... standard uncertainty calibration coefficient BEV

$u_{N_{K_a},T,VINS}$, $u_{N_{D_w},T,VINS}$ .. standard uncertainty calibration coefficient VINS

u_{Drift}........................ standard uncertainty because of a possible Drift of the transfer chambers

The results from BEV before and after the measurements at VINS suggest a drift in response for some transfer chambers. The value u_{Drift} considers this possible drift as a type B uncertainty calculated from the half difference of the two values. The resulting value was for all chambers is less than 0,1 %. Therefore no significant effect on the expanded uncertainty of the ratio VINS/BEV was determined.

6 Results

The results in terms of Degree of Equivalence are given in Table 7. The link to the BIPM is given by the key comparisons reported in [2], [3] and [4]. The Degree of Equivalence D_{ij} between a pair of national measurement standards accompanying expanded uncertainty U_{ij} is defined in these reports.

Dose quantity		Air Kerma K_a		Absorbed Dose to Water D_w		Air Kerma K_a	
Radio nuclide		Co-60		Co-60		Cs-137	
Level		Therapy		Therapy		Radiation protection	
Link to key comparison data		BIPM.RI(I)-K1		BIPM.RI(I)-K4		BIPM.RI(I)-K5	
Laboratory		D_{ij} (mGy/Gy)	U_{ij} (mGy/Gy)	D_{ij} (mGy/Gy)	U_{ij} (mGy/Gy)	D_{ij} (mGy/Gy)	U_{ij} (mGy/Gy)
BEV	BIPM	3,4	4,2	-0,4	8,8	4,1	6,2
VINS	BEV	-1,0	12,8	0,4	15,0	-7,4	25,0
VINS	BIPM	2,4	10,2	0,0	14,3	-3,3	20,2

Table 7 Summary of the results in terms of Degree of Equivalence

More detailed results including the uncertainty budgets are given in the appendix (sections 9, 10 and 11)

7 Conclusion

A comparison has been carried out between the BEV (Austria) and VINS (Serbia) of standards for Absorbed Dose to Water and Air Kerma in ^{60}Co gamma rays (therapy level) and Air Kerma in ^{137}Cs gamma rays (radiation protection level), using four ionization chambers as transfer standards (two for therapy level and two for radiation protection level). The comparison results, expressed as a ratios of the calibration coefficients measured by the BEV against their primary standards to those of VINS against their secondary standards, are for Absorbed Dose to Water in ^{60}Co beam 0,999 0 (therapy level), for Air Kerma in ^{60}Co beam 1,000 4 (therapy level) and for Air Kerma in ^{137}Cs beam 0,992 6 (radiation protection level).

A connection to the key comparison data base (KCDB) is given as the results are linked to the key comparisons between BEV and Bureau International des Poids et Mesures (BIPM) in 2009. The resulting ratios between VINS and BIPM are are for Absorbed Dose to Water in ^{60}Co beam 1,002 4 (therapy level), for Air Kerma in ^{60}Co beam 1,000 0 (therapy level) and for Air Kerma in ^{137}Cs beam 0,996 7 (radiation protection level).

These results are showing, that the VINS standards for Absorbed Dose to Water in ^{60}Co beam (therapy level), for Air Kerma in ^{60}Co beam (therapy level) and for Air Kerma in ^{137}Cs beam (radiation protection level) are in satisfactory agreement with the international system of dose measurements.

8 References

[1] Report on the PTB project "Support of the Quality Infrastructure in Serbia" with the title "Fact Finding Mission to Vinča Institute of Nuclear Sciences, Department of Radiation and Environmental Protection, Belgrade: Support to the international recognition of measurement capabilities", 01.-03.12.2014.

[2] Kessler C., Allisy-Roberts P.J., Steurer A., Tiefenboeck W., Gabris F.: "Comparison of the standards for Air Kerma of the BEV and the BIPM for ^{60}Co gamma radiation", Metrologia 47 (2010), Tech.Suppl. p. 06006.

[3] Kessler C., Allisy-Roberts P.J., Steurer A., Baumgartner A., Tiefenboeck W., Gabris F.: "Comparison of the standards for Absorbed Dose to Water of the BEV, Austria, and the BIPM for ^{60}Co gamma radiation", Metrologia 47 (2010), Tech.Suppl. p. 06017.

[4] Kessler C., Allisy-Roberts P.J., Steurer A., Tiefenboeck W., Gabris F., 2010, "Comparison of the standards for Air Kerma of the BEV and the BIPM for ^{137}Cs gamma radiation", BIPM.RI(I)_K5_Report, Paris, 2010-01-14, Metrologia 47 (2010) Tech.Suppl. p.06007

[5] Manual for electrometer PTW UNIDOS 10002 (User Manual UNIDOS, PTW -Universal Dosemeter, Firmware No. 2.20 and higher, for type 10001 (connecting system M), S/N ≥ 10620, for type 10002 (connecting system W=TNC), ≥ S/N 20232, for type 10005 (connecting system N=BNT), ≥ S/N 50070, D196.131.00/14 en 2009-04 Sa/Hn)

[6] Manual for ionization chamber PTW T30012 (User Manual Farmer Chamber, Ionization Chamber Type 30010, 30011, 30012, 30013, D596.131.00/05 en 2016-01 ext/Hn)

[7] Manual for ionization chambers PTW 32005 TK-30 and PTW 32002 1 l (User manual 1 l Spherical chamber Type 32002, 10 l Spherical chamber Type 32003, Spherical chamber TK-30 Type 32005, D466.131.00/04 en, 2009-04 Sa/Hn)

[8] Boutillon M., Volume recombination parameter in ionization chambers, 1998, Phys.Med.Biol., 43, 2061-2072

[9] IAEA, TRS No. 398, Absorbed Dose Determination in External Beam Radiotherapy, IAEA, VIENNA, 2000, ISSN 1011–4289, June 2006 (V.12)

[10] Allisy-Roberts P.J., Burns D.T. and Kessler C., 2007, Measuring conditions used for the calibration of ionization chambers at the BIPM, Rapport BIPM-07/06, 20 pp.

[11] International Organization for Standardization. X and gamma reference radiations and calibrating dosemeters and doserate meters and for determining their response as a function of photon energy - Part 3: calibration of area and personal dosemeters and the measurement of their response as a function of energy and angle of incidence. ISO 4037–3 (Geneva: ISO) (1999).

[12] Witzani J., Duftschmid K.E., Strachotinsky Ch. & Leitner A.: A Graphite Absorbed-Dose Calorimeter in the Quasi-Isothermal Mode of Operation, Metrologia 20, 73-79 (1983), Springer-Verlag

[13] Baumgartner A., Steurer A., Tiefenböck W., Gabris F. Maringer F.J., Kapsch R.P. & Stucki G.: "Re-evaluation of correction factors of a primary standard graphite calorimeter in ^{60}Co gamma ray beams as a basis for the appointment of the BEV absorbed dose rate to water reference value", Radiation Protection Dosimetry (2010), pp. 1-10

[14] BIPM, JCGM 100:2008, Evaluation of measurement data - Guide to the expression of uncertainty in measurement (GUM 1995)

9 Appendix A – Results data

9.1 Air Kerma Co-60 (Therapy level)

Ionization chamber	PTW 30012 (0,6 cm^3)		
	SN 0026		
Electrometer	PTW UNIDOS 10002	Setting data BEV	Range: Low 200 pA Modus: ∫ Current dt Intergration time: 60 s
	SN 20478	Setting data VINS	Range: Low 200 pA Modus: ∫ Current dt Intergration time: 60 s
Radio nuclide	Co-60	Geometric setup BEV	Focus-detector-distance: 100 cm Field size: 10 cm x 10 cm
Dose quantity	Air Kerma K_a	Geometric setup VINS	Focus-detector-distance: 100 cm Field size: 10 cm x 10 cm
	Calibration coefficient N_{K_a}	Measurement Uncertainty (k = 2)	Dose rate $\dot{D}_w$
BEV 1	4,811 8 · 10^7 Gy/C	0,8 %	8,70 mGy/s
VINS	4,802 6 · 10^7 Gy/C	1,0 %	2,18 mGy/s
BEV 2	4,810 5 · 10^7 Gy/C	0,8 %	8,11 mGy/s
BEV (mean)	4,811 1 · 10^7 Gy/C	0,8 %	
	Ratio VINS/BEV $N_{K_a,\mathrm{VINS}} / N_{K_a,\mathrm{BEV}}$		
	0,998 2	1,3 %	
	Ratio BEV/BIPM $N_{K_a,\mathrm{BEV}} / N_{K_a,\mathrm{BIPM}}$ (Key Comparison 2009)		
	1,003 4		
	Resulting Ratio VINS/BIPM $N_{K_a,\mathrm{VINS}} / N_{K_a,\mathrm{BIPM}}$		
	1,001 6		

Table 8 Results Air Kerma Co-60 (therapy level) ionization chamber PTW 30012-0026

Ionization chamber	PTW 30012 (0,6 cm^3)		
	SN 0027		
Electrometer	PTW UNIDOS 10002	Setting data BEV	Range: Low 200 pA Modus: ∫ Current dt Intergration time: 60 s
	SN 20478	Setting data VINS	Range: Low 200 pA Modus: ∫ Current dt Intergration time: 60 s
Radio nuclide	Co-60	Geometric setup BEV	Focus-detector-distance: 100 cm Field size: 10 cm x 10 cm
Dose quantity	Air Kerma K_a	Geometric setup VINS	Focus-detector-distance: 100 cm Field size: 10 cm x 10 cm
	Calibration coefficient N_{K_a}	Measurement Uncertainty (k = 2)	Dose rate $\dot{D}_w$
BEV 1	4,795 6 · 10^7 Gy/C	0,8 %	8,70 mGy/s
VINS	4,786 9 · 10^7 Gy/C	1,0 %	2,18 mGy/s
BEV 2	4,780 8 · 10^7 Gy/C	0,8 %	8,11 mGy/s
BEV (mean)	4,788 2 · 10^7 Gy/C	0,8 %	
	Ratio VINS/BEV $N_{K_a,\mathrm{VINS}} / N_{K_a,\mathrm{BEV}}$		
	0,999 7	1,3 %	
	Ratio BEV/BIPM $N_{K_a,\mathrm{BEV}} / N_{K_a,\mathrm{BIPM}}$ (Key Comparison 2009)		
	1,003 4		
	Resulting Ratio VINS/BIPM $N_{K_a,\mathrm{VINS}} / N_{K_a,\mathrm{BIPM}}$		
	1,003 1		

Table 9 Results Air Kerma Co-60 (therapy level) ionization chamber PTW 30012-0027

9.2 Absorbed Dose to Water Co-60 (Therapy level)

Ionization chamber	PTW 30012 (0,6 cm^3)		
	SN 0026		
Electrometer	PTW UNIDOS 10002	Setting data BEV	Range: Low 200 pA Modus: ∫ Current dt Intergration time: 60 s
	SN 20478	Setting data VINS	Range: Low 200 pA Modus: ∫ Current dt Intergration time: 60 s
Radio nuclide	Co-60	Geometric setup BEV	Focus-detector-distance: 100 cm Field size: 10 cm x 10 cm Water depth: 5 g/cm^2
Dose quantity	Absorbed Dose to Water D_w	Geometric setup VINS	Focus-detector-distance: 100 cm Field size: 10 cm x 10 cm Water depth: 5 g/cm^2
	Calibration coefficient N_{D_w}	Measurement Uncertainty (k = 2)	Dose rate $\dot{D}_w$
BEV 1	5,204 7 · 10^7 Gy/C	0,9 %	8,51 mGy/s
VINS	5,209 2 · 10^7 Gy/C	1,2 %	2,17 mGy/s
BEV 2	5,215 4 · 10^7 Gy/C	0,9 %	8,04 mGy/s
BEV (mean)	5,210 0 · 10^7 Gy/C	0,8 %	
	Ratio VINS/BEV $N_{D_w,\mathrm{VINS}} / N_{D_w,\mathrm{BEV}}$		
	0,999 8	1,5 %	
	Ratio BEV/BIPM $N_{D_w,\mathrm{BEV}} / N_{D_w,\mathrm{BIPM}}$ (Key Comparison 2009)		
	0,999 6		
	Resulting Ratio VINS/BIPM $N_{D_w,\mathrm{VINS}} / N_{D_w,\mathrm{BIPM}}$		
	0,999 4		

Table 10 Results Absorbed Dose to Water Co-60 (therapy level) ionization chamber PTW 30012-0026

Ionization chamber	PTW 30012 (0,6 cm^3)		
	SN 0027		
Electrometer	PTW UNIDOS 10002	Setting data BEV	Range: Low 200 pA Modus: ∫ Current dt Intergration time: 60 s
	SN 20478	Setting data VINS	Range: Low 200 pA Modus: ∫ Current dt Intergration time: 60 s
Radio nuclide	Co-60	Geometric setup BEV	Focus-detector-distance: 100 cm Field size: 10 cm x 10 cm Water depth: 5 g/cm^2
Dose quantity	Absorbed Dose to Water D_w	Geometric setup VINS	Focus-detector-distance: 100 cm Field size: 10 cm x 10 cm Water depth: 5 g/cm^2
	Calibration coefficient N_{D_w}	Measurement Uncertainty (k = 2)	Dose rate $\dot{D}_w$
BEV 1	5,208 1 · 10^7 Gy/C	0,9 %	8,51 mGy/s
VINS	5,206 0 · 10^7 Gy/C	1,2 %	2,17 mGy/s
BEV 2	5,193 9 · 10^7 Gy/C	0,9 %	8,04 mGy/s
BEV (mean)	5,201 0 · 10^7 Gy/C	0,8 %	
	Ratio VINS/BEV $N_{D_w,\mathrm{VINS}} / N_{D_w,\mathrm{BEV}}$		
	1,001 0	1,5 %	
	Ratio BEV/BIPM $N_{D_w,\mathrm{BEV}} / N_{D_w,\mathrm{BIPM}}$ (Key Comparison 2009)		
	0,999 6		
	Resulting Ratio VINS/BIPM $N_{D_w,\mathrm{VINS}} / N_{D_w,\mathrm{BIPM}}$		
	1,000 6		

Table 11 Results Absorbed Dose to Water Co-60 (therapy level) ionization chamber PTW 30012-0027

9.3 Air Kerma Cs-137 (Radiation protection level)

Ionization chamber	PTW 32002 (30 cm^3)		
	SN 000136		
Electrometer	PTW UNIDOS 10002	Setting data BEV	Range: Low 200 pA Modus: ∫ Current dt Intergration time: 60 s
	SN 20478	Setting data VINS	Range: Low 200 pA Modus: ∫ Current dt Intergration time: 60 s
Radio nuclide	Cs-137	Geometric setup BEV	Focus-detector-distance: 100 cm Field size: 26 cm (diameter)
Dose quantity	Air Kerma K_a	Geometric setup VINS	Focus-detector-distance: 200 cm Field size: 43 cm (diameter)
	Calibration coefficient N_{K_a}	Measurement Uncertainty (k = 2)	Dose rate $\dot{D}_w$
BEV 1	1,114 0 · 10^6 Gy/C	1,0 %	150,6 mGy/h
VINS	1,108 7 · 10^6 Gy/C	2,0 %	2,11 mGy/h
BEV 2	1,116 5 · 10^6 Gy/C	1,0 %	148,6 mGy/h
BEV (mean)	1,115 3 · 10^4 Gy/C	1,0 %	
	Ratio VINS/BEV $N_{K_a,\text{VINS}} / N_{K_a,\text{BEV}}$		
	0,994 1	2,2 %	
	Ratio BEV/BIPM $N_{K_a,\text{BEV}} / N_{K_a,\text{BIPM}}$ (Key Comparison 2009)		
	1,004 1		
	Resulting Ratio VINS/BIPM $N_{K_a,\text{VINS}} / N_{K_a,\text{BIPM}}$		
	0,998 1		

Table 12 Results Air Kerma Cs-137 (radiation protection level) ionization chamber PTW 32005-000136

Ionization chamber	PTW 32002 (1 l)		
	SN 000592		
Electrometer	PTW UNIDOS 10002	Setting data BEV	Range: Med 11nA Modus: ∫ Current dt Intergration time: 60 s
	SN 20478	Setting data VINS	Range: Low 200 pA Modus: ∫ Current dt Intergration time: 60 s
Radio nuclide	Cs-137	Geometric setup BEV	Focus-detector-distance: 200 cm Field size: 52 cm (diameter)
Dose quantity	Air Kerma K_a	Geometric setup VINS	Focus-detector-distance: 200 cm Field size: 43 cm (diameter)
	Calibration coefficient N_{K_a}	Measurement Uncertainty (k = 2)	Dose rate $\dot{D}_w$
BEV 1	2,525 3 · 10^4 Gy/C	1,3 %	37,5 mGy/h
VINS	2,504 8 · 10^4 Gy/C	2,0 %	2,11 mGy/h
BEV 2	2,528 9 · 10^4 Gy/C	1,3 %	36,9 mGy/h
BEV (mean)	2,527 1 · 10^4 Gy/C	1,3 %	
	Ratio VINS/BEV $N_{K_a,\mathrm{VINS}} / N_{K_a,\mathrm{BEV}}$		
	0,991 2	2,5 %	
	Ratio BEV/BIPM $N_{K_a,\mathrm{BEV}} / N_{K_a,\mathrm{BIPM}}$ (Key Comparison 2009)		
	1,004 1		
	Resulting Ratio VINS/BIPM $N_{K_a,\mathrm{VINS}} / N_{K_a,\mathrm{BIPM}}$		
	0,995 3		

Table 13 Results Air Kerma Cs-137 (radiation protection level) ionization chamber PTW 32002-000592

9.4 Summary

Dose quantity	Air Kerma K_a	Absorbed Dose to Water D_w	Air Kerma K_a
Radio nuclide	Co-60	Co-60	Cs-137
Level	Therapy	Therapy	Radiation protection
Link to Key comparison data	BIPM.RI(I)-K1	BIPM.RI(I)-K4	BIPM.RI(I)-K5
Ratio VINS/BEV	$N_{K_a,\mathrm{VINS}} / N_{K_a,\mathrm{BEV}}$	$N_{D_w,\mathrm{VINS}} / N_{D_w,\mathrm{BEV}}$	$N_{K_a,\mathrm{VINS}} / N_{K_a,\mathrm{BEV}}$
	0,999 0 u_c= 0,64 % U = 1,3 % (k = 2)	1,000 4 u_c= 0,75 % U = 1,5 % (k = 2)	0,992 6 u_c= 1,24 % U = 2,5 % (k = 2)
Ratio BEV/BIPM (Key Comparison 2009)	$N_{K_a,\mathrm{BEV}} / N_{K_a,\mathrm{BIPM}}$	$N_{D_w,\mathrm{BEV}} / N_{D_w,\mathrm{BIPM}}$	$N_{K_a,\mathrm{BEV}} / N_{K_a,\mathrm{BIPM}}$
	1,003 4	0,999 6	1,004 1
Resulting ratio VINS/BIPM	$N_{K_a,\mathrm{VINS}} / N_{K_a,\mathrm{BIPM}}$	$N_{D_w,\mathrm{VINS}} / N_{D_w,\mathrm{BIPM}}$	$N_{K_a,\mathrm{VINS}} / N_{K_a,\mathrm{BIPM}}$
	1,002 4	1,000 0	0,996 7

Table 14 Summary of the results (Mean values)

10 Appendix B – Diagrams

10.1 Air Kerma Co-60 (Therapy level)

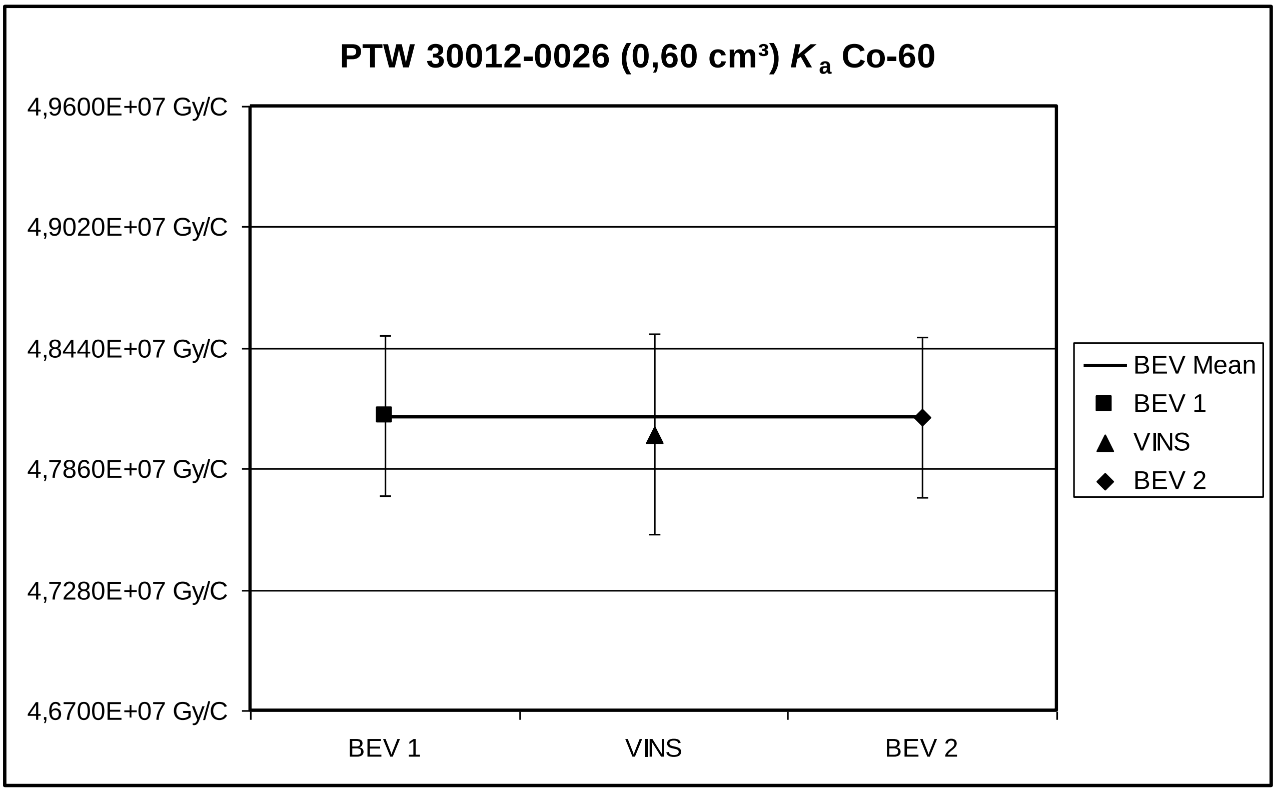

Figure 1 Results Air Kerma Co-60 (therapy level) ionization chamber PTW 30012-0026

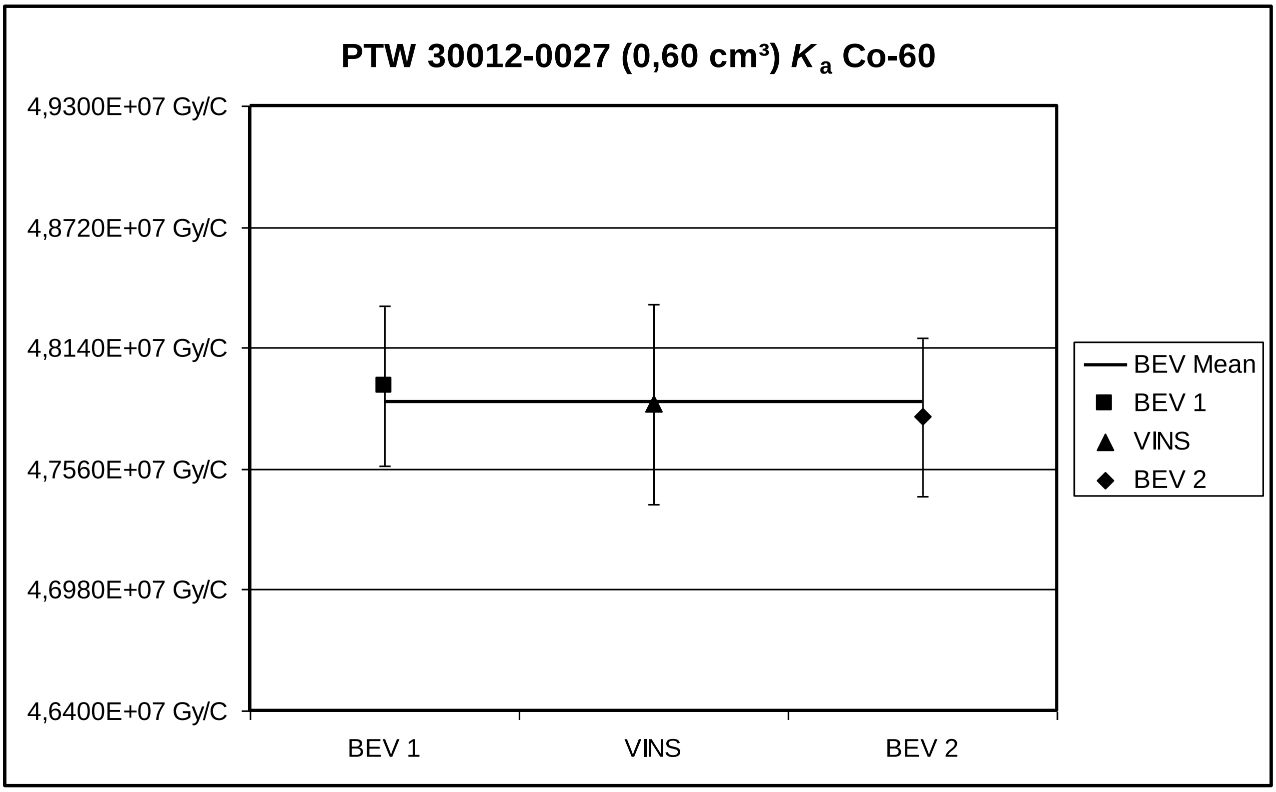

Figure 2 Results Air Kerma Co-60 (therapy level) ionization chamber PTW 30012-0027

10.2 Absorbed Dose to Water Co-60 (Therapy level)

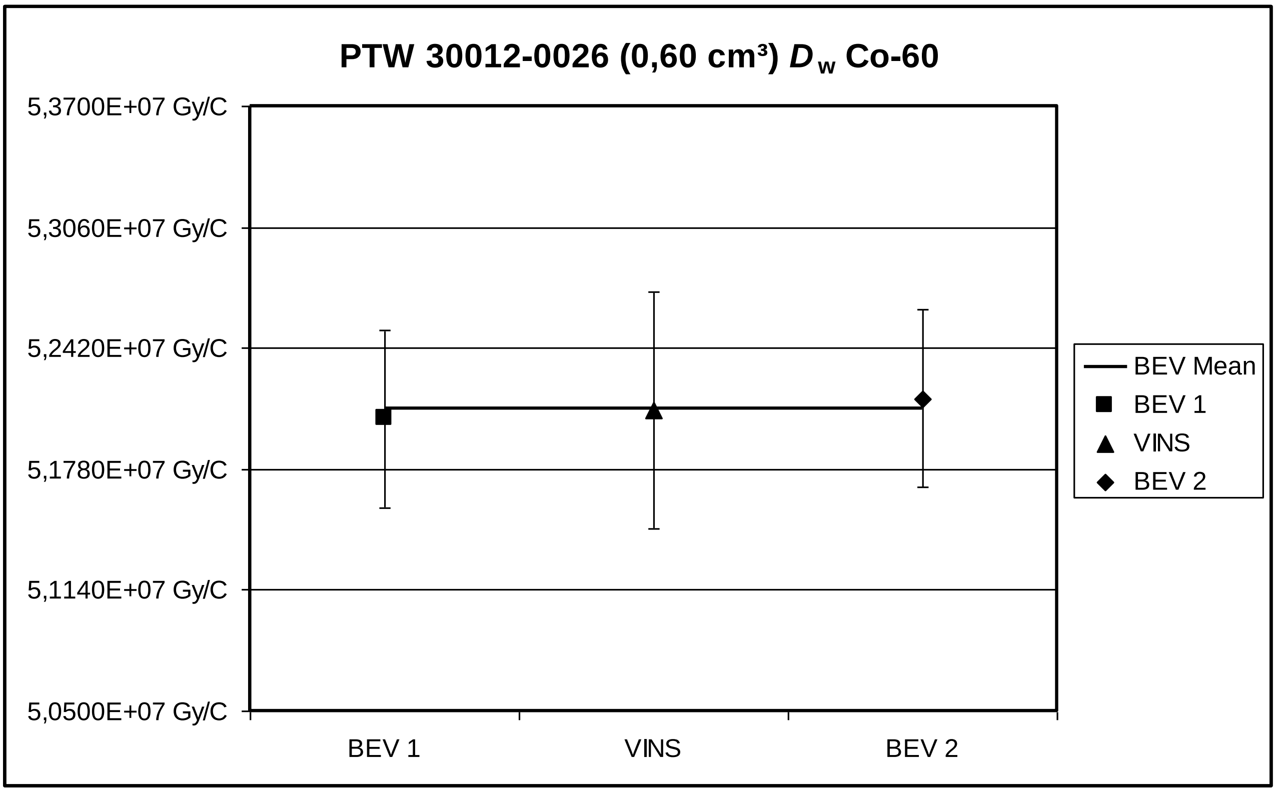

Figure 3 Results Absorbed Dose to Water Co-60 (therapy level) ionization chamber PTW 30012-0026

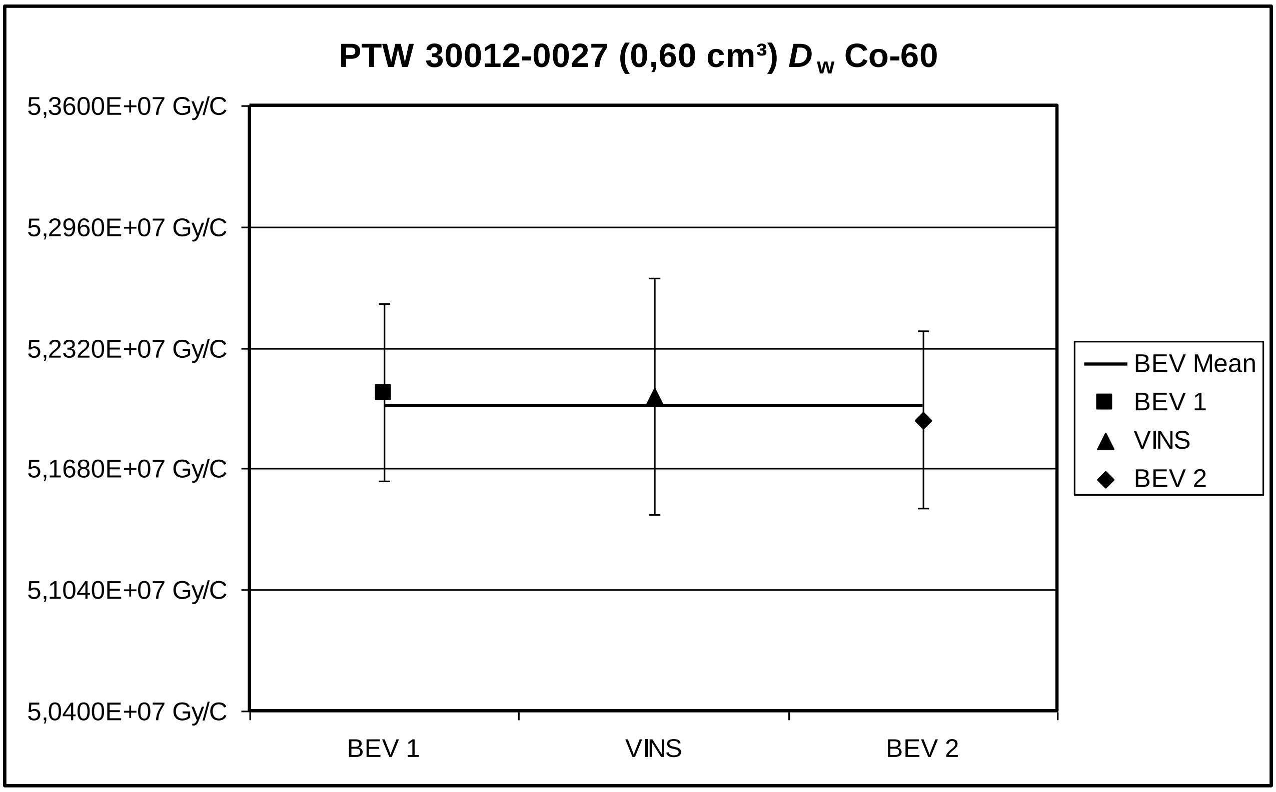

Figure 4 Results Absorbed Dose to Water Co-60 (therapy level) ionization chamber PTW 30012-0027

10.3 Air Kerma Cs-137 (Radiation protection level)

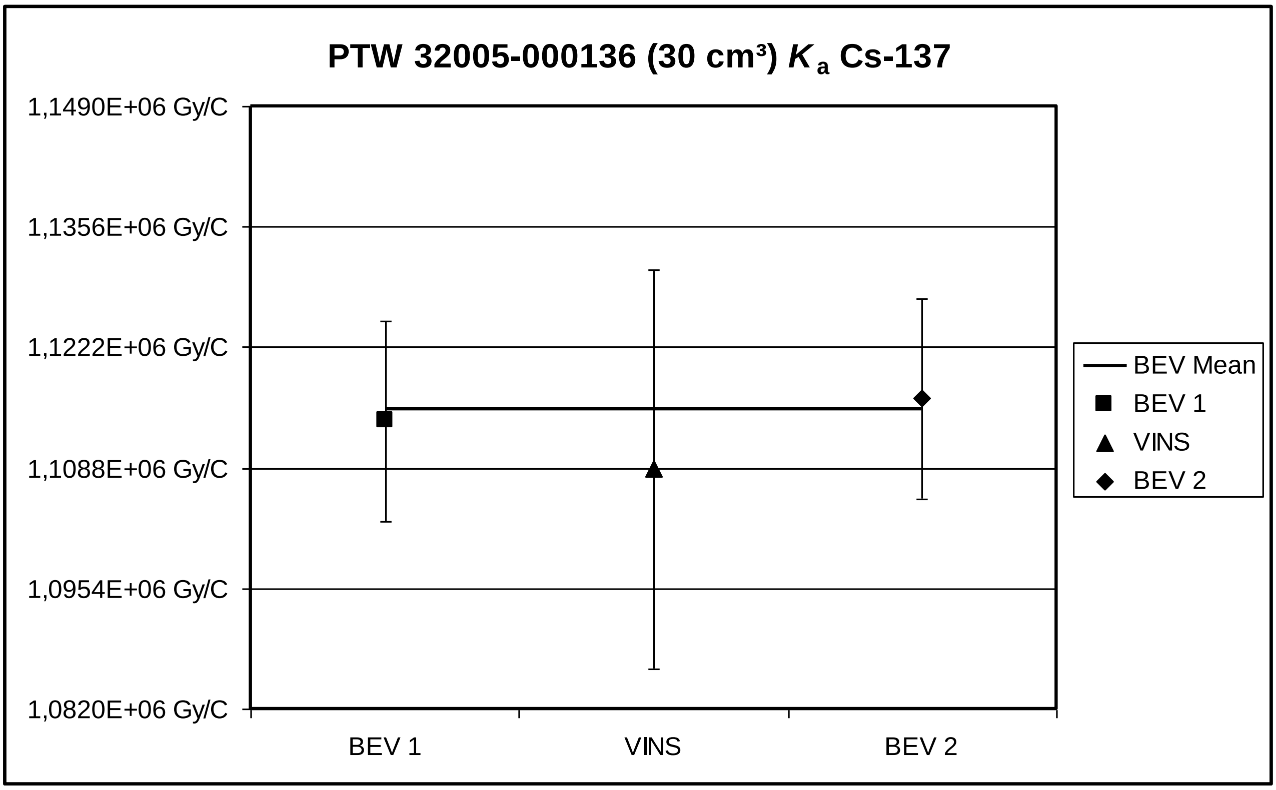

Figure 5 Results Air Kerma Cs-137 (radiation protection level) ionization chamber PTW 32005-000136

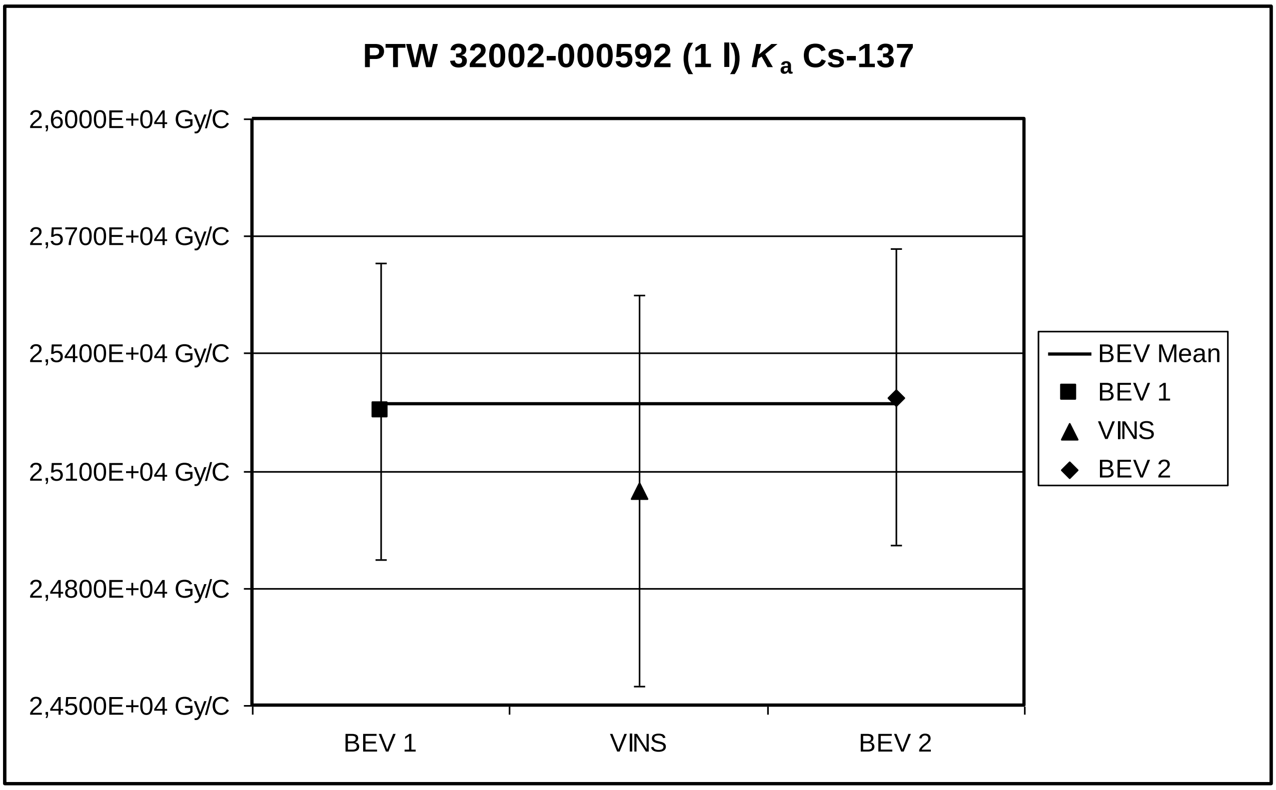

Figure 6 Results Air Kerma Cs-137 (radiation protection level) ionization chamber PTW 32002-000592

11 Appendix C – Uncertainty budgets

The uncertainty budgets are calculated with the schema given in section 5.

Step	Symbol	BEV			VINS		
		$u_{i,\mathrm{A}}$	$u_{i,\mathrm{B}}$	$u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2$	$u_{i,\mathrm{A}}$	$u_{i,\mathrm{B}}$	$u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2$
Step 1 (Determination of the dose rate)	$N_{K_\mathrm{a},\mathrm{S}}$	0,00 %	0,30 %	0,090 0 %²	0,21 %	0,41 %	0,212 2 %²
	I_S	0,10 %	0,02 %	0,010 4 %²	0,02 %	0,01 %	0,000 5 %²
	k_{pT}	0,00 %	0,05 %	0,002 5 %²	0,00 %	0,06 %	0,003 6 %²
	$k_{\mathrm{s,S}}$	0,02 %	0,02 %	0,000 8 %²	0,00 %	0,07 %	0,004 9 %²
	$k_{\mathrm{r,S}}$	0,00 %	0,12 %	0,014 4%²	0,00 %	0,03 %	0,000 9%²
	$\dot{K}_\mathrm{a}$	$u_\mathrm{c} = \sqrt{\sum_i \left(u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2\right)} =$		0,344 %	$u_\mathrm{c} = \sqrt{\sum_i \left(u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2\right)} =$		0,471 %
Step 2 (Determination of the calibration coefficient of the transfer chamber)	$\dot{K}_\mathrm{a}$	0,10 %	0,33 %	0,118 5 %²	0,21 %	0,42 %	0,222 1 %²
	I_T	0,10 %	0,05 %	0,012 5 %²	0,08 %	0,01 %	0,006 5 %²
	k_{pT}	0,00 %	0,05 %	0,002 5 %²	0,00 %	0,06 %	0,003 6 %²
	$k_{\mathrm{s,T}}$	0,02 %	0,05 %	0,002 9 %²	0,00 %	0,07 %	0,004 9 %²
	$k_{\mathrm{r,T}}$	0,00 %	0,12 %	0,014 4 %²	0,00 %	0,12 %	0,014 4 %²
	$N_{K_\mathrm{a},\mathrm{T}}$	$u_\mathrm{c} = \sqrt{\sum_i \left(u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2\right)} =$		0,388 %	$u_\mathrm{c} = \sqrt{\sum_i \left(u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2\right)} =$		0,501 %
		$U = 2 \cdot u_\mathrm{c} =$		0,78 %	$U = 2 \cdot u_\mathrm{c} =$		1,00 %

Table 15 Uncertainty budgets BEV and VINS: Air Kerma Co-60 (therapy level) ionization chambers PTW 30012-0026 and PTW 30012-0027

Step	Symbol	BEV			VINS		
		$u_{i,\mathrm{A}}$	$u_{i,\mathrm{B}}$	$u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2$	$u_{i,\mathrm{A}}$	$u_{i,\mathrm{B}}$	$u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2$
Step 1 (Determination of the dose rate)	$N_{D_\mathrm{w},\mathrm{S}}$	0,00 %	0,38 %	0,144 4 %^{2}	0,21 %	0,51 %	0,300 3 %^{2}
	I_S	0,10 %	0,02 %	0,010 4 %^{2}	0,03 %	0,01 %	0,001 0 %^{2}
	k_{pT}	0,00 %	0,05 %	0,002 5 %^{2}	0,00 %	0,06 %	0,003 6 %^{2}
	$k_{\mathrm{s,S}}$	0,02 %	0,02 %	0,000 8 %^{2}	0,00 %	0,07 %	0,004 9 %^{2}
	$k_{\mathrm{r,S}}$	0,00 %	0,12 %	0,014 4%^{2}	0,00 %	0,03 %	0,000 9%^{2}
	$\dot{D}_\mathrm{w}$	$u_\mathrm{c} = \sqrt{\sum_i \left(u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2\right)} =$		0,415 %	$u_\mathrm{c} = \sqrt{\sum_i \left(u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2\right)} =$		0,557 %
Step 2 (Determination of the calibration coefficient of the transfer chamber)	$\dot{D}_\mathrm{w}$	0,10 %	0,40 %	0,172 5 %^{2}	0,21 %	0,52 %	0,310 7 %^{2}
	I_T	0,10 %	0,05 %	0,012 5 %^{2}	0,01 %	0,01 %	0,000 2 %^{2}
	k_{pT}	0,00 %	0,05 %	0,002 5 %^{2}	0,00 %	0,06 %	0,003 6 %^{2}
	$k_{\mathrm{s,T}}$	0,02 %	0,05 %	0,002 9 %^{2}	0,00 %	0,07 %	0,004 9 %^{2}
	$k_{\mathrm{r,T}}$	0,00 %	0,12 %	0,014 4 %^{2}	0,00 %	0,13 %	0,016 9 %^{2}
	$N_{D_\mathrm{w},\mathrm{T}}$	$u_\mathrm{c} = \sqrt{\sum_i \left(u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2\right)} =$		0,415 %	$u_\mathrm{c} = \sqrt{\sum_i \left(u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2\right)} =$		0,580 %
		$U = 2 \cdot u_\mathrm{c} =$		0,83 %	$U = 2 \cdot u_\mathrm{c} =$		1,16 %

Table 16 Uncertainty budgets BEV and VINS: Absorbed Dose to Water Co-60 (therapy level) ionization chambers PTW 30012-0026 and PTW 30012-0027

Step	Symbol	BEV			VINS		
		$u_{i,\mathrm{A}}$	$u_{i,\mathrm{B}}$	$u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2$	$u_{i,\mathrm{A}}$	$u_{i,\mathrm{B}}$	$u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2$
Step 1 (Determination of the dose rate)	$N_{K_\mathrm{a},\mathrm{S}}$	0,00 %	0,35 %	0,122 5 %^{2}	0,52 %	0,42 %	0,446 8 %^{2}
	I_S	0,20 %	0,02 %	0,040 4 %^{2}	0,32 %	0,01 %	0,102 5 %^{2}
	k_{pT}	0,00 %	0,05 %	0,002 5 %^{2}	0,00 %	0,06 %	0,003 6 %^{2}
	$k_{\mathrm{s,S}}$	0,02 %	0,02 %	0,000 8 %^{2}	0,00 %	0,13 %	0,016 9 %^{2}
	$k_{\mathrm{r,S}}$	0,00 %	0,12 %	0,014 4 %^{2}	0,00 %	0,13 %	0,016 9%^{2}
	$\dot{K}_\mathrm{a}$	$u_\mathrm{c} = \sqrt{\sum_i \left(u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2\right)} =$		0,425 %	$u_\mathrm{c} = \sqrt{\sum_i \left(u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2\right)} =$		0,766 %
Step 2 (Determination of the calibration coefficient of the transfer chamber)	$\dot{K}_\mathrm{a}$	0,20 %	0,37 %	0,180 6 %^{2}	0,61 %	0,46 %	0,586 7 %^{2}
	I_T	0,20 %	0,05 %	0,042 5 %^{2}	0,54 %	0,01 %	0,291 7 %^{2}
	k_{pT}	0,00 %	0,05 %	0,002 5 %^{2}	0,00 %	0,06 %	0,003 6 %^{2}
	$k_{\mathrm{s,T}}$	0,02 %	0,05 %	0,002 9 %^{2}	0,00 %	0,21 %	0,044 1 %^{2}
	$k_{\mathrm{r,T}}$	0,00 %	0,12 %	0,014 4 %^{2}	0,00 %	0,18 %	0,032 4 %^{2}
	$N_{K_\mathrm{a},\mathrm{T}}$	$u_\mathrm{c} = \sqrt{\sum_i \left(u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2\right)} =$		0,493 %	$u_\mathrm{c} = \sqrt{\sum_i \left(u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2\right)} =$		0,979 %
		$U = 2 \cdot u_\mathrm{c} =$		0,99 %	$U = 2 \cdot u_\mathrm{c} =$		1,96 %

Table 17 Uncertainty budgets BEV and VINS: Air Kerma Cs-137 (radiation protection level) ionization chamber PTW 32005-000136

Step	Symbol	BEV			VINS		
		$u_{i,\mathrm{A}}$	$u_{i,\mathrm{B}}$	$u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2$	$u_{i,\mathrm{A}}$	$u_{i,\mathrm{B}}$	$u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2$
Step 1 (Determination of the dose rate)	$N_{K_\mathrm{a},\mathrm{S}}$	0,00 %	0,49 %	0,238 7 %^{2}	0,52 %	0,42 %	0,446 8 %^{2}
	I_S	0,20 %	0,02 %	0,040 4 %^{2}	0,32 %	0,01 %	0,102 5 %^{2}
	k_{pT}	0,00 %	0,05 %	0,002 5 %^{2}	0,00 %	0,06 %	0,003 6 %^{2}
	$k_{\mathrm{s,S}}$	0,02 %	0,02 %	0,000 8 %^{2}	0,00 %	0,13 %	0,016 9 %^{2}
	$k_{\mathrm{r,S}}$	0,00 %	0,20 %	0,040 0 %^{2}	0,00 %	0,13 %	0,016 9%^{2}
	$\dot{K}_\mathrm{a}$	$u_\mathrm{c} = \sqrt{\sum_i \left(u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2\right)} =$		0,571 %	$u_\mathrm{c} = \sqrt{\sum_i \left(u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2\right)} =$		0,766 %
Step 2 (Determination of the calibration coefficient of the transfer chamber)	$\dot{K}_\mathrm{a}$	0,20 %	0,53 %	0,326 6 %^{2}	0,61 %	0,46 %	0,586 7 %^{2}
	I_T	0,20 %	0,05 %	0,042 5 %^{2}	0,52 %	0,01 %	0,270 5 %^{2}
	k_{pT}	0,00 %	0,05 %	0,002 5 %^{2}	0,00 %	0,06 %	0,003 6 %^{2}
	$k_{\mathrm{s,T}}$	0,02 %	0,05 %	0,002 9 %^{2}	0,00 %	0,22 %	0,048 4 %^{2}
	$k_{\mathrm{r,T}}$	0,00 %	0,20 %	0,040 0 %^{2}	0,00 %	0,18 %	0,032 4 %^{2}
	$N_{K_\mathrm{a},\mathrm{T}}$	$u_\mathrm{c} = \sqrt{\sum_i \left(u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2\right)} =$		0,644 %	$u_\mathrm{c} = \sqrt{\sum_i \left(u_{i,\mathrm{A}}^2 + u_{i,\mathrm{B}}^2\right)} =$		0,970 %
		$U = 2 \cdot u_\mathrm{c} =$		1,29 %	$U = 2 \cdot u_\mathrm{c} =$		1,94 %

Table 18 Uncertainty budgets BEV and VINS: Air Kerma Cs-137 (radiation protection level) ionization chamber PTW 32002-000592

12 Appendix D – Figures

12.1 Pictures of the electrometer and the ionization chambers

Figure 7 Electrometer PTW UNIDOS 10002, SN 20478

Figure 8 Extension cable PTW T26002.1.001-20 (20 m length)

Figure 9 Ionization chamber PTW T30012, SN 0026, including PMMA-Sleeve 4322/U13 and case

Figure 10 Ionization chamber PTW T30012, SN 0027, including PMMA-Sleeve 4322/U13 and case

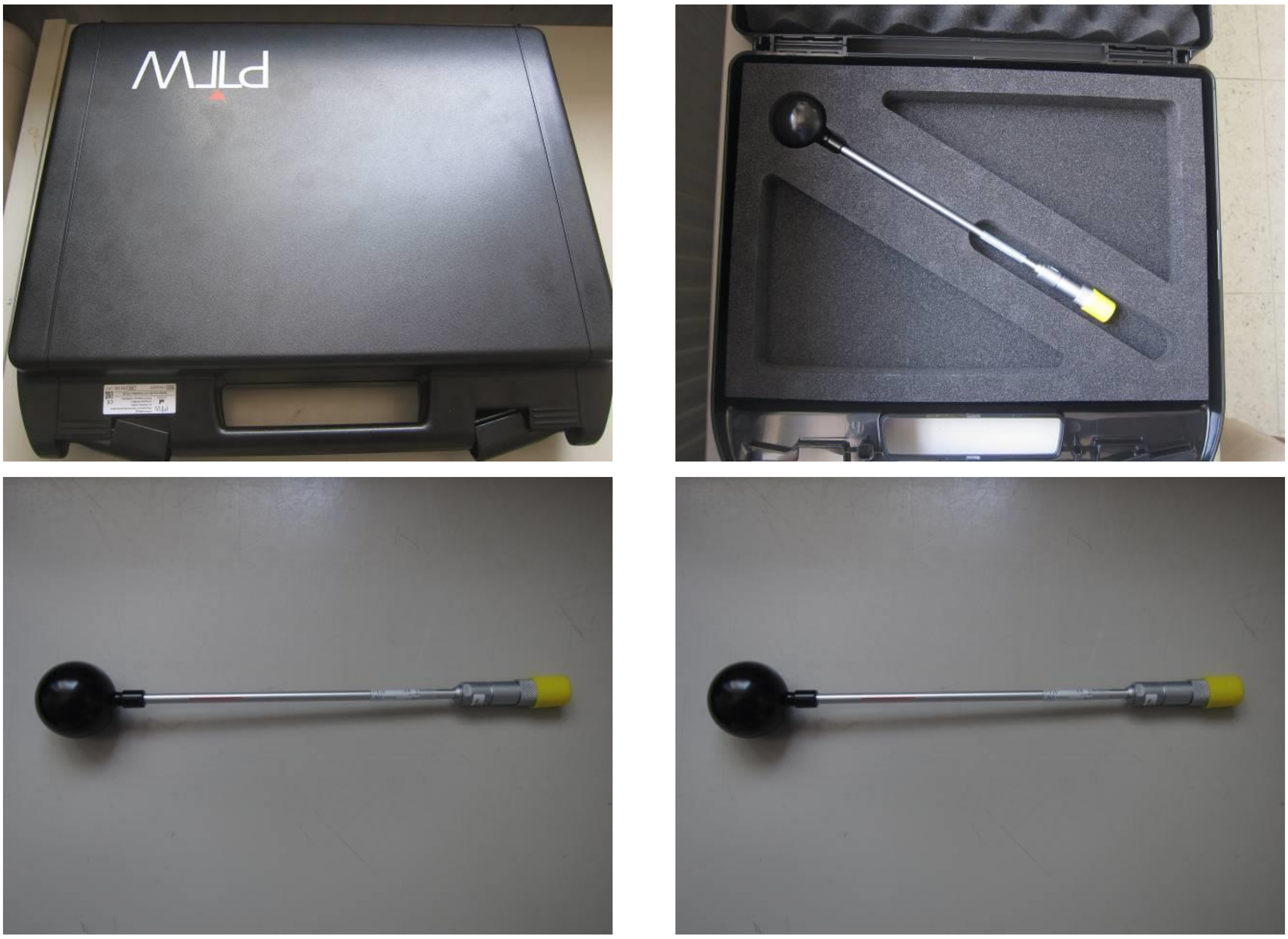

Figure 11 Ionization chamber PTW 32005 30 cm^3 (TK-30), SN 000136 and case

Figure 12 Ionization chamber PTW 32002 1 l, SN 000592 and case

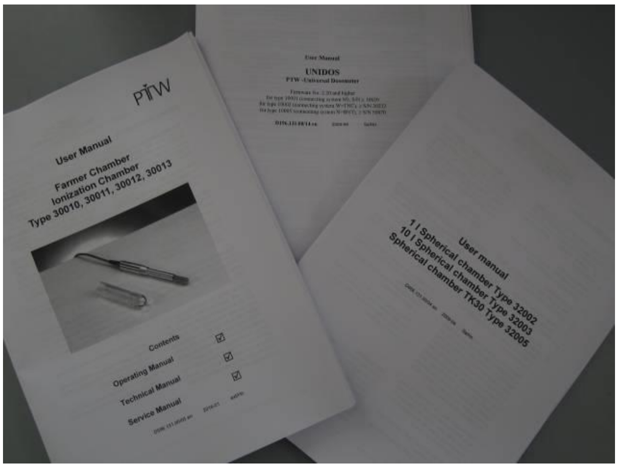

Figure 13 Manuals electrometer Unidos 10002, Ionization chamber PTW 30012, Ionization chambers 32005 30 cm^3 (TK-30) and PTW 32002 1 l

12.2 Pictures of the BEV measuring setups

12.2.1 Absorbed Dose to Water, therapy level

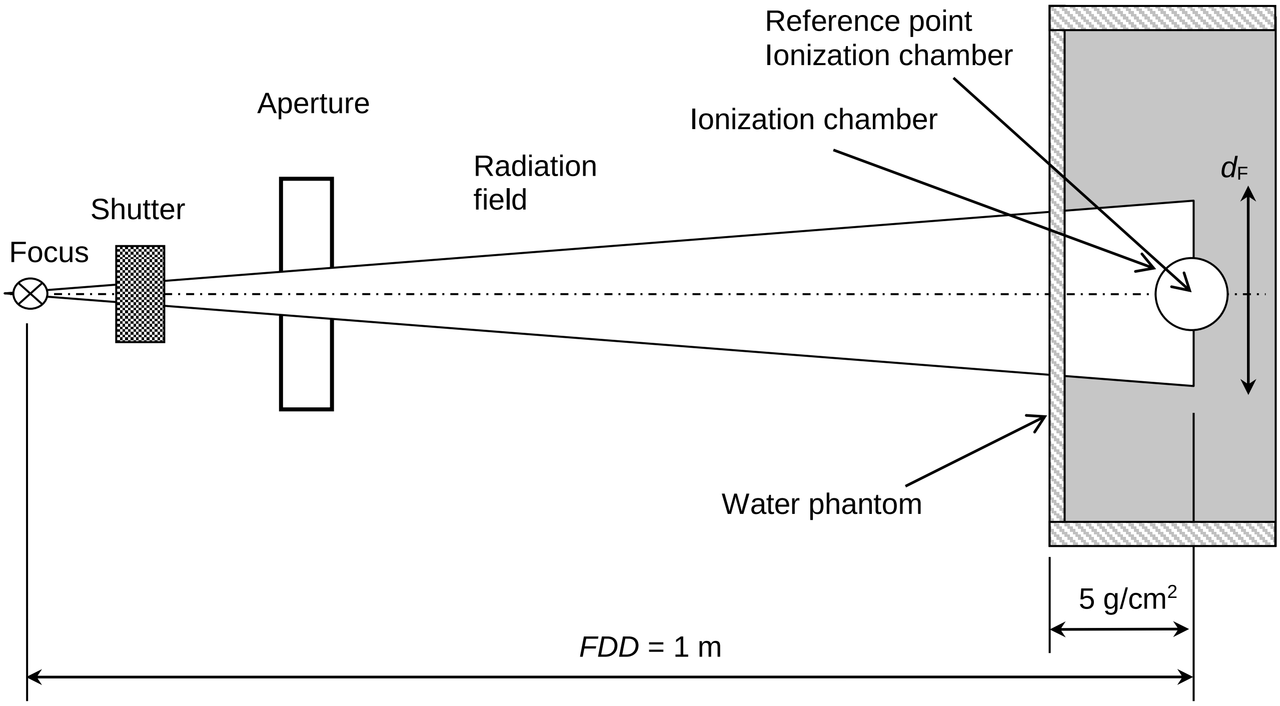

Figure 14 Schema of measurement setup for Absorbed Dose to Water, therapy level Co-60

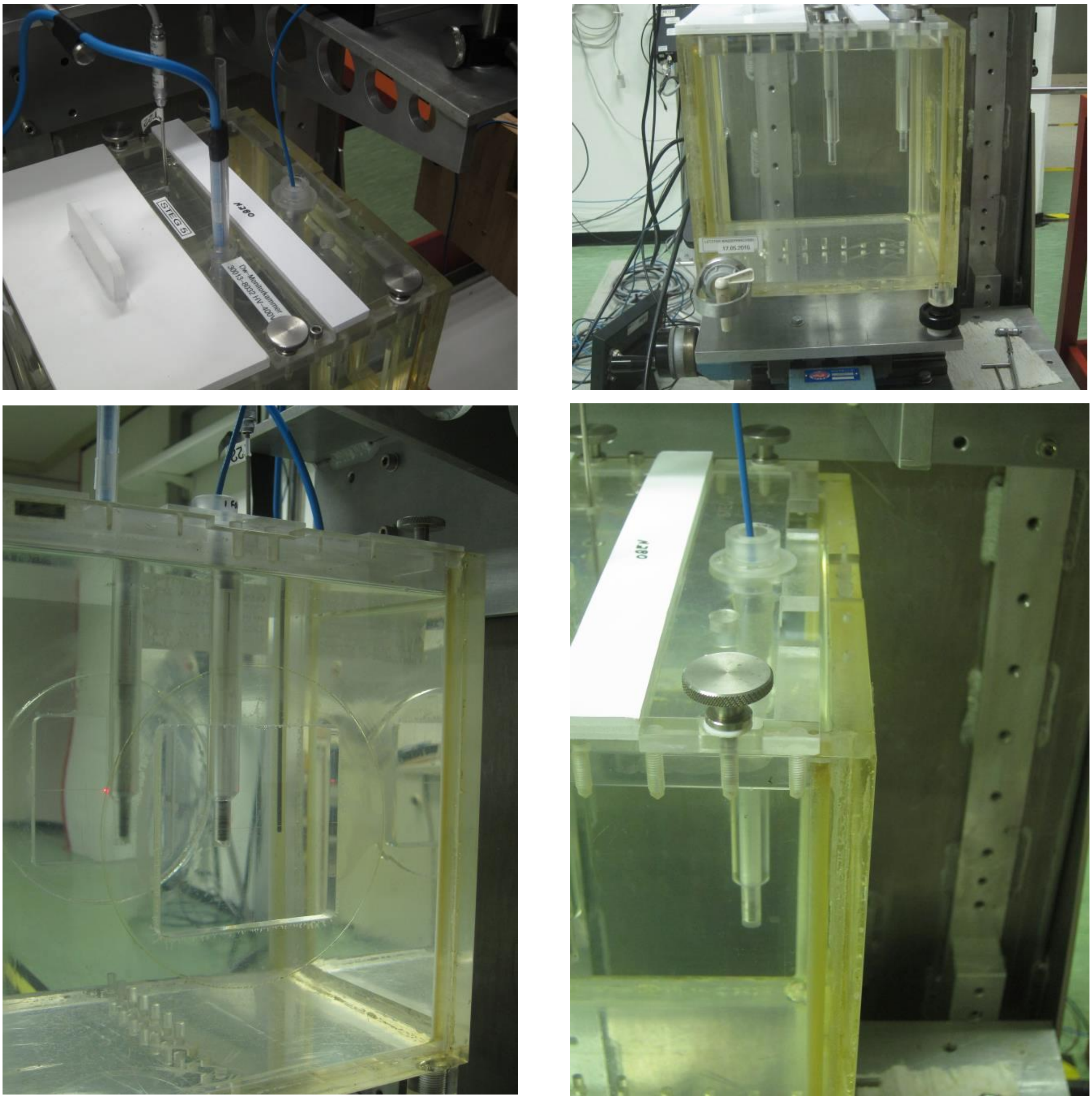

Figure 15 Absorbed Dose to Water, therapy level Co-60, ionization chamber PTW T30012 in the 30 cm x 30 cm x 30 cm water phantom including temperature sensor

12.2.2 Air Kerma, therapy level

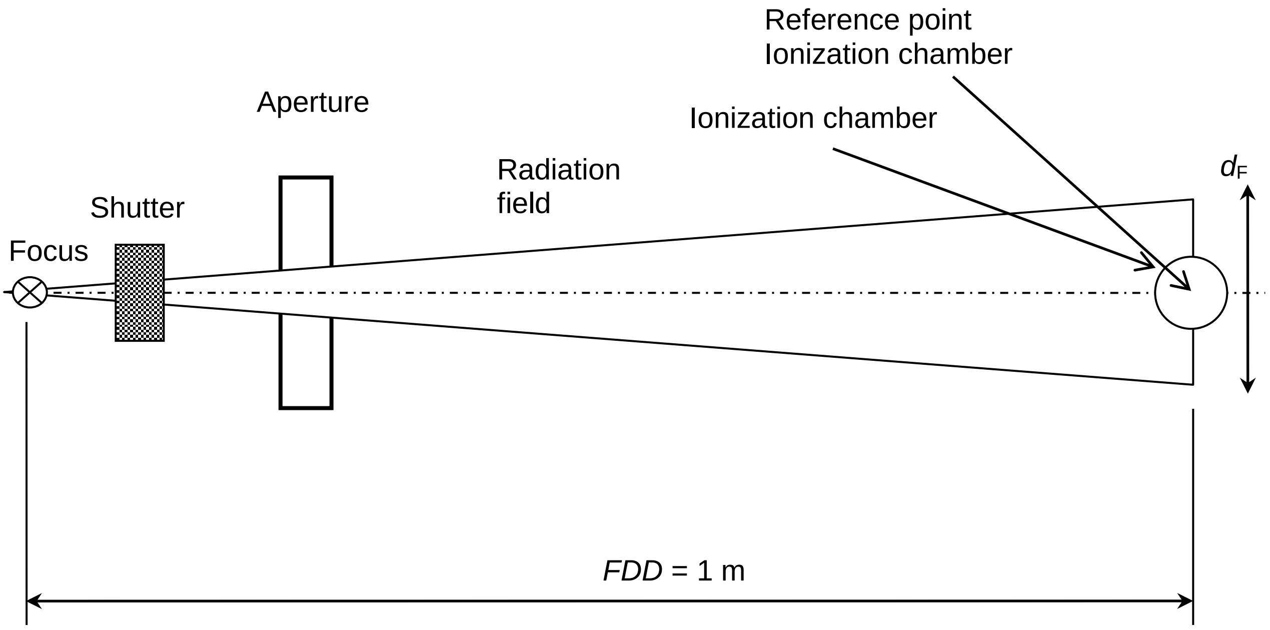

Figure 16 Schema of measurement setup for Air Kerma, therapy level Co-60

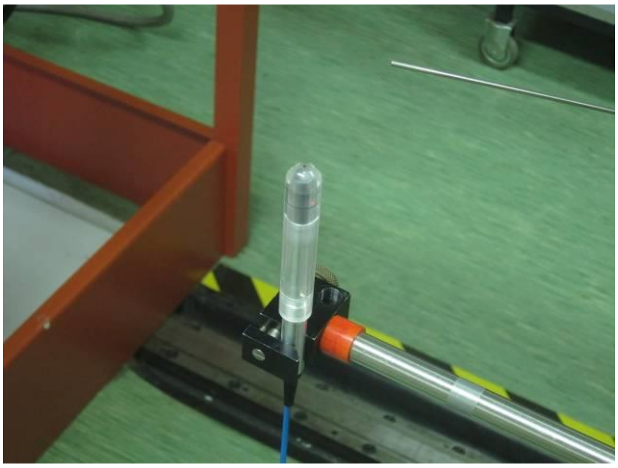

Figure 17 Air Kerma, therapy level Co-60, ionization chamber PTW T30012 including temperature sensor

12.2.3 Air Kerma, radiation protection level

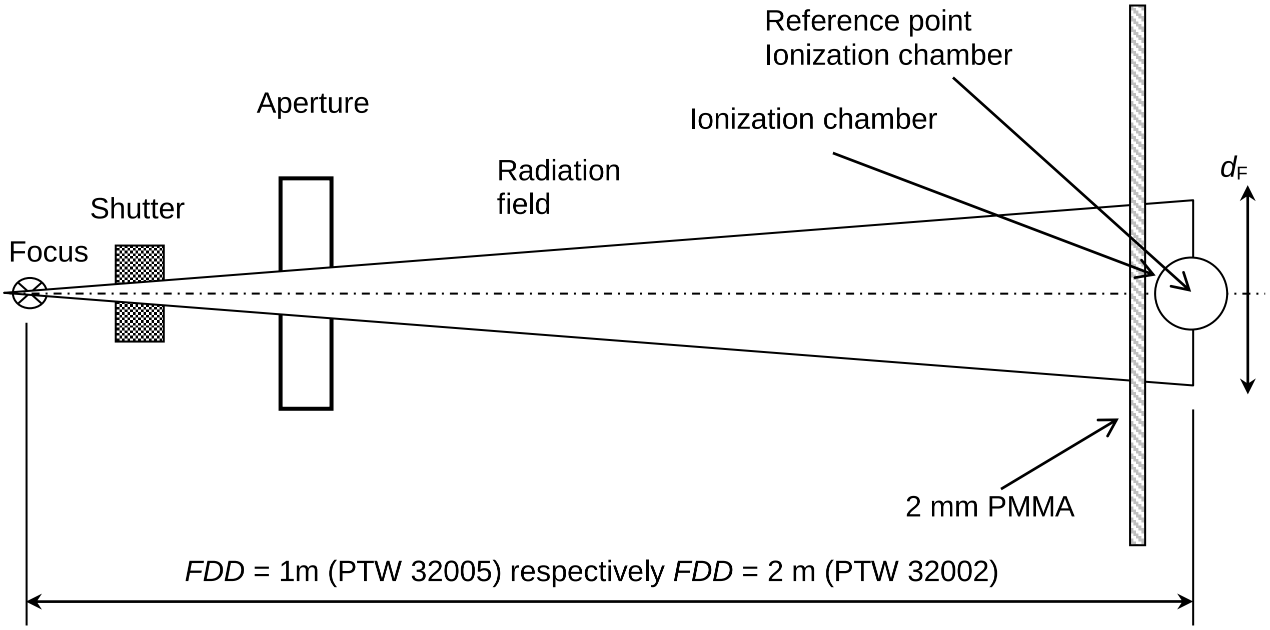

Figure 18 Schema of measurement setup for Air Kerma, radiation protection level Cs-137

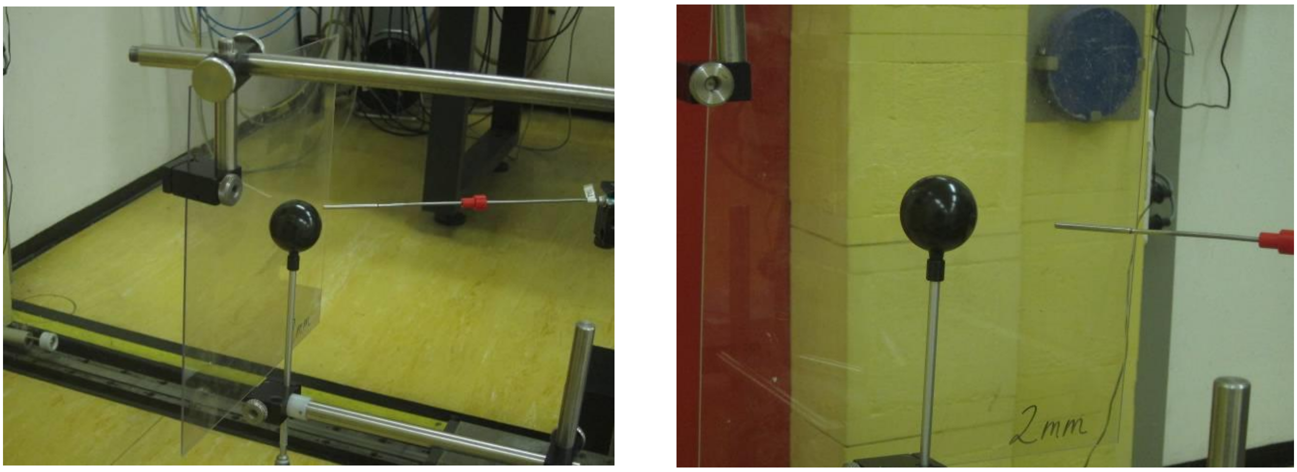

Figure 19 Air Kerma, radiation protection level Cs-137, ionization chamber PTW 32005 30 cm^3 (TK-30), including 2 mm PMMA plate and temperature sensor

Figure 20 Air Kerma, radiation protection level Cs-137, ionization chamber PTW 32002 1 l, including 2 mm PMMA plate and temperature sensor