COMPARISON OF EXTRAPOLATION CHAMBER MEASUREMENTS OF THE ABSORBED DOSE RATE FOR BETA RADIATION BETWEEN VNIIM (RUSSIA) AND PTB (GERMANY)

K. Helmstädter[1]), J. Böhm[1]), P. Ambrosi[1]), V. Fominych[2]), E. Rumyantseva[2]), S. Fedina[2])

[1])Physikalisch-Technische Bundesanstalt (PTB), 38116 Braunschweig, Germany

[2])D. I. Mendeleyev Institute for Metrology (VNIIM), 198005 St. Petersburg, Russia

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[2])D. I. Mendeleyev Institute for Metrology (VNIIM), 198005 St. Petersburg, Russia

Abstract - An comparison of absorbed dose rates, $\dot{D}_{\mathrm{t}}(0.07)$, in tissue at radiation protection levels for beta dosimetry was performed between two national laboratories, the D. I. Mendeleyev Institute for Metrology (VNIIM) in St. Petersburg (Russia) and the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig (Germany), in 1999 and 2001 using flat ionisation chambers as transfer standards. The dose rates were determined at the calibration distances by measurements with the primary standard measuring devices of VNIIM and PTB with extrapolation chambers to realise the unit of absorbed dose rate to tissue for beta radiation. In the two steps reported on here, transfer chambers of VNIIM and PTB were calibrated in beta radiation reference fields at VNIIM and at PTB. The values of the calibration factors for the flat ionisation chambers agreed within ± 2 % for ^{90}Sr/^{90}Y, ^{85}Kr and ^{204}Tl and ± 4 % for ^{147}Pm beta radiation.

Introduction

Comparisons of National Metrology Institutes are very important for the quality assurance of measurements with primary standard devices. In the field of beta dosimetry, extrapolation chambers have been designed at standards institutes to measure the absorbed dose rate to tissue, $\dot{D}_t(d)$, in a semi-infinitely extended tissue phantom and at several depths *d*. For beta radiation such as weakly penetrating radiation, the tissue depth d = 0.07 mm is the reference depth.

The comparison between the D. I. Mendeleyev Institute for Metrology (VNIIM) in St. Petersburg and the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig (Germany) was planned in two steps. For the first step in 1999, the flat ionisation chamber ND 1009 of the PTB, developed in 1988 at the National Office of Measures (OMH) and for the second step in 2001, the flat ionisation chamber PK2-01 of the VNIIM were used as transfer chambers. At PTB these chambers were calibrated in the beta radiation fields of the Beta Secondary Standards BSS 1(1) and BSS 2(2) produced by sources with the radionuclides of ^{147}Pm, ^{204}Tl, ^{85}Kr and ^{90}Sr/^{90}Y. and at VNIIM in beta radiation fields from radionuclides of ^{147}Pm, ^{204}Tl and ^{90}Sr/^{90}Y. In both institutes extrapolation chambers were used as standard measuring devices(3, 4, 5) and standardised procedures were adopted to determine $\dot{D}_t(d)$ for depths *d* of 0.07 mm(6).

Experimental arrangement

Irradiation conditions

The beta radiation fields of PTB are the calibration fields of the Beta Secondary Standard BSS 1 with ^{147}Pm, ^{204}Tl, ^{85}Kr and ^{90}Sr/^{90}Y sources and of the BSS 2 with ^{147}Pm, ^{85}Kr and ^{90}Sr/^{90}Y sources. These sources are almost point sources with active diameters of 15 mm at most. The measuring conditions are as follows:

> ^{147}Pm sources: distance 20 cm, with beam flattening filter, absorbed dose rate in 0.07 mm tissue depth 1.05 µGy/s (June 1999);
>
> ^{204}Tl and ^{85}Kr sources: distance 30 cm, with beam flattening filters, absorbed dose rate in 0.07 mm tissue depth 0.06 µGy/s (1996) and 33 µGy/s (June 1999), respectively,
>
> ^{90}Sr/^{90}Y sources: distance 30 cm, with beam flattening filter, absorbed dose rate in 0.07 mm tissue depth 10.2 µGy/s (June 1999),
>
> ^{90}Sr/^{90}Y sources: distances 11 cm, 20 cm, 30 cm and 50 cm, without beam flattening filter, absorbed dose rate in 0.07 mm tissue depth from 5.5 µGy/s to 116 µGy/s (June 1999).

Reference air conditions: pressure 101.3 kPa, temperature 293.15 K, humidity 45 %,
air density 1.1995 kg/m³
At the calibration distances the homogeneity of the radiation field was better than 2 % within a diameter of 60 mm.

The VNIIM beta radiation fields are characterised by area beta sources

> ^{90}Sr/^{90}Y (active diameter 50 mm): distances 8 cm, 20 cm and 30 cm, without beam flattening filter, absorbed dose rate in 0.07 mm tissue depth from 0.1 mGy/s to 1 mGy/s (June 1999),
>
> ^{204}Tl (active diameter 40 mm): distances 8 cm, 20 cm and 30 cm, without beam flattening filter, absorbed dose rate in 0.07 mm tissue depth from 5 µGy/s to 90 µGy/s (June 1999) and
>
> ^{147}Pm (active diameter 50 mm): distances 8 cm and 20 cm, without beam flattening filter, absorbed dose rate in 0.07 mm tissue depth 6 µGy/s to 76 µGy/s (May 1999).

Reference air conditions: pressure 101.3 kPa, temperature 293.15 K, humidity 0 %,
air density 1.2047 kg/m³
At the calibration distances the homogeneity of the radiation field was better than 2 % within a diameter of 100 mm.

Transfer chamber:

As a transfer chamber PTB made available a flat ionisation chamber with constant volume. This chamber of type ND 1009 No. 868 was constructed in1988 at the National Office of Measures (OMH, Hungary). The main parameters are the following:

diameter of collecting electrode:	29.72 mm
chamber depth:	2.023 mm
window foil material / tissue thickness:	aluminized mylar / 1.51 mg/cm²
chamber voltage	± 20 V
reference area:	the window surface
ring thickness in front of window	5 mm.

The transfer chamber for the second step of the comparison measurements was the flat ionisation chamber with constant volume PK2-01 No. 2, developed at VNIIM. The main parameters are the following:

diameter of collecting electrode:	29.83 mm
chamber depth:	2.0 mm
window foil material / tissue thickness:	aluminized mylar / 5.52 mg/cm²
chamber voltage	± 100 V
reference area:	on the 1 mm beyond the centre of the window surface
ring thickness in front of window	2 mm.

For measurements of the ionisation current both in the extrapolation chamber and in the transfer chamber, the integrating current measuring systems of high metrological quality of VNIIM and PTB were used. These are a Keithley 642 electrometer at PTB operating in the capacitor feedback mode and a Keithley 6517A electrometer at VNIIM. The leakage currents of the extrapolation chamber / transfer chamber - electrometer combinations were for the PTB chamber always below 0.3 fA at PTB and 2 fA at VNIIM, and for the VNIIM chamber between 2 fA and 4 fA at PTB and 5 fA at VNIIM.

Extrapolation chambers

The objects of the comparison are the primary standard measuring devices for realising the unit of absorbed dose rate to tissue for beta radiation at VNIIM and PTB, both using extrapolation ionisation chambers. The detailed descriptions of these devices can be found in previous publications[3, 4, 5]. The most important parameters are summarised in Table 1.

Table 1: Main characteristics of the beta primary standard measuring devices of VNIIM and PTB used for the comparison measurements

Parameter	**VNIIIM**	**PTB**
Type of chamber	Extrapolation chamber EK-2M	Extrapolation chamber I
Entrance window: Material, Mass per area in mg/cm² Equivalent tissue depth d_{win} in mm	 aluminized Mylar (polyethyleneterephtalate) 1.43 0.0131	 graphited Hostaphan (polyethyleneterephtalate) 0.6224 0.00574
Additional absorber: Material, Mass per area in mg/cm² Equivalent tissue depth d_{win} in mm	 Mylar 6.22 0.0569	 Hostaphan 6.963 0.0654
Collector: Material Thickness in mm Diameter in mm and Area in cm² of collecting electrode used Guard ring width in mm Width / depth of insulation gap in mm	 PMMA 25 30.03 7.0816 40 0.2 / 0.2	 PMMA 31 30.37 7.2458 15 0.2 / 0.2
Range of chamber depth for extrapolation in mm	0.3 to 0.7	0.25 to 2.5
Chamber voltage applied in V	± 30 constant for all chamber depths	± 2.5 to ± 25 variable with chamber depth

For measurements of the absorbed dose rate to tissue in the beta radiation reference fields, each partner used the respective primary standard measuring devices of VNIIM and PTB. Without describing these procedures in detail, the equation (1) for the dose calculation should be mentioned here:

$$\dot{D}_{\mathrm{t}} = \left(\frac{\mathrm{d}}{\mathrm{d}l}(k\,I)\right)_{l=0} \cdot k' \cdot \left(\frac{\overline{W_{\mathrm{o}}}}{e}\right) \cdot \frac{s_{\mathrm{t,a}}}{a \cdot \rho_{\mathrm{ao}}} \quad , \qquad (1)$$

where

I is the ionisation current,

k is the product of different correction factors(4, 6) which are dependent on the chamber depth and

k' is the product of different correction factors(4, 6) which are independent on the chamber depth,

$\left(\dfrac{\mathrm{d}(kI)}{\mathrm{d}l}\right)_{l=0}$	is the limiting value of the slope of the corrected current versus the chamber depth function,
$\overline{W}_{\mathrm{o}}/e$	is the quotient of the mean energy to produce an ion pair in air under reference conditions and the elementary charge, e,
$s_{\mathrm{t,a}}$	is the quotient of mass electronic stopping powers of ICRU tissue and air,
ρ_{ao}	is the air density under reference conditions,
a	is the effective area of the collecting electrode.

For the comparison of the results of VNIIM and PTB, it is also important to know the values used for the constants in the above formula. Table 2 shows the comparison of these parameters used at VNIIM and at PTB

Table 2: Constants for dose calculation in the formula (1) used at VNIIM and at PTB

Constant	Values used at VNIIM	Values used at PTB
$\overline{W}_{\mathrm{o}}/e$	33.97 eV for dry air	33.87 eV for air with a relative humidity of 0.45
$s_{\mathrm{t,a}}$ for ^{147}Pm	1.140	1.124 (6)
$s_{\mathrm{t,a}}$ for ^{204}Tl	1.120	1.121 (6)
$s_{\mathrm{t,a}}$ for ^{85}Kr	--	1.121 (6)
$s_{\mathrm{t,a}}$ for ^{90}Sr/^{90}Y	1.117	1.110 (6)
ρ_{ao}	1.2047 kg/m³ for dry air	1.1995 kg/m³ for air with a relative humidity of 0.45
$T_{1/2}$ for ^{147}Pm	958.05 d	958.2 d (7)
$T_{1/2}$ for ^{204}Tl	1380.6 d	1381 d (7)
$T_{1/2}$ for ^{85}Kr	–	3915 d (7)
$T_{1/2}$ for ^{90}Sr/^{90}Y	10 636 d	10 523 d (7)
E_{mean} for ^{147}Pm	62 keV	64 keV
E_{mean} for ^{204}Tl	244 keV	240 keV
E_{mean} for ^{85}Kr	–	240 keV
E_{mean} for ^{90}Sr/^{90}Y	935 keV	800 keV

Procedure for the comparison:

In the beta radiation fields at VNIIM and PTB the two transfer chambers were calibrated by measuring the ionisation currents and putting them in relation to the conventional true value of the absorbed dose rates. The evaluated calibration factors determined at VNIIM and PTB are compared with each other.

Determination of the calibration factor:

The calibration factor N is defined as the quotient of the conventional true value of a quantity, $\dot{D}_t$, and the indicated value, M_r, of the ionisation current at the point of test for a specified reference radiation under specified reference conditions(8). It is expressed as

$$N = \frac{\dot{D}_t}{M_r} \qquad (2)$$

Applied to the transfer chamber where the indicated value M_r is the mean ionisation current $I(d)$ measured in the collecting volume of the chamber at positive and negative chamber voltage and corrected for air density (k_{ad}), saturation (k_{sat}), radioactive decay (k_{de}), perturbation by the chamber side walls (k_{pe}), beam divergence (k_{di}), window absorption ($k_{0.07}$) and absorption along the path between the source and the chamber for ^{147}Pm (k_{ab}) the formula reads as follows:

$$N = \dot{D}_t(0.07)/(k_{ad} \cdot k_{sat} \cdot k_{pe} \cdot k_{di} \cdot k_{0.07} \cdot k_{ab} \cdot I(d)) \qquad (3)$$

where	N	is the calibration factor of the transfer chamber in µGy/s fA
	$\dot{D}_t(0.07)$	is the conventional true dose rate at the surface of tissue in µGy/s measured with the extrapolation chamber device (primary standard)
	$I(\mathrm{d}) = (I_+ + I_-)/2$	is the mean ionisation current I in fA measured in the flat chamber behind the window thickness d at positive and negative polarities of the chamber voltage and averaged for these two polarities.

Results of the measurements

The calibration factors for the two transfer chambers evaluated at VNIIM and at PTB for different radionuclides, their expanded uncertainties (k = 2) and the ratio of the PTB values to the VNIIM values are summarised in the following tables:

Table 3: Corrected calibration factors of the PTB transfer chamber ND 1009 and the ratio of these factors from PTB and VNIIM for different radionuclides and their expanded uncertainties

Beta radiation of nuclides	Calibration factor in µGy/s fA	Expanded uncertainty (k = 2) in µGy/s fA	Calibration factor in µGy/s fA	Expanded uncertainty (k = 2) in µGy/s fA	Ratio of calibration factors	Expanded uncertainty of ratio (k = 2)
	VNIIM	**VNIIM**	**PTB**	**PTB**	**PTB/VNIIM**	**PTB/VNIIM**
^{147}Pm	0.0200	0.0004	0.0204	0.0005	1.02	0.019
^{204}Tl and/or ^{85}Kr	0.0219	0.0004	0.0221	0.0003	1.01	0.013
^{90}Sr/^{90}Y	0.0223	0.0004	0.0221	0.0004	0.99	0.015

The agreement of these factors is better than 2 % for ^{147}Pm beta radiation and 1 % for ^{90}Sr/^{90}Y, ^{85}Kr and ^{204}Tl beta radiation. The calibration factors of PTB are mean values from the calibration series of 1994,1996 and 1999. The calibration factors of VNIIM were determined by measurements carried out on 15-06-1999 to 17-06-1999. The expanded uncertainties are determined as described in the next section for an example.

Table 4: Corrected calibration factors of the VNIIM transfer chamber PK2-01 and the ratio of these factors from PTB and VNIIM for different radionuclides and their expanded uncertainties

Beta radiation of nuclides	Calibration factor in µGy/s fA	Expanded uncertainty (k = 2) in µGy/s fA	Calibration factor in µGy/s fA	Expanded uncertainty (k = 2) in µGy/s fA	Ratio of calibration factors	Expanded uncertainty of ratio (k = 2)
	VNIIM	**VNIIM**	**PTB**	**PTB**	**PTB/VNIIM**	**PTB/VNIIM**
^{147}Pm	0.0169	0.0004	0.0162	0.0005	0.96	0.022
^{204}Tl and/or ^{85}Kr	0.0233	0.0004	0.0229	0.0003	0.98	0.012
^{90}Sr/^{90}Y	0.0229	0.0004	0.0233	0.0004	1.017	0.014

The agreement of these factors is about 4 % for ^{147}Pm beta radiation and 2 % for ^{90}Sr/^{90}Y, ^{85}Kr and ^{204}Tl beta radiation. The calibration factors of PTB were evaluated by measurements from 14th to 17th November 2001. The calibration factors of VNIIM were determined by measurements at the VNIIM. The expanded uncertainties are determined as described in the next section for an example.

Uncertainty in measurement

The practical procedure for the calculation of the expanded uncertainty of measurement is in accordance with the "Guide to the Expression of Uncertainty in Measurement" first published in 1993 on behalf of BIPM, IEC, IFFC, ISO, IUPAC, IUPAP and OIML[(9)].
The uncertainty analysis for a measurement - sometimes called the uncertainty budget of the measurement - should include a list of all sources of uncertainty together with the associated standard uncertainties of measurement and the methods for evaluating them. For the sake of clarity, it is advisable to present the data relevant to this analysis in the form of a table. In this table all quantities are referenced by a physical symbol or a short identifier. For each of them at least the estimate x_i, the associated standard uncertainty of measurement $u(x_i)$, the sensitivity coefficient c_i and the different uncertainty contributions $u_i(y)$ are specified. The dimension of each of the quantities is also stated with the numerical values given in the table. Table 5 illustrates this procedure for $^{90}Sr/^{90}Y$ examples from both VNIIM and PTB. At the end of the table, the expanded standard uncertainty (k = 2) is documented.

Table 5: Uncertainty budget for the measurement of $^{90}Sr/^{90}Y$ beta radiation

PTB ^{90}**Sr/**^{90}**Y**					**VNIIM** ^{90}**Sr/**^{90}**Y**				
$N = \dot{D}_t(0.07)/(k_{ad}*k_{sat}*k_{pe}*k_{di}*k_{0.07}*k_{ab}*I(d))$					$N = \dot{D}_t(0.07)/(k_{ad}*k_{sat}*k_{pe}*k_{di}*k_{0.07}*k_{ab}*I(d))$				
quantity	x_i	$u(x_i)$	c_i	$u_i(y)$	quantity	x_i	$u(x_i)$	c_i	$u_i(y)$
$\dot{D}_t(0,07)$	10.11 µGy/s	0.06 µGy/s	0.00218 fA^{-1}	0.0001 31 µGy/s fA	$\dot{D}_t(0.07)$	80.1 µGy/s	0.7 µGy/s	0.0002 79 fA^{-1}	0.0001 95 µGy/sfA
$I(d)$	443.35 fA	0.5 fA	-4.98E-05 µGy/s fA^{-2}	-0.000 025 µGy/s fA	$I(d)$	3532 fA	10 fA	-6.32E-06 µGy/s fA^{-2}	-0.000 063 µGy/sfA
k_{ad}	1.0343	0.002	-0.0214 µGy/s fA	-0.000043 µGy/s fA	k_{ad}	1.0092	0.002	-0.022 12 µGy/s fA	-0.000 044 µGy/sfA
k_{sat}	1.0084	0.002	-0.0219 µGy/s fA	-0.000 043 µGy/s fA	k_{sat}	1	0.002	-0.022 32 µGy/s fA	-0.000 045 µGy/sfA
k_{pe}	0.9864	0.002	-0.0224 µGy/s fA	-0.000 045 µGy/s fA	k_{pe}	1	0.002	-0.022 32 µGy/s fA	-0.000 045 µGy/sfA
k_{di}	1.0067	0.005	-0.0219 µGy/s fA	-0.000 11 µGy/s fA	k_{di}	1.0067	0.005	-0.022 17 µGy/s fA	-0.0001 11 µGy/sfA
$k_{0.07}$	0.9967	0.002	-0.0221 µGy/s fA	-0.000 044 µGy/s fA	$k_{0.07}$	1	0.002	-0.0223 µGy/s fA	-0.000 045 µGy/s fA
k_{ab}	1	0.005	-0.0221 µGy/s fA	-0.000 11 µGy/s fA	k_{ab}	1	0.005	-0.022 32 µGy/s fA	-0.0001 12 µGy/sfA
N	0.022 09 µGy/sfA			0.000 223 µGy/sfA	N	0.022 32 µGy/sfA			0.0002 73 µGy/sfA
				0.000 446 µGy/sfA					0.000 546 µGy/sfA

Conclusions

The use of the flat ionisation chamber as transfer chamber turned out to be suitable for comparison measurements in beta radiation fields. The calibration factors of the transfer chamber determined at VNIIM and PTB agree better than 2 %, only for low energy beta radiation up to 4 %. These results show that the primary standards of VNIIM and PTB realise the unit of absorbed dose rate for beta radiation in tissue in a comparably high quality. The results of this comparison fit in very well with the results of former comparisons between PTB and the National Metrology Institutes LPRI (France), NIST (U.S.), NPL (UK), OMH (Hungary), RIS∅ (Denmark) and between VNIIM and the National Metrology Institutes LPRI, NPL, OMH and ASMW (former GDR, up to 1990), shown in Table 6.

Table 6: Summary of comparison results of PTB, ASMW and VNIIM, respectively, and other National Metrology Institutes(NMI), each written as the quotient of the calibration factors

Nuclide	National Metrology Institutes	Year	N_{NMI}/N_{PTB}	Year	N_{NMI}/N_{ASMW}	Year	N_{NMI}/N_{VNIIM}
$^{90}Sr/^{90}Y$	LPRI	1976	0.996	-	-	2000	0.996
	NPL	1978	0.997	-	-	1981	0.943
	NIST	2000	1.014	-	-	-	-
	OMH	1988	1.008	1983 1985 1987	0.994 1.008 1.010	1983	1.008
	VNIIM	1999 2001	0.998 0.983	1971 1983 1987	1.007 1.008 1.008	-	1.000
	PTB	-	1.000	-	-	1999 2001	1.002 1.017
	ASMW	-	-	-	1.000	1971 1983 1987	0.993 0.992 0.992
^{85}Kr and / or ^{204}Tl.	LPRI	1996	1.015	-	-	2000	1.000
	NPL	1978	0.990	-	-	1981	1.034
	NIST	1996	0.995	-	-	-	-
	NIST	2000	1.010	-	-	-	-
	RISO	1996	0.983	-	-	-	-
	OMH	-	-	1983 1985 1987	1.005 0.983 0.990	1983	1.010
	VNIIM	1999 2001	0.991 1.017	1983	1.015	-	1.000
	PTB	-	1.000	-	-	1999 2001	1.009 0.983
	ASMW	-	-	-	1.000	1983	0.985
^{147}Pm	LPRI	-	-	-	-	2000	0.994
	NPL	1978	0.930	-	-	1981	1.033
	NIST	2000	0.990	-	-	-	-
	RISO	1993	1.020	-	-	-	-
	OMH	-	-	1983 1985	0.948 0.994	-	-
	VNIIM	1999 2001	0.982 1.043	1978 1983	1.020 1.014	-	1.000
	PTB	-	1.000	-	-	1999 2001	1.018 0.958
	ASMW	-	-	-	1.000	1978 1983	0.980 0.986

References:

1. Helmstädter, K. and Böhm, J. *The PTB Beta Secondary Standard for the Absorbed Dose to Tissue* Proceedings of the 24th International Symposium on Radiation Protection Physics, Gaussig (near Dresden), FRG, April 6-10, 1992, Published by Dresden University of Technology, Institute of Radiation Protection Physics, pp 259-269 (1992)

2. Ambrosi, P. *Improved Beta Secondary Standard* PTB-News 97.1 (1997)

3. Tarbeyev, Yu. V., Uryaev, I. A., Rumyantseva E. N. and Fominych, V. I. *Metrology of beta radiation dosimetry in Russia* Radiat. Prot. Dosim. **39** (1/3), 105-108 (1991)

4. Böhm, J. *The National Primary Standard of the PTB for Realizing the Unit of the Absorbed Dose Rate to Tissue for Beta Radiation* PTB Report DOS-13 (1986)

5. Drake, K.-H. and Böhm, J. *Automatisierter Meßstand für die Dosimetrie von Betastrahlung* PTB Report DOS-19 (1990)

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

7. Schötzig,U. and Schrader, H. *Halbwertszeiten und Photonen-emissionswahr-scheinlichkeiten von häufig verwendeten Radionukliden* PTB Report Ra-16/6 (2000)

8. ISO 6980-3, 2003 *Reference beta particle radiation – Part 3: Calibration of area and personal dosemeters and determination of their response as a function of energy and angle of incidence*

9. *Guide to the Expression of Uncertainty in Measurement* ISO 1993

TABLE CAPTIONS

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