EURAMET supplementary comparison of ambient dose equivalent $H^*(10)$ in ^{137}Cs and ISO Narrow Beam Series N-60 x-ray beams at low dose rates

EURAMET project No. 1132

BIPM KCDB: EURAMET.RI(I)-S11

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ABSTRACT

Comparison measurements among national standards laboratories are required to demonstrate their equivalence in the realization and transfer of the quantity ambient dose equivalent, $H^*(10)$, for photon radiation by these laboratories.

The first comparison of the radiation protection quantity $H^*(10)$ with focus on the special needs for calibration of area dosemeters, low dose rates and large fields, started in January 2013 and was completed in December 2014. The comparison was piloted by the PTB as EURAMET project No. 1132 known also as EURAMET.RI(I)-S11.

The operation and results of the comparison are reported here. The transfer instrument was a secondary standard ionization chamber for $H^*(10)$ with a volume of 10000 cm^3. The response of this transfer instrument in various photon reference fields (N-60 and 1 mSv/h, S-Cs and 10 µSv/h, S-Cs and 1 mSv/h, radiation quality according to ISO 4037-1:1996 [1]) was compared. Measurements were made by the fourteen participants from the following countries: Germany, Austria, Greece, Norway, Sweden, Finland, Portugal, Spain, Czech Republic, Romania, the Netherlands, Slovenia, Italy and by one international organization. The results obtained by almost all of the participants are consistent with the stated uncertainties.

1 Introduction

The CIPM Mutual Recognition Arrangement (CIPM MRA) is the framework through which National Metrology Institutes demonstrate the international equivalence of measurement standards. In this context, BIPM publishes on its homepage a list of Calibration and Measurement Capabilities (CMC-lists) of the institutes which have signed the MRA. Calibration services can, however, only be included if a quality management system according to ISO standard 17025 is established. However, quality assurance and confidence in the capabilities of other laboratories can be ensured by the successful participation in a comparison in which the degree of equivalence with other national metrology institutes or calibration laboratories is determined.

In the last years the comparison for personal dose equivalent $H_p(10)$ initiated by the Physikalisch-Technische Bundesanstalt (PTB) was performed as a supplementary comparison using the radiation qualities N-15 and 0°, N-20 and 45°, N-30 and 75°, N-60 and 0°, N-120 and 0° [2] . This comparison could be used to some extent for the ambient dose equivalent, $H^*(10)$, as well, because the quantity $H_p(10)$ on the slab phantom for 0° radiation incidence is nearly identical to $H^*(10)$ in the case of unidirectional radiation incidence [3].

It remained that it was quite important to perform an international comparison with the focus on the special needs for calibration of area dosemeters: large radiation fields and low dose rates (10 µSv/h and 1 mSv/h) for the radiation qualities S-Cs and N-60 (only at 1 mSv/h) of the ISO narrow spectrum series.

Measurements at S-Cs with 500 nSv/h are very demanding, because of the very low ionization current to be measured when using an ionization chamber. Therefore, only three laboratories were able to participate at these low dose rates and the results are presented as an appendix to the comparison (Annex B).

For this comparison, a secondary standard ionization chamber for $\dot{H}^*(10)$ with a large active volume of 10000 cm^3 was used as a transfer instrument [4]. The aim of this comparison was to compare the calibration coefficient of the transfer instrument. The circulation of the chamber was in effect a cloverleaf shape, after sending to three participants, the chamber was sent back to the pilot laboratory for testing.

As already has been noted in EURAMET Project #738 [2], there are technical difficulties at low energy x-ray qualities (below 50 kV, e.g. N-60); this comparison does not address this energy range and a further comparison may be necessary.

The comparison was coordinated by the PTB as the pilot laboratory, which has also evaluated the results. After the approval by the CCRI(I) of the official final report, it should be published in Metrologia. In addition, the results will be sent to BIPM for inclusion as a link in the Key Comparison Data Base (KCDB).

The radiation qualities and doserates selected for the comparison were:

N-60 at 1 mSv/h
S-Cs at 10 µSv/h
S-Cs at 1 mSv/h.

All these radiation qualities are according to ISO 4037-1:1996 [1].

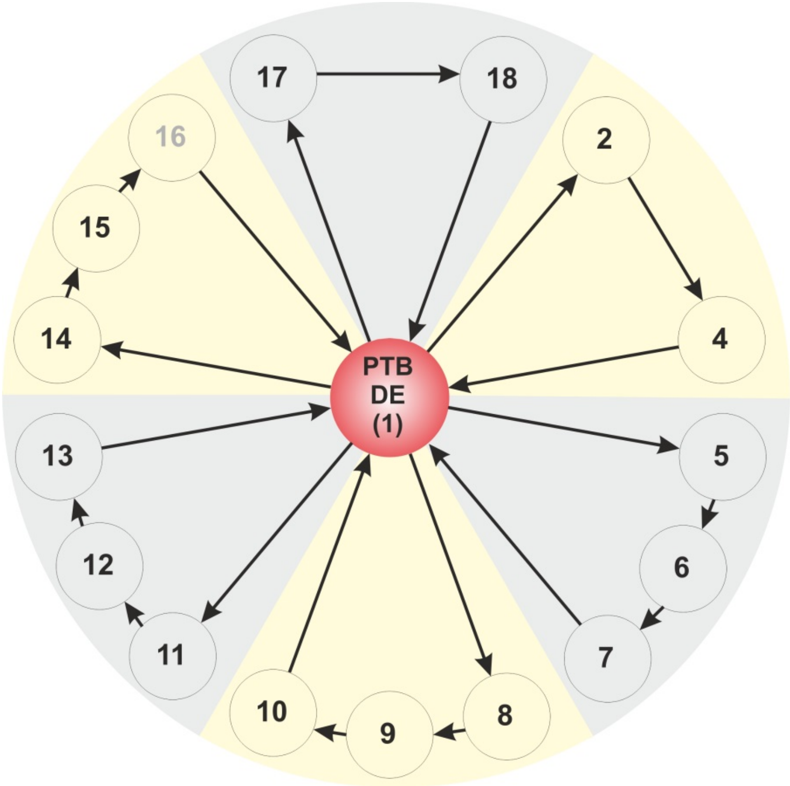
The following time schedule, see Table 1, was agreed among the 16 participants. The start of the comparison was January 2013. After the start of the comparison, the VMT/FTMC/LT withdrew, as well as the BIM /BG. In agreement with all others, the SMU/SK was added as new participant. But unfortunately, after performing the measurements, SMU had to withdraw as well. Additionally, the schedule was changed so that IAEA took part at position 18 instead of position 3 as the IAEA was occupied with other duties for that period. All measurements were finished within the planned schedule.

The MKEH/HU had to be excluded after the measurements, as they did not provide the required uncertainty budget.

Table 1: Schedule

Time	Participant/Country	Quality control checks	remarks
01 / 2013	PTB / DE		1
02 / 2013	BEV / AT		2
03 /2013	-none-		(schedule changed-> 18)
04 /2013	IRCL/GAEC-EIM / GR		4
05 / 2013		PTB / DE	
06 / 2013	NRPA / NO		5
07 / 2013	SSM / SE		6
08 / 2013	STUK / FI		7
09 / 2013		PTB / DE	
10 / 2013	IST-LPSR-LMRI / PT		8
11 / 2013	CIEMAT / ES		9
12 / 2013	CMI / CZ		10
01 / 2014		PTB / DE	
02 / 2014	SMU /SK		11 BIM / BG withdrew
03 / 2014	IFIN-HH / RO		12
04 / 2014	~~MKEH / HU~~		13 excluded
05 / 2014		PTB / DE	
06 / 2014	VSL / NL		14
07 / 2014	IJS / SI		15
08 / 2014	~~VTM/FTMC/LT~~		16 withdrew
09 / 2014		PTB / DE	
10 / 2014	ENEA-INMRI / IT		17
11 / 2014	IAEA / Int. Org.		3 (schedule changed)
12 / 2014		PTB / DE	

The clover leaf circulation scheme is shown in Figure 1.



1	DE	PTB
2	AT	BEV
4	GR	IRCL/GAEC-EIM
5	NO	NRPA
6	SE	SSM
7	FI	STUK
8	PT	IST-LPSR-LMRI
9	ES	CIEMAT
10	CZ	CMI
~~11~~		
12	RO	IFIN-HH
~~13~~	~~HU~~	~~MKEH~~
14	NL	VSL
15	SI	IJS
~~16~~		
17	IT	ENEA-INMRI
18	Int.Org.	IAEA

Figure 1: List of participants and circulation scheme.

Table 2: List of participants and abbreviations:

Abbr.	Institute	Abbr.	Country
BEV	Bundesamt für Eich- und Vermessungswesen	AT	Austria
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas	ES	Spain
CMI	Czech Metrology Institute	CZ	Czech Republic
ENEA-INMRI	Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti	IT	Italy
IAEA	International Atomic Energy Agency	Org. Int.	International Organization
IFIN-HH	Horia Hulubei National Institute of R&D for Physics and Nuclear Engineering	RO	Romania
IJS	Jožef Stefan Institute	SI	Slovenia
IRCL/GAEC-EIM	Ionizing Calibration Laboratory / Greek Atomic Commission-Helenic Institute of Metrology	GR	Greece
IST-LPSR-LMRI	Instituto Superior Técnico	PT	Portugal
~~MKEH~~	~~Hungarian Trade Licensing Office~~	~~HU~~	~~Hungary~~
NRPA	Norwegian Radiation Protection Authority	NO	Norway
PTB	Physikalisch-Technische Bundesanstalt	DE	Germany
SSM	Swedish Radiation Safety Authority	SE	Sweden
STUK	Radiation and Nuclear Safety Authority	FI	Finland
VSL	Dutch Metrology Institute	NL	The Netherlands

2 Measurement conditions

The object of the comparison is the calibration of an ionization chamber in terms of the ambient dose equivalent rate, $\dot{H}^*(10)$. As transfer instrument, a secondary standard chamber for $\dot{H}^*(10)$ [4] was used, see figure 2.

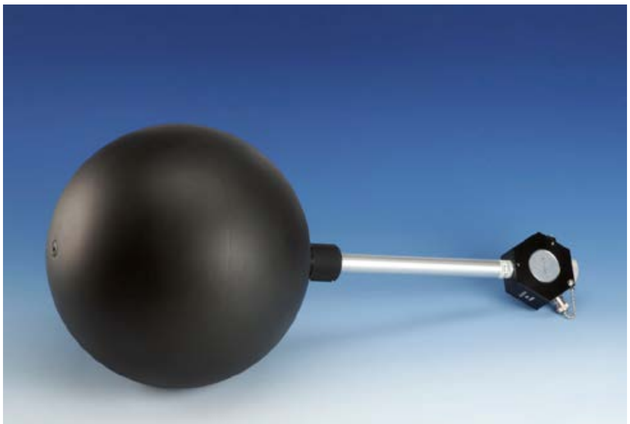


Figure 2: HS10, Secondary standard chamber for $\dot{H}^*(10)$, manufactured by Seibersdorf Labor GmbH.

Figure 3: Holder to mount the chamber on the experimental table.

The uniformity of the doserate distribution across the beam diameter at the measuring point should be about 5 % and better [1]. For calibration purposes the chamber must be irradiated completely.

Technical specification of the ionization chamber:

- Ionization chamber HS10, see figure 2.
- Outer diameter of about 274 mm.
- The chamber voltage should be +400 V (chamber wall).
- Special holder for the chamber for mounting on the experimental table, see figure 3.
- BNC connector for current measurement and Lemo connector for the high voltage supply at the end of the stem.
- For the high voltage: Adaptor with a Lemo (FFA.1S.304.CLAC52) connector to a banana plug (4 mm pin plug).

3 Measurement programme and quantity measured by the participants

Each participant calibrated the transfer chamber at the radiation qualities S-Cs and N-60 of the ISO narrow spectrum series [1]. The calibration coefficient in Sv/C is given by:

$$N_H = \frac{\dot{H}^*(10)}{I}$$

I = current measured by the ionization chamber with the current measuring instruments of the participant, corrected for the environmental influences and the leakage current.

$\dot{H}^*(10)$ = conventional quantity value of the ambient dose equivalent rate determined by the participant.

Measurements were performed at the following radiation qualities and doserates:
N-60 at 1 mSv/h and S-Cs at 10 µSv/h and S-Cs at 1 mSv/h.

Optional Measurement: S-Cs at 0.5 µSv/h
These measurement results are given as an informative Annex B in the report.

The comparison reference value x_R was determined at each radiation quality (see Appendix A) and for each doserate as the weighted mean of the calibration coefficient N_H given by the participants. Only values from participants with traceability for K_a to their own primary standard contributed to the comparison reference value:

N-60 at 1 mSv/h: BEV, PTB, VSL
S-Cs at 10 µSv/h: BEV, IST-LPSR-LMRI, PTB, VSL
S-Cs at 1 mSv/h: BEV, IST-LPSR-LMRI, PTB, VSL
S-Cs at 0.5 µSv/h: PTB

4 Realization of the radiation protection quantity at the participants′ laboratory

The common approach is to measure the air kerma in a given point of the radiation field (using a secondary standard calibrated against an own primary standard or against the primary standard of a different NMI) and multiplying the obtained value by a conversion coefficient given by the standards or determined for the particular reference beam. Few participants have used standards calibrated directly in the quantity $H^*(10)$. The methods for the determination of the conventional quantity vale are described in Table 3.
It has to be emphasized that the relation of $H^*(10)/K_a$, the conversion coefficient, has an important dependence with the photon energy. Due to the fact that the reference fields used by each participant's laboratory have different spectra, an additional uncertainty is introduced during the calibration in the quantity $H^*(10)$.

Table 3: List of participants and their method for the determination of the conventional quantity value of $H^*(10)$

Participant	Quality	$h^*_K(10;R,\alpha)$	Method for the determination of K_a	Determination of conversion coefficients	traceability
PTB	N-60 and 0° S-Cs and 0°	1.59 1.20* * This value was used for the IC. It has been shown that this factor in ISO 4037-3:1999 is incorrect and will be adopted to 1.21 in the new version of ISO 4037-3	N-60: PTW M23361 (cylindrical, 30 cm^3) as transfer chamber, calibrated against the primary standard. S-Cs: For the irradiations at the gamma radiation facility, the doserate of the sources were determined in advance by measurements with the primary standard chambers. In cases where the doserate were too low to measure with the primary standard chambers, a secondary standard chamber with larger volume was used. This secondary standard chamber has been calibrated against the primary standard at higher doserates. [5]	HPGe-spectrometer, spectrum deconvolution and ICRU report 57 [6] monoenergetic values, published as PTB-DOS-34 [7] Conversion coefficient for S-Cs taken from ISO 4037-3:1999 [8]	N-60 and S-Cs K_a: PTB
BEV	N-60 and 0° S-Cs and 0°	1.59 1.20	N-60: Primary standard PKG for K_a at 1350 mm for calibration of LS01. HS10 calibrated at 2500 mm against LS01. S-Cs: Primary standard CC01 for K_a used for calibrating TK30 at 1000 mm. HS10 calibrated at 2500 mm against the TK30.	Conversion coefficients taken from ISO 4037-3:1999 [8]	N-60 and S-Cs K_a: BEV
IRCL/GAEC-EIM	N-60 and 0° S-Cs and 0°	1.59 1.20	PTW TW 32002 (LS-01) and PTW W32003 (LS-10) were used for the determination of the reference value. 1 mSv/h with 10 mm Pb absorber	Conversion coefficients taken from ISO 4037-3:1999 [8]	N-60 and S-Cs K_a: PTB
NRPA	N-60 and 0° S-Cs and 0°	1.59 1.20	N-60: Capintec PM-30 for calibration of Exradin A6. HS10 calibrated against Exradin A6 S-Cs: NE2575, for calibration of Exradin A6. HS10 calibrated against Exradin A6	Conversion coefficients taken from PTB-DOS-34 [7]	N-60: K_a: VSL S-Cs: K_a: BIPM
SSM	N-60 and 0° S-Cs and 0°	1.59 1.20	Secondary standard ionization chamber Exradin A4 (30 cm^3)	Conversion coefficients taken from ISO 4037-3:1999 [8]	N-60: K_a: PTB S-Cs: K_a: BIPM

STUK	N-60 and 0° S-Cs and 0°	1.59 1.20	N-60: NE 2575 S-Cs: TM 32002	Conversion coefficients taken from ISO 4037-3:1999 [8]	N-60 and S-Cs K_a: PTB
IST-LPSR-LMRI	N-60 and 0° S-Cs and 0°	1.59 1.20	N-60: PTW TM 32002 S-Cs: LS01 (ÖFZ)	Conversion coefficients taken from ISO 4037-3:1999 [8]	N-60: K_a: PTB S-Cs: K_a: IST_LPSR_LMRI
LMRI(CIEMAT)	N-60 and 0° S-Cs and 0°	1.59 1.20	N-60 Secondary standard ionization chamber NE 2575C S-Cs: TM 32003 (LS10 with 10 l) S-Cs with 20 mm Pb absorber	Conversion coefficients taken from ISO 4037-3:1999 [8]	N-60: K_a: PTB S-Cs: K_a: NPL
CMI	N-60 and 0° S-Cs and 0°	1.616 1.204	Secondary standard ionization chamber Exradin A4 S-Cs (10 µSv/h) Exradin A4 -> ND-100 chamber	Conversion coefficient determined by using the effective energy method	N-60 and S-Cs K_a: BIPM
IFIN-HH	N-60 and 0° S-Cs and 0°	1.585 1.197 (1 mSv/h) 1.20 (10 µSv/h)	Standard instrument: PTW TM 32003 (LS10 with 10 l)	Standard instrument was calibrated in $H^*(10)$, no additional conversion coefficient.	N-60 and S-Cs K_a: PTB $H^*(10)$: PTB
VSL	N-60 and 0° S-Cs and 0°	1.59 1.20	N-60: Primary air kerma standard chamber (10 cm³), transfer to lower dose rates done by secondary standard ionization chamber Exradin A5 (100 cm³) S-Cs: Primary air kerma standard chamber and three different transfer secondary standard ionization chambers (30 cm³, 1000 cm³ and 10000 cm³)	Conversion coefficients taken from ISO 4037-3:1999 [8]	N-60 and S-Cs K_a: VSL
IJS	N-60 and 0° S-Cs and 0°	1.59 1.20	Secondary standard ionization chamber TM 32003 (LS10 with 10 l) S-Cs with 7 mm Pb and 46 mm Pb absorber	Conversion coefficients taken from ISO 4037-3:1999 [8]	N-60 and S-Cs K_a: MKEH
ENEA-INMRI	N-60 and 0°	1.59	N-60: Primary air kerma standard chamber. Use of transfer chambers for lower dose rates Exradin A4 (30 cm³) and OFZS LS-01 (1000 cm³)	Conversion coefficients taken from ISO 4037-3:1999 [8]	N-60: K_a: ENEA-INMRI

	S-Cs and 0°	1.20 1.22 (0,5 µSv/h)	Secondary standard ionization chamber PTW TM 32002 (LS-01) Use of transfer chamber for lower dose rates OFZS LS-10	S-Cs: *H**(10):direct calibration of LS-01 at BIPM; h^*_K=1.22 given by BIPM	S-Cs: K_a: BIPM *H**(10): BIPM
IAEA	N-60 and 0° S-Cs and 0°		Secondary standard chamber HS01 Secondary standard chamber TM 32003 (LS10 with 10 l S-Cs lower dose rates: Secondary standard chamber LS-10 calibrated at BIPM S-Cs with lead attenuator	Direct measurement of *H**(10)	N-60: *H**(10): PTB S-Cs: *H**(10): BIPM

5 Measurement results

In Table 4 to 6 the values given in the measuring protocols of the participants are listed.

The uncertainty stated is the expanded measurement uncertainty obtained by multiplying the standard measurement uncertainty by the coverage factor k = 2. It has been determined by each participant in accordance with the “Guide to the Expression of Uncertainty in Measurement (GUM)” [9]. The value of the measurand then normally lies, with a probability of approximately 95 %, within the attributed coverage interval.

Table 4: Measurement values given by the participants for S-Cs and 1 mSv/h.

S-Cs 1 mSv/h																				
Participant	Date of measurement	Activity of the Cs-137 -Source	K_a rate	$H^*(10)$ rate	Temperature	Air Pressure	Number of measurements of I_leak	Leakage current, I_leack	Number of measurements of I_meas(net)	Measurement current, I_meas(net)	Ratio of I_leak to I_meas(net)	Distance source to ionisation chamber	Field size, diameter	Conversion coefficient h^*K	Calibration coefficient for air kerma	Uncertainty of calibration coefficient for air kerma (k=2)	Uncertainty of calibration coefficient for air kerma (k=2)	Calibration coefficient for $H^*(10)$	Uncertainty of calibration coefficient $H^*(10)$ (k=2)	Uncertainty of calibration coefficient $H^*(10)$ (k=2)
Abbreviation	yyyy-mm-dd	in GBq	in mGy/h	in mSv/h	in °C	in hPa	No.	in A	No.	in A	1	in m	in cm	in Sv/Gy	in Gy/C	in Gy/C	in %	in Sv/C	in Sv/C	in %
PTB	2013-01-21	n.i.*	0.827	0.993	20.9	993	2	1.3995E-14	10	7.506E-11	0.00019	2.202	53	1.20	3.0613E+03	n.i.*	n.i.*	3.67E+03	100	2.7
BEV	2013-02-08 - 2013-03-11	45	0.863	1.035	20.0 to 21.5	975 to 1000	13	1.1020E-14	4 x 10	7.8495E-11	0.00014	2.0	52	1.20	3.0526E+03	n.i.*	1.5	3.6631E+03	158	4.3
IRCL/GAEC-EIM	2013-04-24	n.i.*	0.8341	1.001	21.7	996.0	12	2E-15	12	7.45E-11	n.i.*	3.30	91.7	1.2	n.i.*	n.i.*	n.i.*	3.73E+03	180	4.83
NRPA	2013-06-12	863	1.104	1.341	21.32	1000.3	5 x 50	9.15E-14	16 x 50	1.0038E-10	0.0009	8.0	188	n.i.*	3.055E+03	61	2.0	3.71E+03	186	5.0
SSM	2013-07-09	37	0.654	0.7852	19.80	1021.9	2	5.36E-14	10	6.097E-11	0.00088	2.0	80	1.20	3.011E+03	36	1.2	3.614E+03	152	4.2
STUK	2013-08-14	100	0.834	1.001	22.8	1001.0	1	2.300E-14	2	7.623E-11	0.0003	3.0	54	1.20	3.041E+03	60.32	2.0	3.649E+03	163	4.5
IST-LPSR-LMRI	2013-10-22	n.i.*	n.i.*	n.i.*	19.9	1005.8	5	4.10E-15	10	6.59E-11	n.i.*	2	30	1.2	n.i.*	n.i.*	n.i.*	3.680E+03	155	4.21
CIEMAT	2013-11-11	722 Pb filter 20 mm	0.831	0.997	19.77	949.0	4	2.625E-15	10	7.477E-11	3.51E-05	2.716	38.0	1.20	3.086E+03	49.99	1.62	3.704E+03	159	4.30
CMI	2014-01-02	450	0.838	1.008	21.6	979.2	4	1.05E-14	7.710E-11	7.709E-11	1.36E-04	6.385	135	1.204	3.016E+03	56	1.88	3.631E+03	68	1.88
IFIN-HH	2014-03-20	38.76	0.83	1.00	20.75	1016.0	10	4.6060E-15	10	7.5601E-11	0.00006	1.83	46.24	1.20	3.0690E+03	39.9	1.3	3.6746E+03	114	3.1
VSL	June, 2014	240	0.86	1.03	21.5	102.0	18	5E-15	27	7.9E-11	≤6E-05	4.5	68	1.20	2.994E+03	93	3.1	3.593E+03	183	5.1
IJS	2014-07-09	85	0.831	1.00	23.8	973.0	5	8.0000E-15	5	7.1400E-11	0.00011	1.86	74	1.20	3.059E+03	42	1.4	3.670E+03	155	4.2
ENEA-INMRI	2014-09-25	42	0.800	0.973	20.2	999.1	1246	-3.47E-15	2937	7.47E-11	-0.00005	2.0	36	1.22	2.973E+03	80	2.7	3.62E+03	100	2.8
IAEA	2014-11 - 2015-01	n.i.*	n.i.*	4.5 to 0.02	n.i.*	n.i.*	n.i.*	5.00E-14	n.i.*	n.i.*	n.i.*	3 to 4.5	80	n.i.*	n.i.*	n.i.*	n.i.*	3.663E+03	40	1.1
		* no information available																		

Table 5: Measurement values given by the participants for S-Cs and 10 µSv/h.

S-Cs 10 µSv/h																				
Participant	Date of measurement	Activity of the Cs-137 -Source	K_a rate	$H^*(10)$ rate	Temperature	Air Pressure	Number of measurements of I_leak	Leackage current, I_leak	Number of measurements of I_meas(net)	Measurement current, I_meas(net)	Ratio of I_leak to I_meas(net)	Distance source to ionisation chamber	Field size, diameter	Conversion coefficient h^*K	Calibration coefficient for air kerma	Uncertainty of calibration coefficient for air kerma (k=2)	Uncertainty of calibration coefficient for air kerma (k=2)	Calibration coefficient for $H^*(10)$	Uncertainty of calibration coefficient $H^*(10)$ (k=2)	Uncertainty of calibration coefficient $H^*(10)$ (k=2)
Abbreviation	yyyy-mm-dd	in MBq	in µGy/h	in µSv/h	in °C	in hPa	No.	in A	No.	in A	1	in m	in cm	in Sv/Gy	in Gy/C	in Gy/C	in %	in Sv/C	in Sv/C	in %
PTB	2013-01-21		8.29	9.954	20.8	993.0	2	1.9879E-14	10	7.572E-13	0.02625	2.180	55	1.20	3.043E+03	n.i.*	n.i.*	3.65E+03	120	3.3
BEV	2013-02-08 - 2013-03-11	442	8.56	10.27	20.0 to 21.5	975 to 1000	13	1.1020E-14	6 x 10	7.7635E-13	0.014	2.0	52	1.20	3.0682E+03	n.i.*	2.1	3.6818E+03	166	4.5
IRCL/GAEC-EIM	2013-04-25	n.i.*	8.79	10.55	21.5	993.0	12	2E-15	12	7.89E-13	n.i.*	2.30	118	10.5	n.i.*	n.i.*	n.i.*	3.71E+03	211	5.67
NRPA	2013-06-13	885	9.509	11.55	21.13	987.7	8 x 50	2.65E-14	17 x 50	8.719E-13	0.030	3.0	70	NA	3.029E+03	61	2.0	3.68E+03	184	5.0
SSM	2013-07-09	1100	7.974	9.569	19.79	1019.6	2	4.366E-14	10	7.862E-13	0.056	3.0	120	1.20	3.004E+03	39	1.3	3.605E+03	151	4.2
STUK	2013-08-14	6	8.30	9.96	22.8	1001.0	1	1.900E-14	2	7.545E-13	0.025	7.400	133	1.20	3.057E+03	80.69	2.6	3.668E+03	176	4.8
IST-LPSR-LMRI	2013-10-21	n.i.*	n.i.*	n.i.*	18.4	1011.0	5	2.70E-15	10	7.88E-13	n.i.*	2	isotropic	1.20	n.i.*	n.i.*	n.i.*	3.708E+03	157	4.23
CIEMAT	2013-11-11	7220 Pb filter 20 mm	8.329	9.994	19.53	946.9	4	-3.363E-15	10	7.471E-13	-4.501E-03	2.575	36.1	1.20	3.097E+03	51.41	1.66	3.716E+03	161	4.34
CMI	2014-01-06	1800	8.333	10.04	20.5	978.8	4	6.2E-15	7.717E-13	7.655E-13	8.10E-03	4.016	85	1.204	3.032E+03	78	2.56	3.650E+03	94	2.56
IFIN-HH	2014-03-24	429	8.5	10.3	20.6	999.7	10	1.0000E-15	10	7.7800E-13	0.001	2.00	50.53	1.20	3.0504E+03	41.5	1.4	3.6589E+03	112	3.1
VSL	June, 2014	2500	8.8	10.6	21.4	102.0	30	5E-15	45	8.2E-13	≤6E-03	4.7	71	1.20	2.993E+03	93	3.1	3.591E+03	183	5.1
IJS	2014-07-10	85	8.3	9.9	23.2	978.0	3	1.2E-14	3	7.2E-13	0.017	2.03	81	1.20	3.068E+03	44	1.4	3.681E+03	156	4.2
ENEA-INMRI	2014-09-26	1.61E+02	8.93	10.86	20.1	1002.1	890	4.144E-15	4450	8.221E-13	0.0050	1.2	36	1.22	2.98E+03	100	3.5	3.63E+03	130	3.6
IAEA	2014-11 - 2015-01	n.i.*	n.i.*	4.5 to 0.02	n.i.*	n.i.*	n.i.*	5.00E-14	n.i.*	n.i.*	n.i.*	3 to 4.5	80	n.i.*	n.i.*	n.i.*	n.i.*	3.663E+03	40	1.1
		* no information available																		

Table 6: Measurement values given by the participants for N-60 and 1 mSv/h.

N-60 1 mSv/h																				
Participant	Date of measurement	X-ray tube current	K_a rate	$H^*(10)$ rate	Temperature	Air Pressure	Number of measurements of I_leak	Leackage current, I_leak	Number of measurements of I_meas(net)	Measurement current, I_meas(net)	Ratio of I_leak to I_meas(net)	Distance source to ionisation chamber	Field size, diameter	Conversion coefficient h^*K	Calibration coefficient for air kerma	Uncertainty of calibration coefficient for air kerma (k=2)	Uncertainty of calibration coefficient for air kerma (k=2)	Calibration coefficient for $H^*(10)$	Uncertainty of calibration coefficient $H^*(10)$ (k=2)	Uncertainty of calibration coefficient $H^*(10)$ (k=2)
Abbreviation	yyyy-mm-dd	in mA	in mGy/h	in mSv/h	in °C	in hPa	No.	in A	No.	in A	1	in m	in cm	in Sv/Gy	in Gy/C	in Gy/C	in %	in Sv/C	in Sv/C	in %
PTB	2013-01-23	0.7	0.618	0.983	19.14	999	6	-4.2260E-15	6	7.740E-11	-0.00005	2.500	40	1.59	2.2191E+03	n.i.*	n.i.*	3.53E+03	110	3.0
BEV	2013-02-08 - 2013-03-11	0.6	0.594	0.945	20.0 - 21.5	975 to 1000	13	1.1020E-14	8 x 10	7.3183E-11	0.00015	2.500	31 resp. 47	1.59	2.2562E+03	n.i.*	1.1	3.5874E+03	165	4.6
IRCL/GAEC-EIM	2013-04-24	n.i.*	0.6465	1.028	21.7	996.0	12	2E-15	12	8.08E-11	n.i.*	3.000	42	1.59	n.i.*	n.i.*	n.i.*	3.54E+03	162	4.58
NRPA	2013-06-17	1.8	0.714	1.136	21.3	999.2	4 x 50	3.55E-14	23 x 50	8.766E-11	0.00040	4.0	64	1.59	2.263E+03	38	1.7	3.60E+03	180	5.0
SSM	2013-07-15	1	0.576	0.916	22.33	1008.7	4	1.2E-14	20	7.072E-11	0.00017	3	58	1.59	2.235.E+03	27	1.2	3.554.E+03	149	4.2
STUK	2013-08-09	1	0.691	1.099	22.7	1008.0	1	2.200E-14	1	8.618E-11	0.0003	3.0	43	1.59	2.229E+03	55.54	2.5	3.543E+03	167	4.7
IST-LPSR-LMRI	2013-10-22	n.i.*	n.i.*	n.i.*	18.9	1005.9	5	0.000E+00	10	1.62E-10	n.i.*	2	40	1.59	n.i.*	n.i.*	n.i.*	3.531E+03	150	4.25
CIEMAT	2013-11-20	0.7	0.637	1.013	19.92	941.7	6	-4.667E-15	5	8.064E-11	-5.787E-05	2.551	40.8	1.59	2.194E+03	29.40	1.34	3.488E+03	147	4.20
CMI	2013-12-31	0.5	0.689	1.113	20.4	996.3	4	3.88E-14	n.i.*	8.471E-11	4.58E-04	2.125	28	1.616	2.255E+03	42	1.90	3.645E+03	76	2.10
IFIN-HH	29.03.2014	0.8	0.64	1.01	20	1010.4	10	1.0000E-15	10	7.8750E-11	0.00001	3.11	75.14	1.59	2.25E+03	20.9	0.9	3.5584E+03	110	3.0
VSL	June, 2014	2.20	0.64	1.02	19.9	102.0	22	5 × E-15	33	79 E-12	≤6 E-05	4.2	42	1.59	2.254 E+03	50	2.2	3.584 × E+03	165	4.6
IJS	2014-07-11	0.9	0.65	1.03	24.2	973.0	1	1.2E-14	3	7.9E-11	0.00015	2.7	43	1.59	2.240E+02	36	1.6	3.562E+03	153	4.3
ENEA-INMRI	2014-10-01	3	0.64	1.02	20.3	1006.8	356	4.81E-14	1780	8.40E-11	0.00057	3.2	54	1.59	2.111E+03	27	1.3	3.36E+03	140	4
IAEA	2014-11 - 2015-01	n.i.*	n.i.*	2.0 to 0.4	n.i.*	n.i.*	n.i.*	5.00E-14	n.i.*	n.i.*	n.i.*	4 to 4.5	59	n.i.*	n.i.*	n.i.*	n.i.*	3.578E+03	118	3.3
		* no information available																		

In the following Figures (4 to 6), the determined calibration coefficients with the stated uncertainties are shown.

Details of reference values and degrees of equivalence are given in Annex A.

The verification of the transfer instrument made at the PTB after a clover leaf of about 3 participants shows the reproducibility of such measurements, see Annex C. The detailed uncertainty budgets of the participants are given in the additional Annex E.

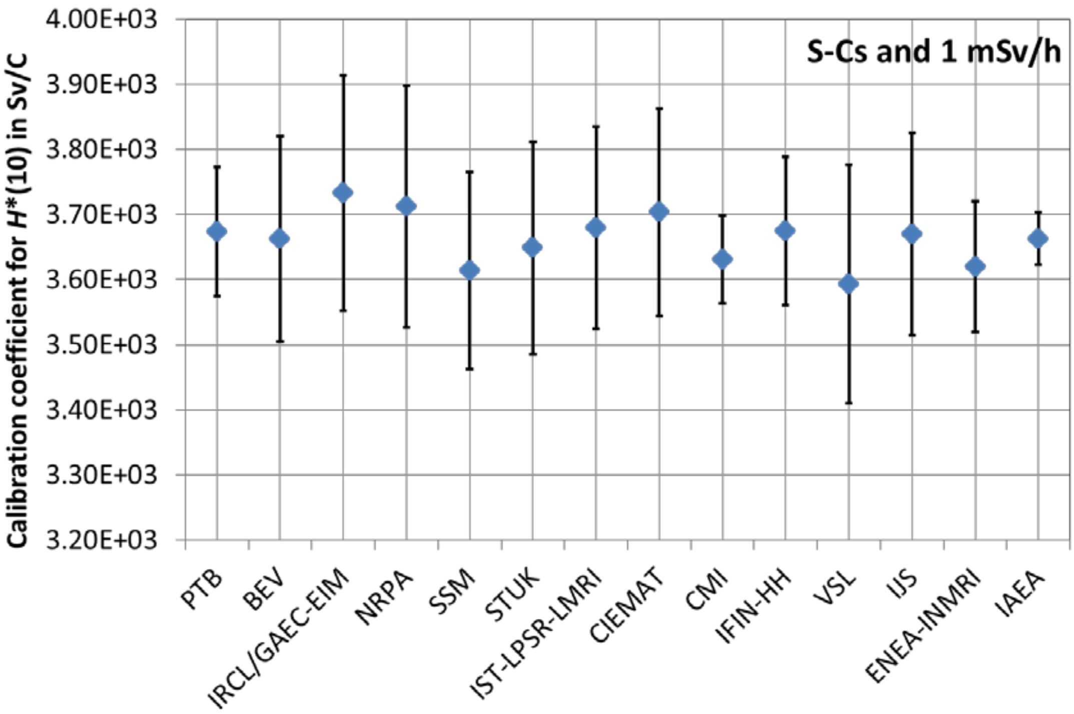


Figure 4: S-Cs and 1 mSv/h; Participants's calibration coefficient and the associated expanded uncertainty (k = 2) determined for the transfer device.

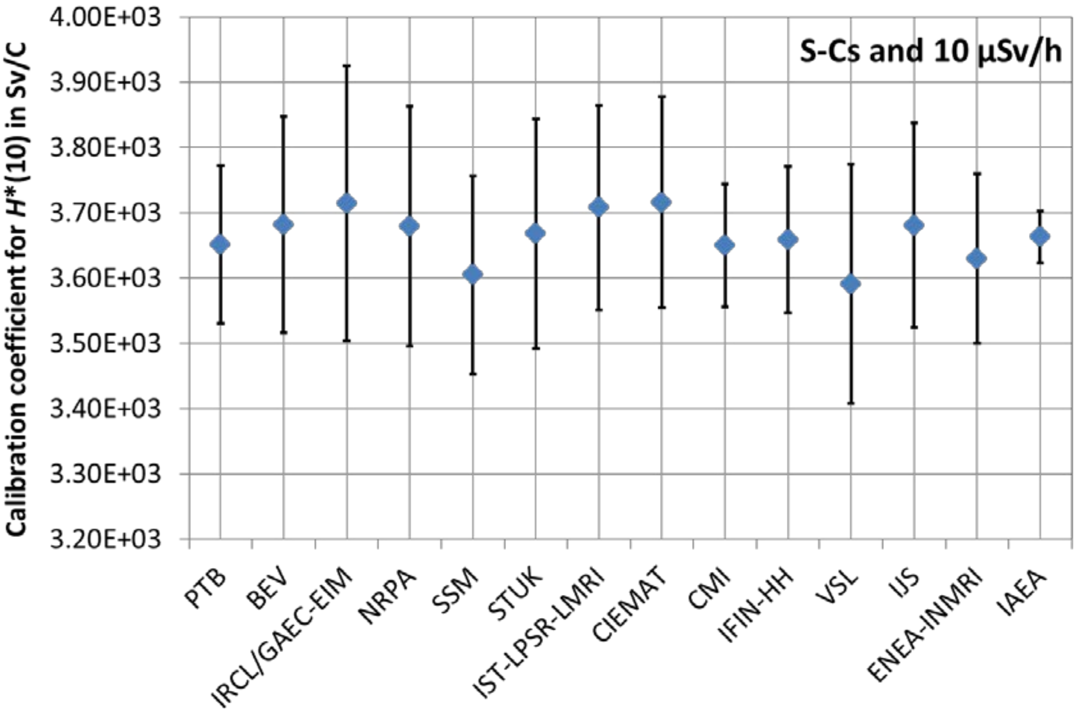


Figure 5: S-Cs and 10 µSv/h; Participant's calibration coefficient and the associated expanded uncertainty (k = 2) determined for the transfer device.

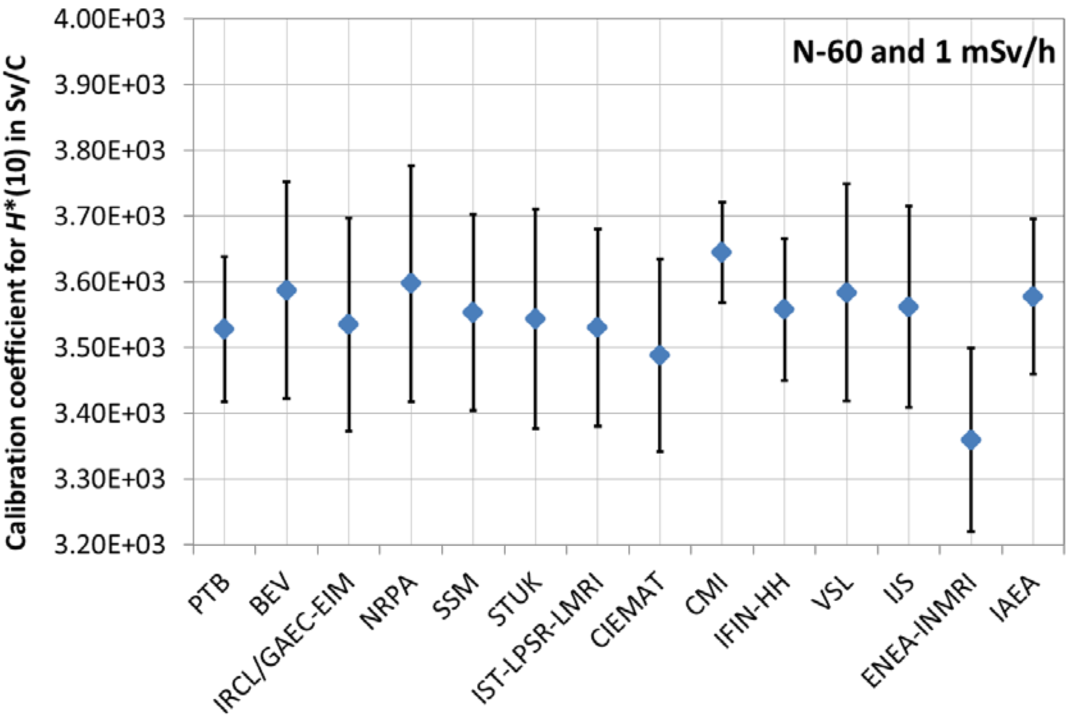


Figure 6: N-60 and 1 mSv/h; Participant's calibration coefficient and the associated expanded uncertainty (k = 2) determined for the transfer device. ENEA-INMRI identified the following: "*The ENEA result for the N-60 x-ray quality was affected by a damage in the x-ray tube tungsten anode, identified after the conclusion of the comparison measurement. A bilateral comparison will be organized by ENEA after the repair/replacement of ENEA medium energy x-ray tube.*"

General remarks:

- All participants stated that the uniformity of their fields fulfilled the required 5 %. No additional uncertainty had to be taken into account.
- CMI determined the air kerma to ambient dose equivalent conversion coefficient by the method of effective energy.
- Although it might be thought that the conversion coefficients are strongly correlated between laboratories, there are differences between the photon spectrum in the laboratory's reference beams and the spectra assumed in ISO 4037-3 [8] for the calculation of the conversion coefficient for the quality S-Cs. These differences have not been evaluated and are different for each laboratory. Therefore, it has been assumed that there is no correlation between results due to the uncertainty in the conversion coefficient, for the quality S-Cs.
- ENEA-INMRI and IAEA are traceable to the BIPM and the conversion coefficient 1.22 used by BIPM
- IRLC/GAEA-EIM, IJS, CIEMAT and IAEA are using lead absorber to reduce the doserate, in accordance with ISO 4037-1:1996 [1]. There was no evidence in the comparison results of a systematic difference arising from the use of an attenuator.

6 Conclusion

The first EURAMET supplementary comparison of ambient dose equivalent for photon radiation (EURAMET project No. 1132 and BIPM KCDB: EURAMET.RI(I)-S11) was performed successfully. The results of most of the participants are consistent within the scope of the assigned uncertainties. The measurements were done with the radiation qualities of S-Cs and the N-series according to ISO 4037-1:1996 [1].

For the N-60, one participant shows a deviation; ENEA-INMRI was off the reference value by more than their stated uncertainty. ENEA-INMRI identified the following: "*The ENEA result for the N-60 x-ray quality was affected by a damage in the x-ray tube tungsten anode, identified after the conclusion of the comparison measurement. A bilateral comparison will be organized by ENEA after the repair/replacement of ENEA medium energy x-ray tube.*"

The reproducibility of the measurements carried out with the transfer chamber was established through repeated measurements made at the PTB over the course of the comparison. The results of these measurements showed that the uncertainty contribution could be neglected.

7 Acknowledgements

The authors would like to thank S. Janßen from the PTB for the extensive calibration measurements at the PTB and the logistical tasks for the shipment of the comparison equipment to the participants.

8 References

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Annex A
Introductory text and degrees of equivalence for the response of the transfer instrument for the measurand ambient dose equivalent *H**(10) for photon radiation

EURAMET comparison:

- EURAMET project No. 1132; CCRI Ref No: EURAMET.RI(I)-S11

Measurand: Calibration coefficient of a transfer chamber for ambient dose equivalent in terms of Sv/C. The uncertainties have been determined by each participant and are given in Annex E

The comparison reference value x_R is determined at each radiation quality and for each doserate as the weighted mean of the calibration coefficient N_H given by the participants, where the weights are equal to the reciprocal of the squares of the associated standard uncertainties. Only values from participants with traceability for K_a to their own primary standard have contributed to the comparison reference value. The data analysis was done according to the publication of M. G. Cox [10].

For the determination of the uncertainty, u_R, of the reference value, x_R, the correlations between each participant have been neglected.

For the determination of the uncertainty of the normalized reference value $\frac{x_i}{x_R}$, the correlation of the participants contributing to the reference value was taken into account. Define:

$$f_i = \frac{x_i}{x_R} \tag{A.1}$$

where: x_i is the value provided by the participant *i* and x_R is the comparison reference value calculated as the weighted mean of the x_i values corresponding only to participating primary laboratories, according to the expression:

$$x_R = \sum_{i=1}^{N} w_i \cdot x_i \quad with \quad \left\{ w_i = \frac{u^2(x_R)}{u^2(x_i)} \right\} \tag{A.2}$$

The summation occurs over all primary laboratories. In this particular case N = 4 for S-Cs and N = 3 for N-60.

The general formula for the uncertainty propagation, considering only the first-order terms and the correlation between the variables x_i and x_{ref} in the equation (A:1) is:

$$u^2(f_i) = \left(\frac{\partial f_i}{\partial x_i}\right)^2 u^2(x_i) + \left(\frac{\partial f_i}{\partial x_R}\right)^2 u^2(x_R) + 2\frac{\partial f_i}{\partial x_i}\frac{\partial f_i}{\partial x_R} cov(x_i, x_R) \tag{A.3}$$

In case of the participating **secondary laboratories,** which did not contribute to the calculation of the comparison reference value, one could consider that x_R and x_i

are independent and non-correlated variables because each institute's measurement was realized independently of the other institute's measurements during the comparison. In this particular case, the covariance between these variables equals zero and the equation (A.3) can be rewritten as:

$$u^2(f_i) = \left(\frac{\partial f_i}{\partial x_i}\right)^2 u^2(x_i) + \left(\frac{\partial f_i}{\partial x_R}\right)^2 u^2(x_R) \tag{A.4}$$

Using equations (A.1) and (A.4) the following relationship for the variance of f_i is thus obtained in case of secondary laboratories:

$$\boxed{u^2(f_i) = f_i^2 \cdot \left[\frac{u^2(x_i)}{x_i^2} + \frac{u^2(x_R)}{x_R^2}\right]} \tag{A.5}$$

However, in case of **primary laboratories** contributing to the calculation of the comparison reference value, the covariance between x_R and x_i (*i* = 1,…,*N*) should be considered in equation (A.3). In this particular case, taking into account the direct dependence of x_R from the variables x_i (*i* = 1,…,*N*) according to the equation (A.2) this covariance can be calculated as:

$$cov(x_i, x_R) = \frac{\partial x_R}{\partial x_i} u^2(x_i) = w_i \cdot u^2(x_i) \tag{A.6}$$

Thus, from equations (A.1), (A.3) and (A.6) the variance of f_i values corresponding to the *N* primary labs is calculated as:

$$u^2(f_i) = \frac{x_i^2}{x_R^2} \cdot \left[\frac{u^2(x_i)}{x_i^2} + \frac{u^2(x_R)}{x_R^2}\right] - 2\frac{x_i}{x_R^3} \cdot w_i \cdot u^2(x_i) \tag{A.7}$$

Substituting $w_i = \frac{u^2(x_R)}{u^2(x_i)}$ in (A.7) the following relationship is obtained:

$$u^2(f_i) = \frac{x_i^2}{x_R^2} \cdot \left[\frac{u^2(x_i)}{x_i^2} + \frac{u^2(x_R)}{x_R^2}\right] - 2\frac{x_i}{x_R^3} \cdot u^2(x_R) \tag{A.8}$$

Transforming the equation (A.8) the following simpler expression is obtained:

$$\boxed{u^2(f_i) = f_i^2 \cdot \left[\frac{u^2(x_i)}{x_i^2} + \frac{u^2(x_R)}{x_R^2} - \frac{2}{f_i} \cdot \frac{u^2(x_R)}{x_R^2}\right]} \tag{A.9}$$

Table A.1: S-Cs and 1 mSv/h Results of the participants and reference values x_R.

Participant i	Radiation quality	Normalized calibration coefficient x_i/x_R	Standard uncertainty $u(x_i/x_R)$, (k = 1)	Reference value x_R	Expanded uncertainty of the reference value U_R (k = 2)
				10^{+3} Sv/C	
PTB	S-Cs and 1 mSv/h	1.003	0.010	3.662	0.068
BEV		1.000	0.019		
IRCL/GAEC-EIM		1.020	0.026		
NRPA		1.014	0.027		
SSM		0.987	0.023		
STUK		0.996	0.024		
IST-LPSR-LMRI		1.005	0.019		
CIEMAT		1.012	0.024		
CMI		0.992	0.013		
IFIN-HH		1.004	0.018		
VSL		0.981	0.023		
IJS		1.002	0.023		
ENEA-INMRI		0.989	0.016		
IAEA		1.000	0.011		

Table A.2: S-Cs and 10 µSv/h Results of the participants and reference values x_R.

Participant i	Radiation quality	Normalized calibration coefficient x_i/x_R	Standard uncertainty $u(x_i/x_R)$, (k = 1)	Reference value x_R	Expanded uncertainty of the reference value U_R (k = 2)
				10^{+3} Sv/C	
PTB	S-Cs and 10 µSv/h	0.998	0.013	3.661	0.075
BEV		1.006	0.020		
IRCL/GAEC-EIM		1.015	0.031		
NRPA		1.005	0.027		
SSM		0.985	0.023		
STUK		1.002	0.026		
IST-LPSR-LMRI		1.013	0.019		
CIEMAT		1.015	0.024		
CMI		0.997	0.016		
IFIN-HH		1.000	0.018		
VSL		0.981	0.023		
IJS		1.006	0.024		
ENEA-INMIR		0.992	0.020		
IAEA		1.001	0.012		

Table A.3: N-60 and 1 mSv/h Results of the participants and reference values x_R.

Participant *i*	Radiation quality	Normalized calibration coefficient x_i/x_R	Standard uncertainty $u(x_i/x_R)$, (k = 1)	Reference value x_R	Expanded uncertainty of the reference value U_R (k = 2)
				10^{+3} Sv/C	
PTB	N-60 and 1 mSv/h	0.992	0.010	3.555	0.080
BEV		1.009	0.020		
IRCL/GAEC-EIM		0.994	0.025		
NRPA		1.012	0.028		
SSM		1.000	0.024		
STUK		0.997	0.026		
IST-LPSR-LMRI		0.993	0.024		
CIEMAT		0.981	0.023		
CMI		1.025	0.016		
IFIN-HH		1.001	0.019		
VSL		1.008	0.020		
IJS		1.002	0.024		
ENEA-INMRI		0.945	0.022		
IAEA		1.006	0.020		

Contents of Tables A.1 to A.3:

- The response values x_i, reported by the participant *i*, are given in Tables 4 to 6.
- The response values, normalized to the reference value, x_i/x_R are given in the third column of tables A.1 to A.3.
- The standard uncertainties of the normalized response values, $u(x_i/x_R)$, were calculated according to the equation A.9 and are presented in the fourth column of tables A.1 to A.3.
- The reference value x_R is determined for each radiation quality and doserate separately, i.e. four reference values were determined:
  1) The comparison reference value x_R is determined at each radiation quality and for each doserate as the weighted mean of the calibration coefficient N_H given by the participants where the weights are equal to the reciprocal of the squares of the associated standard uncertainties, according to the equation A.2.

     Only values from participants with traceability for K_a to their own primary standard will contribute to the comparison reference value.

  2) The standard uncertainty associated with the reference value has been thus calculated using the following equation: $\frac{1}{u^2(x_R)} = \sum_i^{N_c} \frac{1}{u^2(x_i)}$

In Figure A.1 to Figure A.3 the calibration coefficient of the participants with own primary standard relative to the determined comparison reference value x_R is shown. As can be seen by eye, all institutes can contribute to this value within their stated uncertainties.

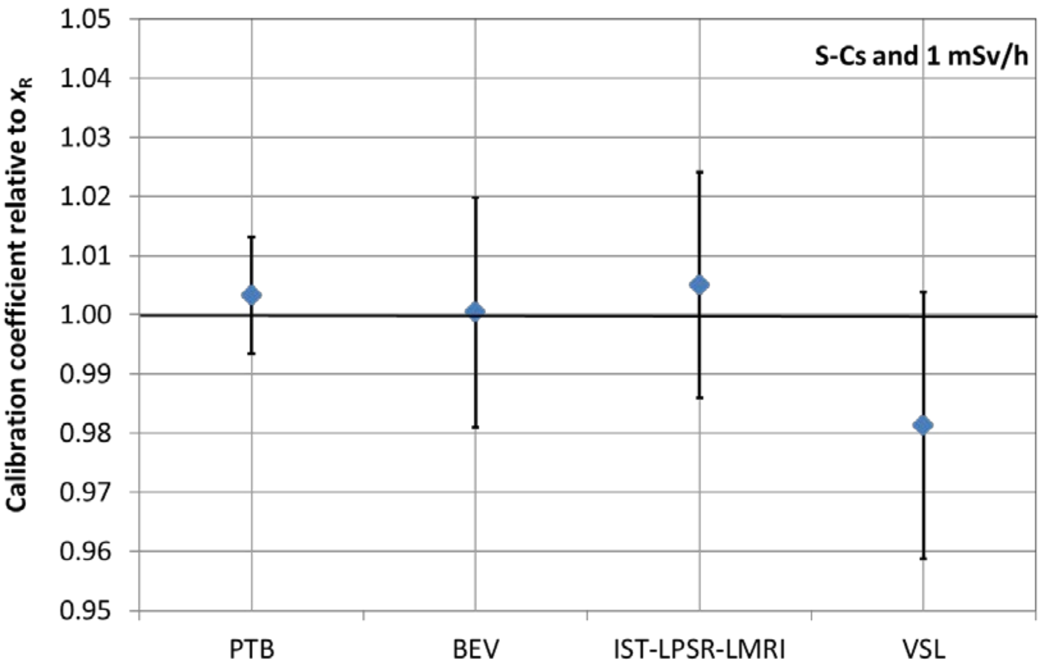

Figure A.1: S-Cs and 1 mSv/h Calibration coefficient for *H**(10) of the participants with own primary standard relative to the determined comparison reference value x_R and the associated relative standard uncertainty.

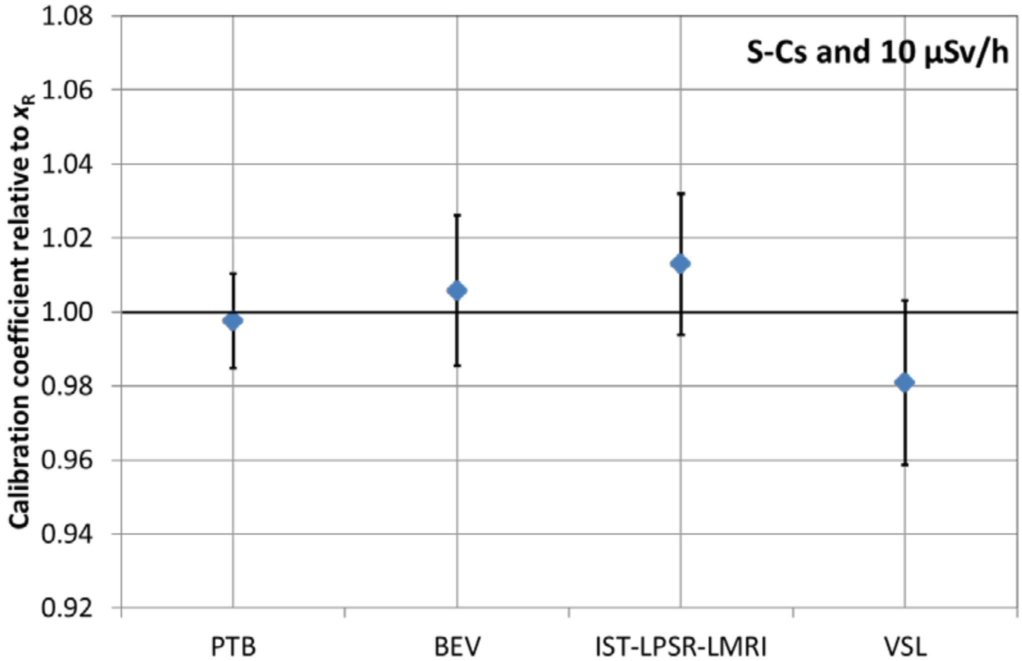

Figure A.2: S-Cs and 10 µSv/h Calibration coefficient for *H**(10) of the participants with own primary standard relative to the determined comparison reference value x_R and the associated relative standard uncertainty.

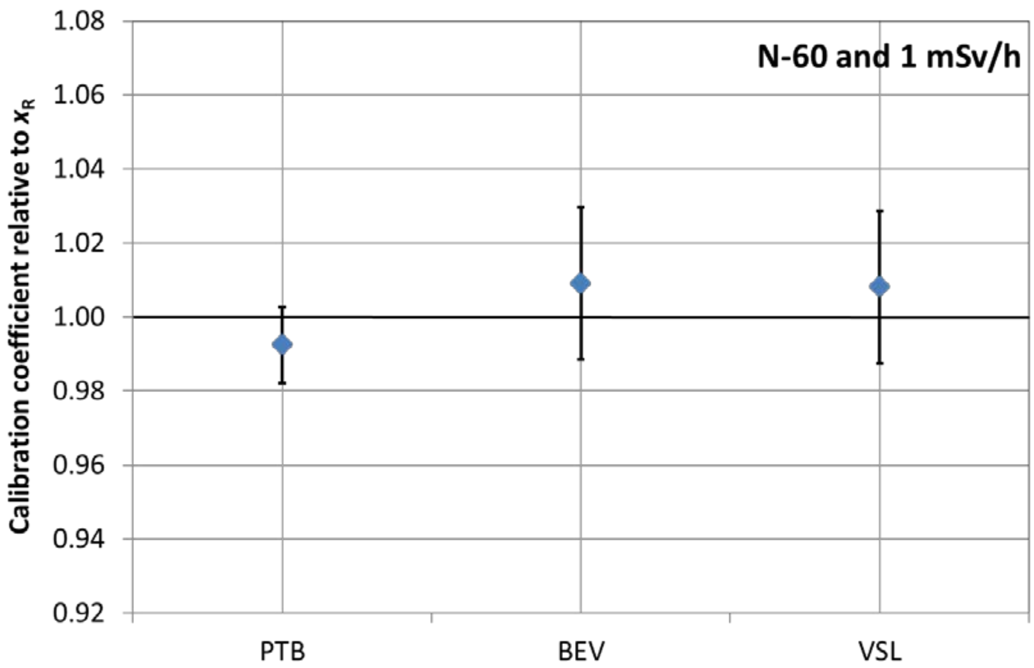

Figure A.3: N-60 and 1 mSv/h Calibration coefficient for *H**(10) of the participants with own primary standard relative to the determined comparison reference value x_R and the associated relative standard uncertainty.

In Figure A.4 to Figure A.6 and Table A.4, the degree of equivalence of each participant *i* relative to the comparison reference value, $x_{R,}$ is given by a pair of terms:

$d_i = (x_i - x_R)$ and its expanded uncertainty U_i, ($k = 2$), both presented as relative values with respect to the comparison reference value, x_R.

To calculate the uncertainty of d_i, the general formula for the uncertainty propagation, considering only the first-order terms and the correlation between the variables x_i and x_R has been used:

$$u^2(d_i) = \left(\frac{\partial d_i}{\partial x_i}\right)^2 u^2(x_i) + \left(\frac{\partial d_i}{\partial x_R}\right)^2 u^2(x_R) + 2\frac{\partial d_i}{\partial x_i}\frac{\partial d_i}{\partial x_R} cov(x_i, x_R) \qquad \text{(A.10)}$$

In case of the participating secondary laboratories, which did not contribute to the calculation of the comparison reference value the covariance between x_i and x_R has been adopted as zero and the equation (A.10) has been rewritten as:

$$u^2(d_i) = \left(\frac{\partial d_i}{\partial x_i}\right)^2 u^2(x_i) + \left(\frac{\partial d_i}{\partial x_R}\right)^2 u^2(x_R)$$

(A.11)

The following relationship for the variance of d_i is thus used in case of secondary laboratories:

$$u^2(d_i) = u^2(x_i) + u^2(x_R) \tag{A.12}$$

In case of **primary laboratories** contributing to the calculation of the comparison reference value, the covariance between x_R and x_i (*i* = 1,…,*N*) has been considered in equation (A.10).

Thus, from equations (A.6) and (A.10), the variance of d_i values corresponding to the *N* primary labs is:

$$u^2(d_i) = u^2(x_i) + u^2(x_R) - 2w_i \cdot u^2(x_i) \tag{A.13}$$

Substituting $w_i = \frac{u^2(x_R)}{u^2(x_i)}$ in (A.13), the following relationship is obtained:

$$u^2(d_i) = u^2(x_i) + u^2(x_R) - 2\frac{u^2(x_R)}{u^2(x_i)} \cdot u^2(x_i) = u^2(x_i) - u^2(x_R) \tag{A.14}$$

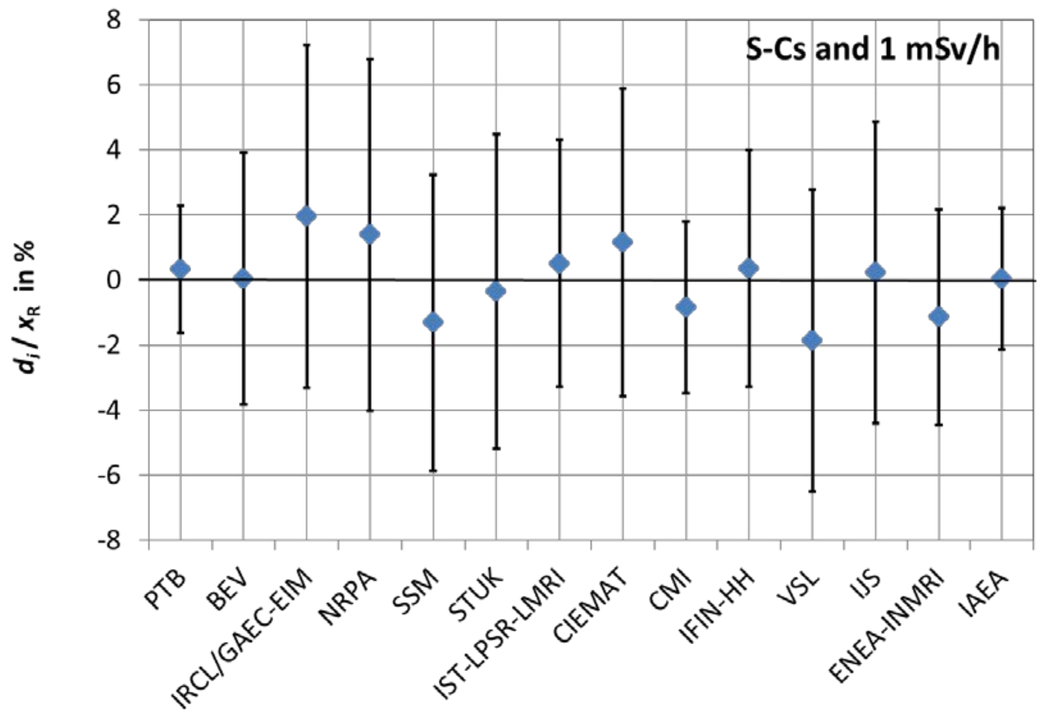

Figure A.4: Degree of equivalence, with the difference $d_i = x_i - x_R$ of each participant *i* relative to the reference value x_R, and the associated expanded uncertainty relative to the reference value x_R, calculated from the standard uncertainties stated by the participants and the uncertainty of the reference value.

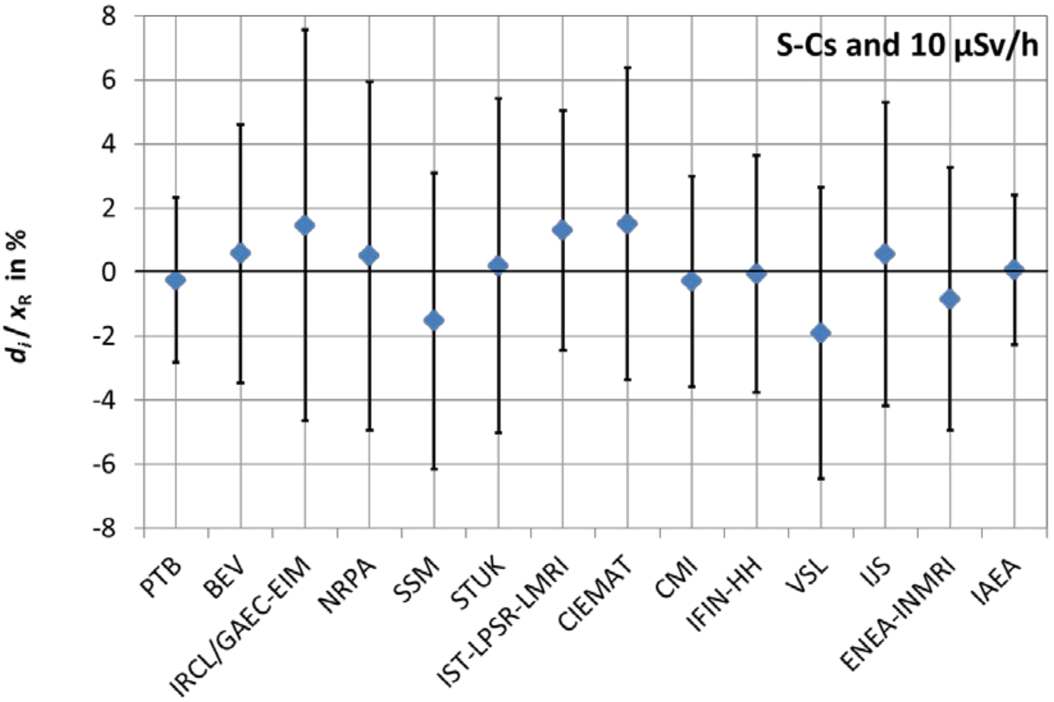

Figure A.5: Degree of equivalence, with the difference $d_i = x_i - x_R$ of each laboratory i relative to the reference value x_R, and the associated expanded uncertainty relative to the reference value x_R, calculated from the standard uncertainties stated by the participants and the uncertainty of the reference value.

IRLC/GAEA-EIM, IST-LPSR-LMRI, IJS and IAEA are using lead absorber to reduce the doserate.

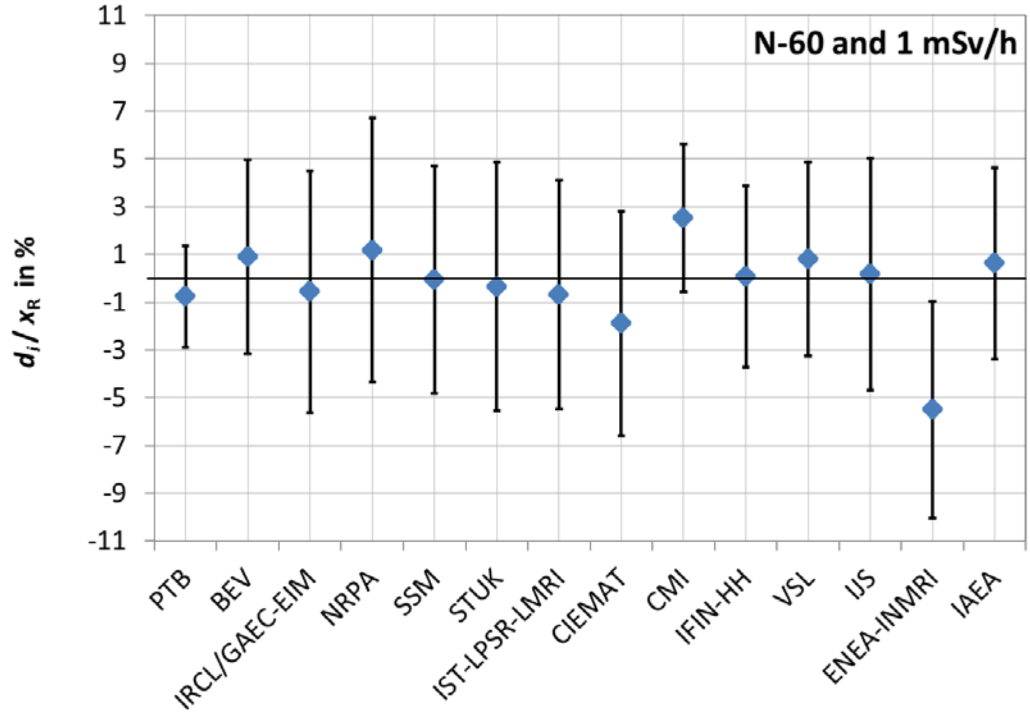

Figure A.6: Degree of equivalence with the difference $d_i = x_i - x_R$ of each laboratory i relative to the reference value x_R, and the associated expanded uncertainty relative to the reference value x_R, calculated from the standard uncertainties stated by the participants and the uncertainty of the reference value.

It can be noted that the ENEA-INMRI is off by more than the stated uncertainty. ENEA-INMRI stated "*The ENEA result for the N-60 x-ray quality was affected by a damage in the x-ray tube tungsten anode, identified after the conclusion of the comparison measurement. A bilateral comparison will be organized by ENEA after the repair/replacement of ENEA medium energy x-ray tube.*"

Table A.4: Degree of equivalence of each laboratory i with respect to the reference value x_R, given by a pair of terms: the difference $d_i = (x_i - x_R)$ and U_i, its expanded uncertainty (k = 2).

	S-Cs and 1 mSv/h		S-Cs and 10 µSv/h		N-60 and 1 mSv/h	
Lab i	d_i/x_R in %	U_i/x_R in %	d_i/x_R in %	U_i/x_R in %	d_i/x_R in %	U_i/x_R in %
PTB	0.33	2.0	-0.25	2.6	-0.76	2.1
BEV	0.04	3.9	0.58	4.0	0.90	4.0
IRCL/GAEC-EIM	2.0	5.3	1.5	6.1	-0.57	5.1
NRPA	1.4	5.4	0.50	5.4	1.2	5.5
SSM	-1.3	4.6	-1.5	4.6	-0.05	4.8
STUK	-0.35	4.8	0.20	5.2	-0.34	5.2
IST-LPSR-LMRI	0.50	3.8	1.3	3.8	-0.68	4.8
CIEMAT	1.2	4.7	1.5	4.9	-1.9	4.7
CMI	-0.84	2.6	-0.29	3.3	2.5	3.1
IFIN-HH	0.36	3.6	-0.05	3.7	0.09	3.8
VSL	-1.9	4.6	-1.9	4.6	0.81	4.0
IJS	0.23	4.6	0.56	4.7	0.19	4.9
ENEA-INMRI	-1.1	3.3	-0.84	4.1	-5.5	4.5
IAEA	0.04	2.2	0.06	2.3	0.64	4.0

Annex B
Optional measurements at S-Cs and 0.5 µSv/h

In this annex the optional measurements at S-Cs and 0.5 µSv/h are shown. These measurements have been performed by three participants. Only PTB has a traceability to an own primary standard for air kerma.

Table B.1: Optional measurement values given by the participants for S-Cs and 0.5 µSv/h.

S-Cs 0.5 µSv/h																				
Participant	Date of measurement	Activity of the Cs-137 - Source	K_a rate	$H^*(10)$ rate	Temperature	Air Pressure	Number of measurements of I_leak	Leackage current, I_leak	Number of measurements of I_meas(net)	Measurement current, I_meas(net)	Ratio of I_leak to I_meas(net)	Distance source to ionisation chamber	Field size, diameter	Conversion coefficient h^*K	Calibration coefficient for air kerma	Uncertainty of calibration coefficient for air kerma (k=2)	Uncertainty of calibration coefficient for air kerma (k=2)	Calibration coefficient for $H^*(10)$	Uncertainty of calibration coefficient $H^*(10)$ (k=2)	Uncertainty of calibration coefficient $H^*(10)$ (k=2)
Abbreviation	yyyy-mm-dd	in GBq	in µGy/h	in µSv/h	in °C	in hPa	No.	in A	No.	in A	1	in m	in cm	in Sv/Gy	in Gy/C	in Gy/C	in %	in Sv/C	in Sv/C	in %
PTB	2012-10-05	n.i.*	0.416	0.499	21.2	993	2	1.31E-14	6	3.81E-14	0.344	3.652	91	1.20	3.036E+03	333	11.0	3.643E+03	400	11
IRCL/GAEC-EIM	2013-04-25	0.053	0.42	0.50	21.5	993	12	2E-15	12	3.84E-14	0.052	3.25	167	1.20	n.i.*	n.i.*	n.i.*	3.63E+03	370	10.9
ENEA-INMRI	2014-10-07	0.47 filter of (16 mm Pb + 3 mm Sn + 3 mm Cu + 3.5 mm Al)	0.383	0.466	20.5	1001.9	534	1.708E-15	2047	3.509E-14	0.049	2.8	50	1.22	3.03E+03	210	7	3.69E+03	260	7

* no information available

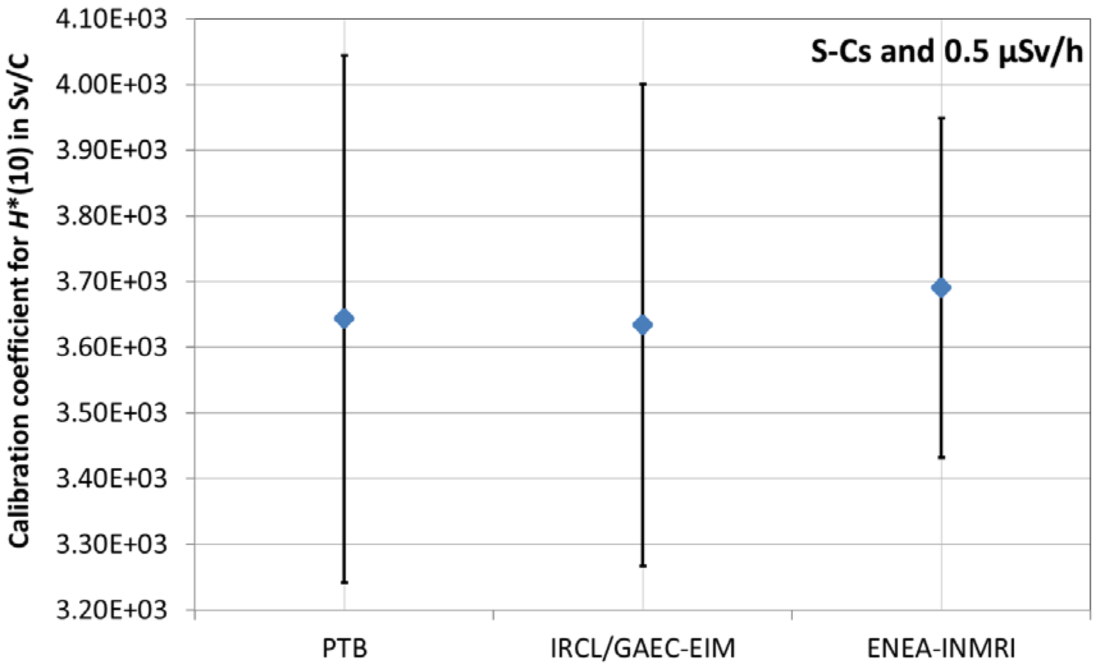

Figure B.1: S-Cs and 0.5 µSv/h; Participant's calibration coefficient for $H^*(10)$ and the associated expanded uncertainty (k = 2) determined for the transfer device.

Table B.2: S-Cs and 0.5 µSv/h Results of the participants and reference values x_R.

Participant *i*	Radiation quality	Normalized response x_i/x_R	Standard uncertainty $u(x_i/x_R)$, (k = 1)	Reference value x_R	Expanded uncertainty of the reference value U_R (k = 2)
				10^{+3} Sv/C	
PTB	S-Cs	1.000	-	3.643	0.401
IRCL/GAEC-EIM	and	0.997	0.074		
ENEA-INMRI	0.5 µSv/h	1.013	0.066		

The reference value, x_R, in this case is the x_i value provided by the PTB, as it is the only participant with own primary standard.

Table B.3: Degree of equivalence of each laboratory *i* with respect to the reference value x_R, given by a pair of terms: the difference $d_i = (x_i - x_R)$ and U_i, its expanded uncertainty ($k = 2$).

	S-Cs and 0.5 µSv/h	
Lab *i*	d_i/x_R in %	U_i/x_R in % ($k = 2$)
IRCL/GAEC-EIM	-0.26	14.91
ENEA-INMRI	1.30	13.09

Annex C
Check of the transfer chamber
Repeated measurements of the calibration coefficient for the transfer instrument at the PTB

After receipt of the transfer chamber, each participant checked it as indicated in the comparison protocol. No damage was reported during the comparison.

The reproducibility of the calibration coefficient, studied at the PTB after each clover leaf, is shown in Figure C.1. The values are normalized to that at the beginning of the comparison. The reproducibility is better than 1 % and no systematic behaviour could be observed.

In May 2014 the calibration at N-60 deviated by about 1 % from the previous and the following measurement values. As this behaviour could neither be observed in both the S-Cs measurements nor in later measurements, it is assumed that its origin is the X-ray irradiation facility and not a systematic effect of the transfer instrument. A change of the energy dependent response of the chamber should have been permanent. As it was not possible to solve this inconsistency by measurement at that time, it was decided to proceed with the comparison and to wait for the next quality check of the transfer instrument a PTB. As expected, it was seen that this effect was not reproducible.

For S-Cs and 1 mSv/h:
Mean value: 1.00148 and standard deviation: 0.0011 (relative deviation of 0.11 %).
For S-Cs and 10 µSv/h:
Mean value: 1.00519 and standard deviation: 0.0036 (relative deviation of 0.36 %).
For N-60 and 1 mSv/h:
Mean value: 0.99975 and standard deviation: 0.0051 (relative deviation of 0.51 %).

The long term stability of the leakage current is shown in Figure C.2

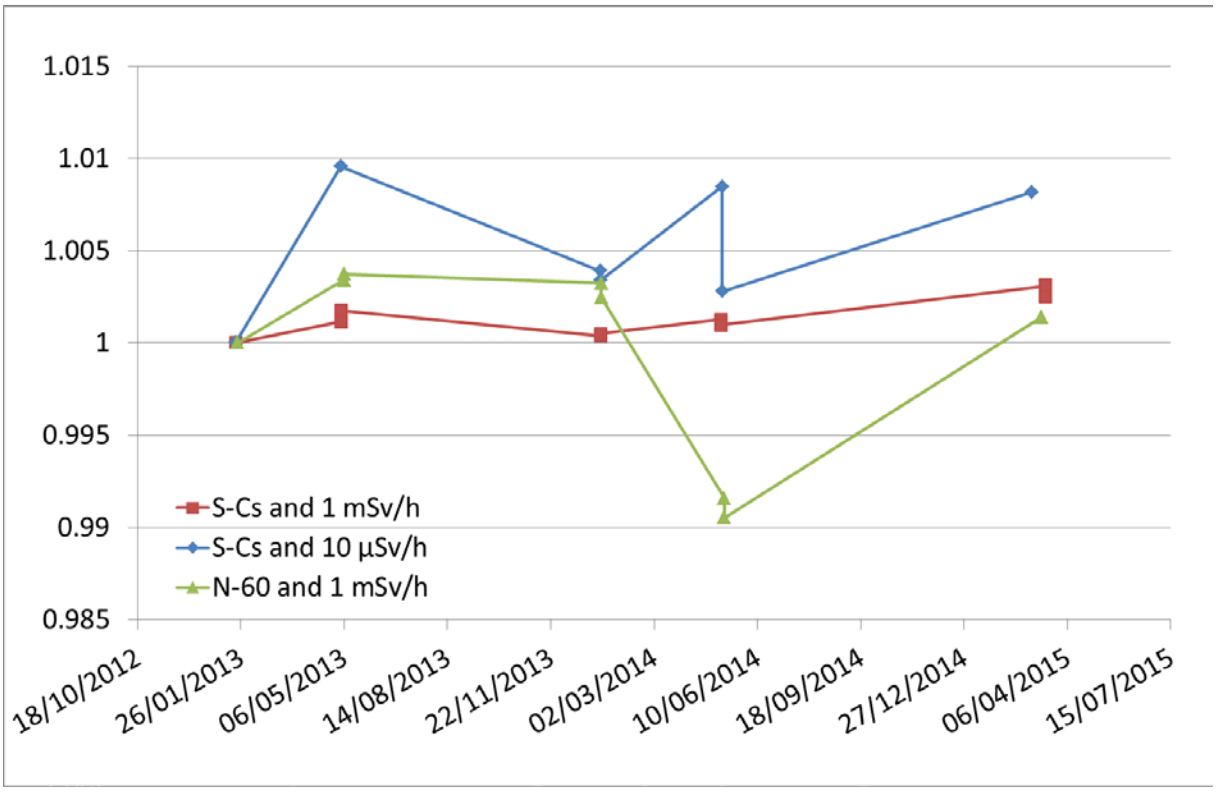

Figure C.1: Reproducibility of the calibration coefficient vs. time measured at the PTB irradiation facilities after each clover leaf. The values are normalized to that at the beginning of the comparison.

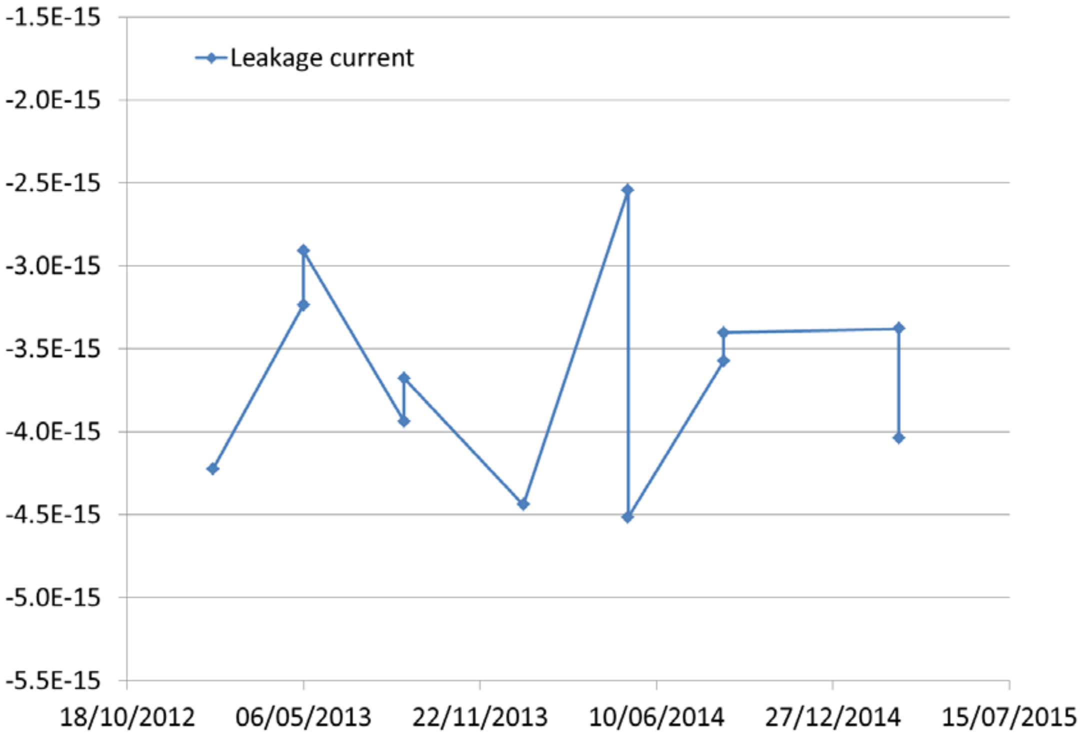

Figure C.2: Stability of the leakage current vs. time measured at the PTB irradiation facilities after each clover leaf. The measurements have been performed at the facility for the N-60 radiation.

Annex D
Addresses of the participants

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ANNEX E

Uncertainty budgets as submitted by the participants

Index

Physikalisch-Technische Bundesanstalt (PTB)

Appendix B: Uncertainty budgets of the measurements:

B.1: N-60 and 1 mSv/h

N-60 and 1 mSv/h	Uncertainty budget for calibration of the HS10-218 ionisation chamber within the EURAMET project 1132: Radiation quality N-60 at 1 mSv/h	PTB

Uncertainty budget for calibration of the HS10-218 ionisation chamber within the EURAMET project 1132: Radiation quality N-60 at 1 mSv/h

The value of H*(10) is determined by the product of air kerma at the reference point and the conversion coefficient h_{SK} . The value of the air kerma at the reference point is given by the calibrated monitor chamber of the X-ray facility. The uncertainty contributions from humidity, temperature and air pressure are negligible. The uncertainty contribution due to the shutter time is neglected as well. The influence of the change of air density on the conversion coefficient from air kerma to H*(10) between the time of calibrating the monitor chamber and the time of irradiating the device under test can be neglected at this radiation quality.

Model Equation:

$$N_{HS}=N_{Ka}*k_{MK}*I_{MK}*sqr(rn)/sqr(rp)*h_{SK}*k_{inhom}/(M-Ugr)$$

List of Quantities:

Quantity	Unit	Definition
N_{HS}	Sv/C	Calibration factor of device under test for the measurand H*(10)
N_{Ka}	Gy/C	Calibration factor of monitor chamber
k_{MK}		Correction factor for longterm stability of the monitor chamber (AA6300-110: 5.2-2)
I_{MK}	A	Current of the monitor chamber during irradiation of the device under test, Leackage current is neglected (less than 0.1%)
rn	mm	Distance between the standard chamber during calibration of the monitor chamber and focal spot; Uncertainty is taken into account in the uncertainty of kMK
rp	mm	Distance between device under test and the focal spot
h_{SK}	Sv/Gy	Conversion coefficient from air kerma to H*(10)
k_{inhom}		Correction factor for inhomogenity of the radiation field
M	A	Current of device under test, during irradiation
Ugr	A	Leackage current of device under test, without additional radiation

N_{Ka}:
Type B normal distribution
Value: $2.244 \cdot 10^{+4}$ Gy/C
Expanded Uncertainty: 2 %
Coverage Factor: 2

k_{MK}:
Type B normal distribution
Value: 1
Expanded Uncertainty: 0.4 %
Coverage Factor: 2

I_{MK}:
Type B normal distribution
Value: $7.6543 \cdot 10^{-12}$ A
Expanded Uncertainty: 0.1 %
Coverage Factor: 1

rn:
Type B rectangular distribution
Value: 2500 mm
Halfwidth of Limits: 0 mm

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N-60 and 1 mSv/h	Uncertainty budget for calibration of the HS10-218 ionisation chamber within the EURAMET project 1132: Radiation quality N-60 at 1 mSv/h	PTB

rp: Type B rectangular distribution
Value: 2500 mm
Halfwidth of Limits: 2 mm

h_{SK}: Type B normal distribution
Value: 1.59 Sv/Gy
Expanded Uncertainty: 2 %
Coverage Factor: 2

k_{inhom}: Type B normal distribution
Value: 1
Expanded Uncertainty: 1 %
Coverage Factor: 2

M: Type B normal distribution
Value: $7.7407 \cdot 10^{-11}$ A
Expanded Uncertainty: $2.1085 \cdot 10^{-14}$ A
Coverage Factor: 1

Ugr: Type B normal distribution
Value: $4.2260 \cdot 10^{-15}$ A
Expanded Uncertainty: $1.3617 \cdot 10^{-15}$ A
Coverage Factor: 1

Uncertainty Budgets:

N_{HS}: **Calibration factor of device under test for the measurand H*(10)**

Quantity	Value	Standard Uncertainty	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
N_{Ka}	22440 Gy/C	224 Gy/C	normal	0.16	35 Sv/C	43.3 %
k_{MK}	1.00000	$2.00 \cdot 10^{-3}$	normal	3500	7.1 Sv/C	1.7 %
I_{MK}	$7.65430 \cdot 10^{-12}$ A	$7.65 \cdot 10^{-15}$ A	normal	$460 \cdot 10^{12}$	3.5 Sv/C	0.4 %
rn	2500.0 mm	0.0 mm	rectangular	0.0	0.0 Sv/C	0.0 %
rp	2500.00 mm	1.15 mm	rectangular	-2.8	-3.3 Sv/C	0.4 %
h_{SK}	1.5900 Sv/Gy	0.0159 Sv/Gy	normal	2200	35 Sv/C	43.3 %
k_{inhom}	1.00000	$5.00 \cdot 10^{-3}$	normal	3500	18 Sv/C	10.8 %
M	$77.4070 \cdot 10^{-12}$ A	$21.1 \cdot 10^{-15}$ A	normal	$-46 \cdot 10^{12}$	-0.96 Sv/C	0.0 %
Ugr	$4.23 \cdot 10^{-15}$ A	$1.36 \cdot 10^{-15}$ A	normal	$46 \cdot 10^{12}$	0.062 Sv/C	0.0 %
N_{HS}	3528.3 Sv/C	53.6 Sv/C				

Results:

Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
N_{HS}	3530 Sv/C	3.0 % (relativ)	2.00	95% (t-table 95.45%)

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B.2: S-Cs and 10 µSv/h

S-Cs and 10 µSv/h	Uncertainty budget for calibration of the HS10-218 ionisation chamber within the EURAMET project 1132: Radiation quality S-Cs at 10 µSv/h	PTB

Uncertainty budget for calibration of the HS10-218 ionisation chamber within the EURAMET project 1132: Radiation quality S-Cs at 10 µSv/h

Value of H*(10) results from the value of air kerma free-in-air and the conversion coefficient h_{SK} (ISO 4037-3). The correction factor for influence of PMMA build-up plate is neglected, because the chamber wall was thick enough to ensure secondary electron equilibrium.The value for air kerma at the reference point is given in the protocol of the gamma radiation facility. The uncertainty contributions from humidity, temperature and air pressure are negligible.

Model Equation:

N_{HS}=Ka/(I-I_0)*sqr(r0)/sqr(r)*h_{SK}*k_{inhom}*k_{nu}*k_ρ

List of Quantities:

Quantity	Unit	Definition
N_{HS}	Sv/C	Calibration factor of device under test for the measurand H*(10)
Ka	Gy/s	Air kerma rate at the reference point
I	A	Current of device under test, during irradiation
I_0	A	Leackage current of device under test, without additional radiation
r0	mm	Nominal distance of the device under test
r	mm	Distance of the standard chamber during calibration of the source
h_{SK}	Sv/Gy	Conversion coefficient from air kerma to H*(10)
k_{inhom}		Correction factor for inhomogenity of the radiation field
k_{nu}		Correction factor for reproducebility of source position
k_ρ		Correction for influence of air density

Ka:
Type B normal distribution
Value: $2.3041 \cdot 10^{-9}$ Gy/s
Expanded Uncertainty: 1.68 %
Coverage Factor: 2

I:
Type A summarized
Mean: $7.77044 \cdot 10^{-13}$ A
Standard Uncertainty: 0.28 %
Degrees of Freedom: 10

I_0:
Type A summarized
Mean: $1.9879 \cdot 10^{-14}$ A
Standard Uncertainty: 30 %
Degrees of Freedom: 2

r0:
Constant
Value: 2180 mm

r:
Type B rectangular distribution
Value: 2180 mm
Halfwidth of Limits: 2 mm

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h_{SK}: Type B normal distribution
Value: 1.2 Sv/Gy
Expanded Uncertainty: 1 %
Coverage Factor: 1

k_{inhom}: Type A summarized
Mean: 1
Standard Uncertainty: 0.002
Degrees of Freedom: 10

k_{nu}: Type B normal distribution
Value: 1
Expanded Uncertainty: 0.005
Coverage Factor: 1

k_{ρ}: Type B normal distribution
Value: 1
Expanded Uncertainty: 0.00027
Coverage Factor: 2

Uncertainty Budgets:

N_{HS}: **Calibration factor of device under test for the measurand H*(10)**

Quantity	Value	Standard Uncertainty	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
Ka	$2.3041 \cdot 10^{-9}$ Gy/s	$19.4 \cdot 10^{-12}$ Gy/s	normal	$1.6 \cdot 10^{12}$	31 Sv/C	26.0 %
I	$777.04 \cdot 10^{-15}$ A	$2.18 \cdot 10^{-15}$ A	normal	$-4.8 \cdot 10^{15}$	-10 Sv/C	3.0 %
I_0	$19.88 \cdot 10^{-15}$ A	$5.96 \cdot 10^{-15}$ A	normal	$4.8 \cdot 10^{15}$	29 Sv/C	22.9 %
r0	2180.0 mm					
r	2180.00 mm	1.15 mm	rectangular	-3.4	-3.9 Sv/C	0.4 %
h_{SK}	1.2000 Sv/Gy	0.0120 Sv/Gy	normal	3000	37 Sv/C	36.9 %
k_{inhom}	1.00000	$2.00 \cdot 10^{-3}$	normal	3700	7.3 Sv/C	1.5 %
k_{nu}	1.00000	$5.00 \cdot 10^{-3}$	normal	3700	18 Sv/C	9.2 %
k_{ρ}	1.000000	$135 \cdot 10^{-6}$	normal	3700	0.49 Sv/C	0.0 %
N_{HS}	3651.7 Sv/C	60.1 Sv/C				

Results:

Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
N_{HS}	3650 Sv/C	3.3 % (relativ)	2.00	95% (normal)

B.3: S-Cs and 1 mSv/h

S-Cs and 1 mSv/h	Uncertainty budget for calibration fo the HS10-218 ionisation chamber within the EURAMET project 1132: Radiation quality S-Cs at 1 mSv/h	PTB

Uncertainty budget for calibration fo the HS10-218 ionisation chamber within the EURAMET project 1132: Radiation quality S-Cs at 1 mSv/h

Value of H*(10) results from the avlue of air kerma free-in-air and the conversion coefficient h_{SK} (ISO 4037-3). The correction factor for influence of PMM build-up plate is neglected, because the chamber wall was thick enough to ensure secondary electron equilibrium.The value for air kerma at the reference point is given in the protocol of the gamma radiation facility.

Model Equation:

N_{HS}=Ka/(I-I_0)*sqr(r0)/sqr(r)*h_{SK}*k_{inhom}*k_{nu}*k_ρ

List of Quantities:

Quantity	Unit	Definition
N_{HS}	Sv/C	Calibration factor of device under test for the measurand H*(10)
Ka	Gy/s	Air kerma rate at the reference point
I	A	Current of device under test, during irradiation
I_0	A	Leackage current of device under test, without additional radiation
r0	mm	Nominal distance of the devive under test
r	mm	Distance of the device under test
h_{SK}	Sv/Gy	Conversion coefficient from air kerma to H*(10)
k_{inhom}		Correction factor for inhomogenity of the radiation field
k_{nu}		Correction factor for reproducebility of source position
k_ρ		Correction for influence of air density

Ka: Type B normal distribution
Value: $229.77 \cdot 10^{-9}$ Gy/s
Expanded Uncertainty: 1.5 %
Coverage Factor: 2

I: Type A summarized
Mean: $7.50719 \cdot 10^{-11}$ A
Standard Uncertainty: 0.06 %
Degrees of Freedom: 10

I_0: Type A summarized
Mean: $1.399525 \cdot 10^{-14}$ A
Standard Uncertainty: 33 %
Degrees of Freedom: 2

r0: Constant
Value: 2202 mm

r: Type B rectangular distribution
Value: 2202 mm
Halfwidth of Limits: 2 mm

h_{SK}: Type B normal distribution
Value: 1.2 Sv/Gy
Expanded Uncertainty: 1 %
Coverage Factor: 1

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k_{inhom}: Type A summarized
Mean: 1
Standard Uncertainty: 0.002
Degrees of Freedom: 10

k_{nu}: Type B normal distribution
Value: 1
Expanded Uncertainty: 0.005
Coverage Factor: 1

k_ρ: Type B normal distribution
Value: 1
Expanded Uncertainty: 0.00027
Coverage Factor: 2

Uncertainty Budgets:

N_{HS}: **Calibration factor of device under test for the measurand H*(10)**

Quantity	Value	Standard Uncertainty	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
Ka	$229.77 \cdot 10^{-9}$ Gy/s	$1.72 \cdot 10^{-9}$ Gy/s	normal	$16 \cdot 10^{9}$	28 Sv/C	30.1 %
I	$75.0719 \cdot 10^{-12}$ A	$45.0 \cdot 10^{-15}$ A	normal	$-49 \cdot 10^{12}$	-2.2 Sv/C	0.2 %
I_0	$14.00 \cdot 10^{-15}$ A	$4.62 \cdot 10^{-15}$ A	normal	$49 \cdot 10^{12}$	0.23 Sv/C	0.0 %
r0	2202.0 mm					
r	2202.00 mm	1.15 mm	rectangular	-3.3	-3.9 Sv/C	0.6 %
h_{SK}	1.2000 Sv/Gy	0.0120 Sv/Gy	normal	3100	37 Sv/C	53.6 %
k_{inhom}	1.00000	$2.00 \cdot 10^{-3}$	normal	3700	7.3 Sv/C	2.1 %
k_{nu}	1.00000	$5.00 \cdot 10^{-3}$	normal	3700	18 Sv/C	13.4 %
k_ρ	1.000000	$135 \cdot 10^{-6}$	normal	3700	0.50 Sv/C	0.0 %
N_{HS}	3673.5 Sv/C	50.2 Sv/C				

Results:

Quantity	Value	Expanded Uncertainty	Coverage factor	Coverage
N_{HS}	3670 Sv/C	2.7 % (relativ)	2.00	95% (t-table 95.45%)

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N60 - 1 mSv/h	Messung der Luftkerma mit Primärnormal PKG bei 25,9 mGy/h in 1350 mm mit 7 mA		0.37	0.14						
	Kalibrierung LS01 bei 25,9 mGy/h in 1350 mm mit 7 mA		0.20	0.04						
	Messung der Luftkerma mit LS01 bei 0,60 mGy/h in 2500 mm mit 0,6 mA		0.20	0.04						
	Kalibrierung HS10 bei 0,60 mGy/h in 2500 mm mit 0,6 mA		0.30	0.09	Summe:	0.31	Wurzel:	0.55	2*Wurzel:	1.1 (Ka)
	Abstand größer als 2 m (ISO 4037-3)		1.00	1.00						
	Konversion von Ka auf Hp(10) (ISO 4037-3)		2.00	4.00						
		Summe:		5.31						
		Wurzel:		2.30						
		2*Wurzel:		4.6 H*(10)						

Cs-137 - 1 mSv/h	Messung der Luftkerma mit Primärnormal CC01 bei 164 mGy/h in 1000 mm mit Q5 (2,1 TBq)		0.50	0.25						
	Kalibrierung TK30 bei 164 mGy/h in 1000 mm mit Q5 (2,1 TBq)		0.20	0.04						
	Messung der Luftkerma mit TK30 bei 40,5 mGy/h in 2000 mm mit Q5		0.20	0.04						
	Kalibrierung LS01 bei 40,5 mGy/h in 2000 mm mit Q5		0.20	0.04						
	Messung der Luftkerma mit LS01 bei 0,86 mGy/h in 2000 mm mit Q4 (45 GBq)		0.30	0.09						
	Kalibrierung HS10 bei bei 0,86 mGy/h in 2000 mm mit Q4 (45 GBq)		0.30	0.09	Summe:	0.55	Wurzel:	0.74	2*Wurzel:	1.5 (Ka)
	Konversion von Ka auf Hp(10) (ISO 4037-3)		2.00	4.00						
		Summe:		4.55						
		Wurzel:		2.13						
		2*Wurzel:		4.3 H*(10)						

Cs-137 - 10 µSv/h	Messung der Luftkerma mit Primärnormal CC01 bei 164 mGy/h in 1000 mm mit Q5 (2,1 TBq)		0.50	0.25						
	Kalibrierung TK30 bei 164 mGy/h in 1000 mm mit Q5 (2,1 TBq)		0.20	0.04						
	Messung der Luftkerma mit TK30 bei 40,5 mGy/h in 2000 mm mit Q5		0.20	0.04						
	Kalibrierung LS01 bei 40,5 mGy/h in 2000 mm mit Q5		0.20	0.04						
	Messung der Luftkerma mit LS01 bei 8,59 µGy/h in 2000 mm mit Q6 (442 MBq)		0.60	0.36						
	Kalibrierung HS10 bei bei 8,59 µGy/h in 2000 mm mit Q4 (442 MBq)		0.60	0.36	Summe:	1.09	Wurzel:	1.04	2*Wurzel:	2.1 (Ka)
	Konversion von Ka auf Hp(10) (ISO 4037-3)		2.00	4.00						
		Summe:		5.09						
		Wurzel:		2.26						
		2*Wurzel:		4.5 H*(10)						

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Table 2 presents the measured H*(10) values under the irradiation conditions reported in table 1.

Table 2: *The irradiation conditions applied for this comparison*

Radiation Quality	Air kerma µGy/h	Conversion coefficient h Distance, cm	H*(10) µSv/h	Uncertainty of H*(10) K=2
S-Cs (1mSv/h)	834.1	1.20	1001	4.54 %
S-Cs (10µSv/h)	8.79	1.20	10.55	5.22 %
N-60 (1mSv/h)	646.5	1.59	1028	4.40 %
S-Cs (0.5 µSv/h	0.42	1.20	0.50(2)	6.30 %

5. Uncertainties of the $\dot{H}$*(10)

Uncertainties are evaluated according to GUM.

Tables 3, 4, 5 and 6 present the uncertainty evaluation processes of the $\dot{H}$*(10) at S-Cs (1 mSv/h), S-Cs (10µSv/h), N-60 (1 mSv/h and S-Cs (0.5 µSv/h), respectively.

All uncertainty components, either type A or B, refer to the relevant uncertainty at k=1. Type B follow rectangular distribution, i.e. $u_B = \delta x/\sqrt{3}$. Uncertainty values less than 0.01% are considered as zero.

***Table 3 :** Uncertainty evaluation of Ḣ*(10) at S-Cs at 1 mSv/h*

		Type A	Type B
		%	%
A1	Uncertainty of N_K from PTB		0.60
A2	Stability of N_K	0.24	
A3	Electrometer accuracy		0.07
A4	Scale reading / resolution		0.06
A5	Uniformity of radiation beam		0.58
A6	Difference in Cs137 energy spectra		0.10
A7	Temperature & Pressure	0.33	0.08
A8	Difference in Temperature at two places		0.02
A9	Leaksge current		0.00
A10	Recombination loss		0.00
A11	Positioning of std instrument at distance		0.115
A12	Backscatter effect		0.00
A13	Reproducibility of Kair=f(SCD) curve	0.50	
A14	Conversion Coefficients, $h_{HR*(1)/K}$		2.00
	QUADRATIC SUM	**0.65**	**2.18**
	COMBINED UNCERTAINTY	**2.27**	**%**
	EXPANDED UNCERTAINTY	**4.54**	**%**

A1 : The uncertainty of the calibration coefficient of the LS-01 reference – transfer ionization chamber, as reported in the calibration certificate, at k=1
A2 : The stability of the N_K is taken as the stability of the reference – transfer chamber being used for the Ḣ*(10) measurements. The stability of the chamber is the standard uncertainty of the measured current (accumulated charge over 1 min) under fixed geometry, i.e. at 2 m distance from OB2 Cs-137 source
A3 : The uncertainty from the electrometer calibration certificate
A4 : As half of the last digit of the electrometer reading (relevant)
A5 : The uniformity of the radiation beam, as measured from the respective profile (1%).
A6 : Takes into account possible differences in Sc-137 spectra between PTB (reference laboratory) and IRCL/GAEC-EIM.
A7 : Takes into account the uncertainties of the calibration coefficient of the thermometer and barometer (type B), fluctuations of temperature & pressure during the measurements (type A) and scale digit resolution (type B).
A8 : The temperature difference between the place of chamber and thermometer
A9 : Takes into account the leakage current contribution to the chamber signal during the measurements.
A10 : the effect of the ion recombination to the measurement (< 0.01%)
A11 : A mis-positioning of the chamber to the correct distance from source (2 mm)
A12 : The influence of the background radiation to the chamber signal during the measurements, as the ratio of the background pertained at the measurement place and the H*(10) at the same point.
A13 : The uncertainty corresponds to the reproducibility of Kair=f(d, B, I) curve. i.e. the standard uncertainty of all quality control measurements (see previous sections).
A14 : The uncertainty of the $h_{HR*(1)/K}$ as reported in ISO 4037 is taken as 2%.

Table 4 : *Uncertainty evaluation of Ḣ*(10) at S-Cs at 10 µSv/h*

		Type A	Type B
		%	**%**
A1	Uncertainty of Nk from IRCL/GAEC-EIM		1.36
A2	Stability of NK	0.30	
A3	Electrometer accuracy		0.07
A4	Scale reading / resolution		0.06
A5	Uniformity of radiation beam		0.58
A6	Difference in Cs137 energy spectra		0.00
A7	Temperature & Pressure	0.33	0.08
A8	Difference in Temperature at two places		0.02
A9	Leaksge current		0.00
A10	Recombination loss		0.00
A11	Positioning of std instrument at distance		0.115
A12	Backscatter effect		0.00
A13	Reproducibility of Kair=f(SCD) curve	0.64	
A14	Conversion Coefficients, $h_{HR*(1)/K}$		2.00
	QUADRATIC SUM	**0.78**	**2.49**
	COMBINED UNCERTAINTY	**2.61**	**%**
	EXPANDED UNCERTAINTY	**5.22**	**%**

A1 : The uncertainty of the calibration coefficient of the LS-10 working standard, as reported in the IRCL/GAEC-EIM calibration certificate.
A2 , A3, A4. A5 : As previous
A6 : Since LS-10 and LS-01 are used in the same beam of the IRCL/GAEC-EIM
A7, A8, A9, A10, A11, A12, A13 and A14 : As previous

Table 5 : *Uncertainty evaluation of $\dot{H}$*(10) at N-60 at 1 mSv/h*

		Type A	Type B
		%	%
A1	Uncertainty of Nk from PTB		0.40
A2	Stability of NK	0.24	
A3	Electrometer accuracy		0.07
A4	Scale reading / resolution	0.00	0.06
A5	Uniformity of radiation beam		0.29
A6	Difference in X ray spectra (HVL)		0.29
A7	Temperature & Pressure	0.33	0.08
A8	Difference in Temperature at two places		0.12
A9	Leakage current		0.00
A10	Recombination loss		0.00
A11	Positioning of std instrument at same distance		0.115
A12	Backscatter effect	NR	0.00
A13	Reproducibility of Kair=f(SCD) curve	0.55	
A14	Conversion Coefficients		2.00
	QUADRATIC SUM	**0.69**	**2.09**
	COMBINED UNCERTAINTY	**2.20**	**%**
	EXPANDED UNCERTAINTY	**4.40**	**%**

A1 – A14 : as in Table 2.
A5 : Beam profile at the horizontal direction where the tube heel- effect is pronounced (0.5%)

***Table 6:** Uncertainty evaluation of $\dot{H}$*(10) at S-Cs at 0.5 µSv/h*

		Type A	Type B
		%	%
A1	Uncertainty of Nk from IRCL/GAEC-EIM		1.36
A2	Stability of N_K	0.30	
A3	Electrometer accuracy		0.07
A4	Scale reading / resolution		0.06
A5	Uniformity of radiation beam		0.58
A6	Difference in Cs137 energy spectra		0.00
A7	Temperature & Pressure	0.33	0.08
A8	Difference in Temperature at two places		0.02
A9	Leaksge current		0.00
A10	Recombination loss		0.00
A11	Positioning of std instrument at distance		0.115
A12	Backscatter effect		0.00
A13	Reproducibility of Kair=f(SCD) curve	1.88	
A14	Conversion Coefficients, $h_{HR*(1)/K}$		2.00
	QUADRATIC SUM	**1.93**	**2.49**
	COMBINED UNCERTAINTY	**3.15**	**%**
	EXPANDED UNCERTAINTY	**6.30**	**%**

A1 : The uncertainty of the calibration coefficient of the LS-10 working standard, as reported in the IRCL/GAEC-EIM calibration certificate.
A2 , A3, A4. A5 : As previous
A6 : Since LS-10 and LS-01 are used in the same beam of the IRCL/GAEC-EIM
A7, A8, A9, A10, A11, A12, A13 and A14 : As previous

6. Determination of the calibration coefficients of the HS-10 transfer chamber.

6.1 Formalism

The calibration coefficients are determined from the ration of the conventional true $\dot{H}^*(10)$ value and the HS-10 reading corrected for temperature and pressure.

$$N_{H*(10)} = \frac{\dot{H}^*(10)}{(Q_{av} - Q_{leak}) \cdot k_{P,T}}$$

where

- $\dot{H}^*(10)$: the ambient dose equivalent dose rate in µSv/min, as determined in previous sections
- Q_{av} : the mean value of the accumulated charge (nC) over 60 sec (12 successive measurements), in nC/min
- Q_{leak} : the mean value of the accumulated leakage charge (nC) over 60 sec (12 successive measurements), as being measured without the presence of radiation, in nC/min (similar procedure is applied as for the $\dot{H}^*(10)$ determination – previous next sections)
- k_{PT} : the air density correction (temperature and pressure)

6.2 Experimental set-up

The HS-10 is placed in the center of the radiation beam and exposed to the conditions referred to tables 1 and 2. Photo 1 is a typical set up for the HS-10 calibration at the OB34 irradiator.

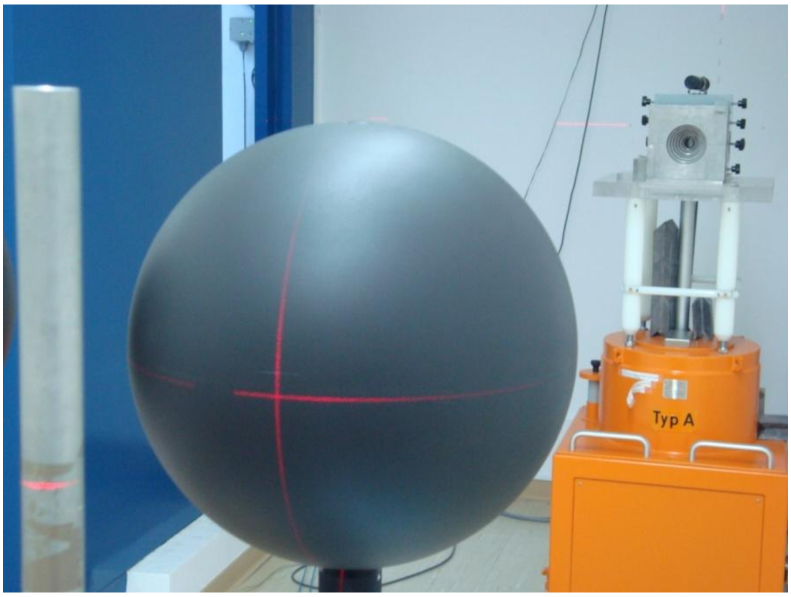

Photo 1 *: The calibration set up of the HS-10 chamber at the OB34 irradiator*

6.3 Calibration coefficients in terms of H(10) and uncertainties*

Table 7 presents the calibration coefficients in terms of $\dot{H}^*(10)$ of the HS-10 transfer chamber.

Table 7 *: Calibration results of the HS-10 ionization chamber*

Radiation Quality	**Conventional true $\dot{H}^*(10)$ µSv/h** (1)	**HS-10 Current Readings** (2)	**HS-10 Leakage Current, pC/min**	**Calibration Coefficients, $N_{\dot{H}^*(10)}$ in µSv/nC** (3)	**Uncertainty % k=2**
S-Cs (1mSv/h)	1001 ± 45	4.469 nC/min	0.12	**3.7 ± 0.2**	4.83
S-Cs (10µSv/h)	10.6 ± 0.6	47.45 pC/min	0.12	**3.7 ± 0.2**	5.67
N-60 (1mSv/h)	1028 ± 45	4.846 nC/min	0.12	**3.5 ± 0.2**	4.58
S-Cs (0.5 µSv/h	0.50 ± 0.03	2.424 pC/min	0.12	**3.6 ± 0.4**	10.9

(1) : From tables 2. The uncertainties at k=2

(2) : corrected for air density (chamber signal, without subtraction of leakage current)

(3) : The uncertainties at k=2

7. Uncertainties of the calibration coefficients $N_{\dot{H}^*(10)}$

Uncertainties are evaluated according to GUM.

Tables 8, 9, 10 and 11 present the uncertainty evaluation processes of the $N_{\dot{H}^*(10)}$ at S-Cs (1 mSv/h), S-Cs (10µSv/h), N-60 (1 mSv/h and S-Cs (0.5 µSv/h), respectively.

All uncertainty components, either type A or B, refer to the relevant uncertainty at k=1. Type B follow rectangular distribution, i.e. $u_B = \delta x/\sqrt{3}$. Uncertainty values less than 0.01% are considered as zero.

***Table 7 :** Uncertainty evaluation of $N_{\dot{H}^*(10)}$ at S-Cs at 1 mSv/h*

		Type A	Type B
		%	%
B1	Uncertainty of H*(10)	0.65	2.18
B2	Reproducibility of procedure	0.25	
B3	Stability of measurements	0.02	
B4	Scale reading / resolution	*	0.01
B5	Positioning of test instrument		0.29
B6	Uniformity of radiation beam		0.58
B7	Temperature & Pressure	0.33	0.08
B8	Difference in Temperature at two places		0.02
B9	Leakage current		0.00
B10	Radiation background		0.01
B11	Electrometer accuracy		0.29
	QUADRATIC SUM	**0.77**	**2.29**
	COMBINED UNCERTAINTY	**2.42**	**%**
B12	**EXPANDED UNCERTAINTY**	**4.83**	**%**

B1 : The uncertainty of the H*(10) as presented in section 5.
B2 : The calibration at each quality was performed a few times (2 or 3 rounds). The standard uncertainty of the calibration coefficients that deduced at each round represents the reproducibility of the procedure.
B3 : The standard uncertainty of the measured current (accumulated charge over 60 sec) with HS-10 ionization chamber in each round. The higher (worst) standard uncertainty in all rounds is entered in B3.
B4 : As half of the last digit of the electrometer reading (relevant)
B5 : A mis-positioning of the chamber to the correct distance from source (5 mm, due to the large chamber volume)
B6 : The uniformity of the radiation beam, as measured for the respective profile, is 1%.
B7 : Takes into account the uncertainties of the calibration coefficient of the thermometer and barometer (type B), fluctuations of temperature & pressure during the measurements (type A) and scale digit resolution (type B).
B8 : The temperature difference between the place of chamber and thermometer is 0.2 ^{o}C.
B9 : Takes into account the leakage current contribution to the chamber signal during the measurements.
B10 : The influence of the background radiation to the chamber signal during the measurements, as the ratio of the background pertained at the measurement place and the H*(10) at the same point.
B11 : The accuracy is taken from manufacturer as 0.5 %.
B12 : The expanded uncertainty represents the uncertainty of the calibration coefficient NH*(10) at k=2 (confidence level 95% approximately).

***Table 8 :** Uncertainty evaluation of $N_{\dot{H}^*(10)}$ at S-Cs at 10 µSv/h*

		Type A	Type B
		%	%
B1	Uncertainty of H*(10)	0.78	2.49
B2	Reproducibility of procedure	0.50	
B3	Stability of measurements	0.16	
B4	Scale reading / resolution	*	0.01
B5	Positioning of test instrument		0.289
B6	Uniformity of radiation beam		0.58
B7	Temperature & Pressure	0.33	0.08
B8	Difference in Temperature at two places		0.02
B9	Leakage current		0.00
B10	Radiation background		0.58
B11	Electrometer accuracy		0.29
	QUADRATIC SUM	**1.00**	**2.65**
	COMBINED UNCERTAINTY	**2.84**	**%**
B12	**EXPANDED UNCERTAINTY**	**5.67**	**%**

B1 – B12 : as above

Table 9 : *Uncertainty evaluation of $N_{\dot{H}^*(10)}$ at N-60 at 1 mSv/h*

		Type A	Type B
		%	%
B1	Uncertainty of H*(10)	0.69	2.09
B2	Reproducibility of procedure	0.18	
B3	Stability of measurements	0.09	
B4	Scale reading / resolution	*	0.01
B5	Positioning of test instrument		0.289
B6	Uniformity of radiation beam		0.289
B7	Temperature & Pressure	0.33	0.08
B8	Difference in Temperature at two places		0.02
B9	Leakage current		0.00
B10	Radiation background		0.01
B11	Electrometer accuracy		0.29
	QUADRATIC SUM	**0.79**	**2.15**
	COMBINED UNCERTAINTY	**2.29**	**%**
B12	**EXPANDED UNCERTAINTY**	**4.58**	**%**

B1 – B12 : as above
B6 : Beam profile at the horizontal direction where the tube heel- effect is pronounced (0.5%)

Table 10 : *Uncertainty evaluation of $N_{\dot{H}^*(10)}$ at S-Cs at 0.5 µSv/h*

		Type A	Type B
		%	%
B1	Uncertainty of H*(10)	1.93	2.49
B2	Reproducibility of procedure	2.00	
B3	Stability of measurements	2.40	
B4	Scale reading / resolution	*	0.13
B5	Positioning of test instrument		0.29
B6	Uniformity of radiation beam		0.58
B7	Temperature & Pressure	0.33	0.08
B8	Difference in Temperature at two places		0.02
B9	Leakage current		3.01
B10	Radiation background		0.58
B11	Electrometer accuracy		0.29
	QUADRATIC SUM	**3.69**	**4.02**
	COMBINED UNCERTAINTY	**5.45**	**%**
B12	**EXPANDED UNCERTAINTY**	**10.9**	**%**

B1 – B12 : as above

Norwegian Radiation Protection Authority (NRPA)

APPENDIX 1

1. **Uncertainty for ambient dose equivalent calibration**

N-60 quality (1 mSv/h):

	Source of uncertainty	Quantity X_i	Estimate x_i	Deviation u_c	rel. st. unce $u(x_i)$	Prob. dist.	Sens. Coeff. c_i	$u(x_i)$ %
	X-ray ISO narrow beam N-60	Uncertaintybudget SSDL NRPA						
	Utarbeidet av: Hans Bjerke	Rev. Nr./Dato: 04/15.09.2014	Dokument nr.: V-3-03-01					
1	**Factors due to radiation field, set-up and calibration:**							
1.1	Differences in energy spectra of radiation beams	k_{spec}	1	0.006	0.0060		1	0.60
1.2	Field inhomogeneity	k_{inhom}	1	0.002	0.0020	N	1	0.20
1.3	Uncertainty of the calibration coefficient reported by PSDL	N_K [Gy/µC]	0.949	0.008	0.0080	N	1	0.80
1.4	Constancy of the calibration coefficient		0.949	0.003	0.0018	R	1	0.18
	Quadratic sum							1.07
	Combined uncertainty						$u_c(y)$ %	1.04
2	**Factors influencing the reference standard:**							
2.1	Calibration factor of electrometer	k_{elec}	1		0.0005	N	1	0.05
2.2	Ionization current (pA)	I [pA]	4.55	0.0007	0.0002	N	1	0.02
2.3	Leakage current	ΔI [pA]	0.01	0.0005	0.0001	N	1	0.01
2.4	Recombination	k_s	1	0.0040	0.0023	R	1	0.23
2.5	Temperature (K)	k_T	1	0.0006	0.0006	N	1	0.06
2.6	Pressure (kPa)	k_P	1	0.0001	0.0001	N	1	0.01
2.7	Humidity	k_h	1	0.0004	0.0002	R	1	0.02
2.8	Chamber orientation		1	0.0015	0.0009	R	1	0.09
2.9	Reproduction of source to chamber distance		1	0.0010	0.0006	R	2	0.12
	Quadratic sum							0.08
	Combined uncertainty						$u_c(y)$ %	0.28
3	**Factors influencing the transfer chamber, Exradin A6**							
3.1	Calibration factor of electrometer	k_{elec}	1		0.0005	N	1	0.05
3.2	Ionization current (pA)	I [pA]	5.22	0.0009	0.0002	N	1	0.02
3.3	Leakage current	ΔI [pA]	0.01	0.0006	0.0001	N	1	0.01
3.4	Recombination	k_s	1	0.0040	0.0023	R	1	0.23
3.5	Temperature (K)	k_T	1	0.0006	0.0006	N	1	0.06
3.6	Pressure (kPa)	k_P	1	0.0001	0.0001	N	1	0.01
3.7	Humidity	k_h	1	0.0004	0.0002	R	1	0.02
3.8	Chamber orientation		1	0.0015	0.0009	R	1	0.09
3.9	Geometrical factor - transfer chamber of diff size		1	0.0100	0.0058	R	1	0.58
3.10	Reproduction of source to chamber distance		1	0.0010	0.0006	N	2	0.12
	Quadratic sum							0.41
	Combined uncertainty						$u_c(y)$ %	0.64
4	**Factors influencing the chamber under test, HS10**							
4.1	Calibration factor of electrometer	k_{elec}	1		0.0005	N	1	0.05
4.2	Ionization current (pA)	I [pA]	86.2	0.0150	0.0002	N	1	0.02
4.3	Leakage current	ΔI [pA]	0.01	0.0004	0.0000	N	1	0.00
4.4	Recombination	k_s	1	0.0040	0.0023	R	1	0.23
4.5	Temperature (K)	k_T	1	0.0006	0.0006	N	1	0.06
4.6	Pressure (kPa)	k_P	1	0.0001	0.0001	N	1	0.01
4.7	Humidity	k_h	1	0.0004	0.0002	R	1	0.02
4.8	Chamber orientation		1	0.0015	0.0009	R	1	0.09
4.9	Geometrical factor - chamber under test of diff size		1	0.0200	0.0115	R	1	1.15
4.10	Reproduction of source to chamber distance		1	0.0010	0.0006	N	2	0.12
	Quadratic sum							1.41
	Combined uncertainty						$u_c(y)$ %	1.19
5	**Total uncertainty**							
	Quadratic sum							2.98
	Combined uncertainty						$u_c(y)$ %	1.73
	Expanded uncertainty (k=2)							3.46
6	**Factors influencing dose equivalent**							
6.1	Conversion coefficient $h^*_K(10)$ - Ambient dose equivalent	$h^*_K(10)$	1.59	PTB Dos-34				1.00
7	**Total uncertainty dose equivalent**							
	Quadratic sum							3.98
	Combined uncertainty						$u_c(y)$ %	2.00
	Expanded uncertainty (k=2)					CMC:	5.00	3.99

Table 1. Combined uncertainty for the calibration in N-60 field (1 mSv/h).

S-Cs quality (10 µSv/h):

	DIR 101 Cs-137 (10 µSv/h)	**Uncertaintybudget SSDL NRPA**						
	Utarbeidet av Hans Bjerke	Rev. Nr./Dato 03/16.09.2014	Dokument nr. V-3-03-01					
	Source of uncertainty	**Quantity** X_i	**Estimate** x_i	**Deviation** u_c	**rel. st. unc** $u(x_i)$	**Prob. di**	**Sens. Coeff.** c_i	$u(x_i)$ **%**
1	**Factors due to radiation field, set-up and calibration:**							
1.1	Differences in energy spectra of radiation beams	k_{spec}	1	0.002	0.0012	R	1	0.12
1.2	Field inhomogeneity	k_{inhom}	1	0.002	0.0020	N	1	0.20
1.3	Uncertainty of the calibration coefficient reported by PSDL	N_H [Gy/µC]	60.6	0.300	0.0050	N	1	0.50
1.4	Constancy of the calibration coefficient		60.6		0.0010	N	1	0.10
	Quadratic sum							0.31
	Combined uncertainty						$u_c(y)$ %	0.56
2	**Factors influencing the reference standard:**							
2.1	Calibration factor of electrometer	k_{elec}	1		0.0005	N	1	0.05
2.2	Ionization current (pA)	I [pA]	44.25	0.0015	0.0000	N	1	0.00
2.3	Leakage current	ΔI [pA]	0.01	0.0015	0.0000	N	1	0.00
2.4	Recombination	k_s	1	0.0040	0.0023	R	1	0.23
2.5	Temperature (K)	k_T	1	0.0006	0.0006	N	1	0.06
2.6	Pressure (kPa)	k_P	1	0.0001	0.0001	N	1	0.01
2.7	Humidity	k_h	1	0.0004	0.0002	R	1	0.02
2.8	Chamber orientation		1	0.0050	0.0029	R	1	0.29
2.9	Reproduction of source to chamber distance		1	0.0020	0.0012	R	2	0.23
	Quadratic sum							0.20
	Combined uncertainty						$u_c(y)$ %	0.44
3	**Factors influencing the transfer chamber, Exradin A6**							
3.1	Calibration factor of electrometer	k_{elec}	1		0.0055	N	1	0.55
3.2	Ionization current (pA)	I [pA]	0.071	0.0002	0.0028	N	1	0.28
3.3	Leakage current	ΔI [pA]	0.009	0.0002	0.0028	N	1	0.28
3.4	Recombination	k_s	1	0.0040	0.0023	R	1	0.23
3.5	Temperature (K)	k_T	1	0.0006	0.0006	N	1	0.06
3.6	Pressure (kPa)	k_P	1	0.0001	0.0001	N	1	0.01
3.7	Humidity	k_h	1	0.0004	0.0002	R	1	0.02
3.8	Chamber orientation		1	0.0050	0.0029	R	1	0.29
3.9	Reproduction of source to chamber distance		1	0.0020	0.0012	R	2	0.23
	Quadratic sum							0.65
	Combined uncertainty						$u_c(y)$ %	0.81
4	**Factors influencing the chamber under test, HS10**							
4.1	Calibration factor of electrometer	k_{elec}	1		0.0030	N	1	0.30
4.2	Ionization current (pA)	I [pA]	0.872	0.0006	0.0007	N	1	0.07
4.3	Leakage current	ΔI [pA]	0.009	0.0002	0.0002	N	1	0.02
4.4	Recombination	k_s	1	0.0040	0.0023	R	1	0.23
4.5	Temperature (K)	k_T	1	0.0006	0.0006	N	1	0.06
4.6	Pressure (kPa)	k_P	1	0.0001	0.0001	N	1	0.01
4.7	Humidity	k_h	1	0.0004	0.0002	R	1	0.02
4.8	Chamber orientation		1	0.0015	0.0009	R	1	0.09
4.9	Geometrical factor - chamber under test of diff size		1	0.0200	0.0115	R	1	1.15
4.10	Reproduction of source to chamber distance		1	0.0010	0.0006	N	2	0.12
	Quadratic sum							1.51
	Combined uncertainty						$u_c(y)$ %	1.23
5	**Total uncertainty for ambient dose equivalent**							
	Quadratic sum							2.67
	Combined uncertainty						$u_c(y)$ %	1.63
	Expanded uncertainty (k=2)					CMC:	5.00	3.27

Table 2. Combined uncertainty for the calibration in S-Cs field (10 µSv/h).

S-Cs quality (1 mSv/h):

	DIR 101 Cs-137 (1 mSv/h)	Uncertaintybudget SSDL NRPA						
	Utarbeidet av Hans Bjerke	Rev. Nr./Dato 03/16.09.2014	Dokument nr. V-3-03-01					
	Source of uncertainty	**Quantity** X_i	**Estimate** x_i	**Deviation** u_c	**rel. st. unc** $u(x_i)$	**Prob. di**	**Sens. Coeff.** c_i	$u(x_i)$ **%**
1	**Factors due to radiation field, set-up and calibration:**							
1.1	Differences in energy spectra of radiation beams	k_{spec}	1	0.002	0.0012	R	1	0.12
1.2	Field inhomogeneity	k_{inhom}	1	0.002	0.0020	N	1	0.20
1.3	Uncertainty of the calibration coefficient reported by PSDL	N_H [Gy/µC]	60.6	0.300	0.0050	N	1	0.50
1.4	Constancy of the calibration coefficient		60.6		0.0010	N	1	0.10
	Quadratic sum							0.31
	Combined uncertainty						$u_c(y)$ %	0.56
2	**Factors influencing the reference standard:**							
2.1	Calibration factor of electrometer	k_{elec}	1		0.0005	N	1	0.05
2.2	Ionization current (pA)	I [pA]	44.25	0.0015	0.0000	N	1	0.00
2.3	Leakage current	ΔI [pA]	0.01	0.0015	0.0000	N	1	0.00
2.4	Recombination	k_s	1	0.0040	0.0023	R	1	0.23
2.5	Temperature (K)	k_T	1	0.0006	0.0006	N	1	0.06
2.6	Pressure (kPa)	k_P	1	0.0001	0.0001	N	1	0.01
2.7	Humidity	k_h	1	0.0004	0.0002	R	1	0.02
2.8	Chamber orientation		1	0.0050	0.0029	R	1	0.29
2.9	Reproduction of source to chamber distance		1	0.0020	0.0012	R	2	0.23
	Quadratic sum							0.20
	Combined uncertainty						$u_c(y)$ %	0.44
3	**Factors influencing the transfer chamber, Exradin A6**							
3.1	Calibration factor of electrometer	k_{elec}	1		0.0005	N	1	0.05
3.2	Ionization current (pA)	I [pA]	7.85	0.0011	0.0001	N	1	0.01
3.3	Leakage current	ΔI [pA]	0.009	0.0040	0.0005	N	1	0.05
3.4	Recombination	k_s	1	0.0040	0.0023	R	1	0.23
3.5	Temperature (K)	k_T	1	0.0006	0.0006	N	1	0.06
3.6	Pressure (kPa)	k_P	1	0.0001	0.0001	N	1	0.01
3.7	Humidity	k_h	1	0.0004	0.0002	R	1	0.02
3.8	Chamber orientation		1	0.0050	0.0029	R	1	0.29
3.9	Reproduction of source to chamber distance		1	0.0020	0.0012	R	2	0.23
	Quadratic sum							0.20
	Combined uncertainty						$u_c(y)$ %	0.45
4	**Factors influencing the chamber under test, HS10**							
4.1	Calibration factor of electrometer	k_{elec}	1		0.0005	N	1	0.05
4.2	Ionization current (pA)	I [pA]	100.35	0.0040	0.0000	N	1	0.00
4.3	Leakage current	ΔI [pA]	0.009	0.0020	0.0000	N	1	0.00
4.4	Recombination	k_s	1	0.0040	0.0023	R	1	0.23
4.5	Temperature (K)	k_T	1	0.0006	0.0006	N	1	0.06
4.6	Pressure (kPa)	k_P	1	0.0001	0.0001	N	1	0.01
4.7	Humidity	k_h	1	0.0004	0.0002	R	1	0.02
4.8	Chamber orientation		1	0.0015	0.0009	R	1	0.09
4.9	Geometrical factor - chamber under test of diff size		1	0.0200	0.0115	R	1	1.15
4.10	Reproduction of source to chamber distance		1	0.0010	0.0006	N	2	0.12
	Quadratic sum							1.41
	Combined uncertainty						$u_c(y)$ %	1.19
5	**Total uncertainty for ambient dose equivalent**							
	Quadratic sum							2.12
	Combined uncertainty						$u_c(y)$ %	1.46
	Expanded uncertainty (k=2)					CMC:	5.00	2.91

Table 3. Combined uncertainty for the calibration in S-Cs field (1 mSv/h).

Swedish Radiation Safety Authority (SSM)

Simplified uncertainty budget.

^{137}Cs: $N_K = \dot{K}_{\mathrm{air}} \cdot I_s \cdot \mathrm{k}_{ih} \cdot \delta_{pos} \cdot \delta_s \cdot \mathrm{k}_{Tp} \cdot \mathrm{k}_h \cdot \mathrm{k}_{spek} \cdot e^{(\ln 2/T_{1/2})\cdot t}$

N-60: $N_K = \dot{K}_{\mathrm{air}} \cdot I_s \cdot \mathrm{k}_{ih} \cdot \delta_{pos} \cdot \mathrm{k}_{Tp} \cdot \mathrm{k}_h \cdot \mathrm{k}_{spek} \cdot \mathrm{k}_{NK} \cdot \mathrm{k}_{HVL} \cdot \delta_K \cdot$

Quantity	**Sensitivity cofficient**	**Probability distribution**	**^{137}Cs-1mSv u_i (%)**	**^{137}Cs-10µSv u_i (%)**	**N-60 u_i (%)**
$\dot{K}_{air}$	-	normal	0,325	0,384	0,47
I_s uncertainty in electrometer calibration	-	normal	0,026	0,26	0,26
$\mathrm{k}_{T,p}$ korrection for air density	-	normal	0,06	0,06	0,06
$e^{(-\ln 2/T1/2*t)}$ uncertainty in half life	-	rectangular	0,05	0,05	--
k_{ih} korrection for non-uniformity of the field	1,0000	normal	0,3	0,3	0,17
k_h korrection for airdenity variation vith humidity	1,0000	rectangular	-	-	-
δ_{pos} uncertainty in detector positioning	1,0000	normal	0,35	0,35	0,06
δ_s uncertainty in positioning of the radiation source	1,0000	normal	0,11	0,11	-
k_{spek} korrektion for different field at PSDL-SSDL	1,0000	normal	0,2	0,2	0,1
k_{NK} korrection for standard stability	1,0000	rectangular	--	--	0,1
k_{HVL} korrection for HVL stability	1,0000	rectangular	--	--	0,03
δ_K uncertainty in short time stability of air kerma rate in x-ray field	1,0000	rectangular	--	--	0,01
Combined uncertainty N_K		normal	0,614	0,647	0,588
U **Expanded uncertainty *k=2* for** N_K		**normal**	**1,23**	**1,29**	**1,18**

The uncertainty for conversion coefficient *h** is 2%

U **Expanded uncertainty *k=2* for** N_{H*}		**normal**	**4,2**	**4,2**	**4,2**

Radiation and Nuclear Safety Authority (STUK)

H*(10)

Uncertainty budget according to GUM

STUK N-60; 1 mSv h^{-1}

Model function: H = Nk(std)*k(stab,std)*k(unif,std)*k(spect,std)*I(std)* k(pT)*h

No.	quantity or group of quantities	estimated value		standard uncertainty		%	probability distribution *)	sensitivity coefficient		contribution to the standard uncertainty		%	remarks
1	Nk(std)	4.293E+04	Gy C^{-1}	2.576E+02	Gy C^{-1}	0.60		2.561E-05	mSv h^{-1}Gy^{-1} C	6.596E-03	mSv h^{-1}		Air kerma calibration factor of ionisation chamber NE 2575 S/N 547 (standard) calibrated at PTB in 2009
2	k(stab,std)	1.000E+00		5.800E-03		0.58	Rectangular (TypeB)	1.099E+00	mSv h^{-1}	6.376E-03	mSv h^{-1}		Long-term stability of the standard
3	k(unif,std)	1.000E+00		5.800E-03		0.58	Rectangular (TypeB)	1.099E+00	mSv h^{-1}	6.376E-03	mSv h^{-1}		B type uncertainty due to differences in beam uniformity (Primary lab. vs. STUK)
4	k(spect,std)	1.000E+00		5.800E-03		0.58	Rectangular (TypeB)	1.099E+00	mSv h^{-1}	6.376E-03	mSv h^{-1}		B type uncertainty due to differences in beam spectra (Primary lab. vs. STUK).
5	I(std)	4.473E-12	A	1.21E-14	A	0.27	(TypeA)	2.458E+11	mSv h^{-1}A^{-1}	2.968E-03	mSv h^{-1}		
6	k(pT)	1.000E+00		8.000E-04		0.08	Rectangular (TypeB)	1.099E+00	mSv h^{-1}	8.795E-04	mSv h^{-1}		
7	h(N-60)	1.590E+00	Sv Gy^{-1}	3.180E-02	Sv Gy^{-1}	2.00		6.914E-01	mSv h^{-1}Sv^{-1} Gy	2.199E-02	mSv h^{-1}		ISO 4037-3:1999
	H(N-60)	3.054E-07	Sv s^{-1}										
	H(N-60)	1.099E+00	mSv h^{-1}	-			-	-		2.566E-02	mSv h^{-1}	2.33	standard uncertainty, k = 1
										5.132E-02	mSv h^{-1}	4.67	standard uncertainty, k = 2

*) used for the determination of the standard uncertainty

Model function: N(N-60) = H(N-60)/[I(tr)*k(setup,tr)*k(tube output)]

No.	quantity or group of quantities	estimated value		standard uncertainty		%	probability distribution *)	sensitivity coefficient		contribution to the standard uncertainty		%	remarks
1	I(tr)	8.618E-11	A	8.62E-14	A	0.10	(TypeA)	4.111E+16	mSv C^{-1} A^{-1}	3.543E+03	mSv C^{-1}		
2	k(setup,tr)	1.000E+00		2.900E-03		0.29	Rectangular (TypeB)	3.543E+06	mSv C^{-1}	1.028E+04	mSv C^{-1}		B type uncertainty due to setup differences between the measurements of the standard and the transfer instruments.
3	k(tube output)	1.000E+00		1.000E-03		0.10	Rectangular (TypeB)	3.543E+06	mSv C^{-1}	3.543E+03	mSv C^{-1}		B type uncertainty due to differences in tube output between the measurements of the standard and the transfer instruments.
4	H(N-60)	1.099E+00	mSv h^{-1}	2.566E-02	mSv h^{-1}			3.223E+06	mSv C^{-1} mSv^{-1} h	8.271E+04	mSv C^{-1}		
	N(N-60)	1.276E+10	mSv (Ah)$^{-1}$										
	N(N-60)	3.543E+06	mSv C^{-1}	-			-	-		8.350E+04	mSv C^{-1}	2.36	standard uncertainty, k = 1
										1.670E+05	mSv C^{-1}	4.71	standard uncertainty, k = 2

*) used for the determination of the standard uncertainty

17/01/2014

Arvi Hakanen

H*(10)

Uncertainty budget according to GUM

STUK S-Cs; 0,01 mSv h^{-1}

Model function: H = Nk(std)*k(stab,std)*k(unif,std)*k(spect,std)*I(std)* k(pT)*h

No.	quantity or group of quantities	estimated value		standard uncertainty		%	probability distribution *)	sensitivity coefficient		contribution to the standard uncertainty		%	remarks
1	Nk(std)	3.138E+03	Gy C^{-1}	1.883E+01	Gy C^{-1}	0.60		3.175E-06	mSv h^{-1}Gy^{-1} C	5.978E-05	mSv h^{-1}		Air kerma calibration factor of ionisation chamber TM 32002 S/N 83 (standard) calibrated at PTB in 2012
2	k(stab,std)	1.000E+00		5.800E-03		0.58	Rectangular (TypeB)	9.963E-03	mSv h^{-1}	5.779E-05	mSv h^{-1}		
3	k(unif,std)	1.000E+00		2.900E-03		0.29	Rectangular (TypeB)	9.963E-03	mSv h^{-1}	2.889E-05	mSv h^{-1}		
4	k(spect,std)	1.000E+00		3.000E-03		0.30	Rectangular (TypeB)	9.963E-03	mSv h^{-1}	2.989E-05	mSv h^{-1}		Additional uncertainty due to higher contribution of background spectrum
5	I(std)	7.349E-13	A	4.56E-15	A	0.62	(TypeA)	1.356E+10	mSv h^{-1}A^{-1}	6.177E-05	mSv h^{-1}		
6	k(pT)	1.000E+00		8.000E-04		0.08	Rectangular (TypeB)	9.963E-03	mSv h^{-1}	7.971E-06	mSv h^{-1}		
7	h(S-Cs)	1.200E+00	Sv Gy^{-1}	2.400E-02	Sv Gy^{-1}	2.00		8.303E-03	mSv h^{-1}Sv^{-1} Gy	1.993E-04	mSv h^{-1}		ISO 4037-3:1999
	H(S-Cs)	2.768E-09	Sv s^{-1}										
	H(S-Cs)	9.963E-03	mSv h^{-1}	-			-	-		2.285E-04	mSv h^{-1}	2.29	standard uncertainty, k = 1
										4.571E-04	mSv h^{-1}	4.59	standard uncertainty, k = 2

*) used for the determination of the standard uncertainty

Model function: N(S-Cs) = H(S-Cs)/[I(tr)*k(setup,tr)]

No.	quantity or group of quantities	estimated value		standard uncertainty		%	probability distribution *)	sensitivity coefficient		contribution to the standard uncertainty		%	remarks
1	I(tr)	7.545E-13	A	4.75E-15	A	0.63	(TypeA)	4.861E+18	mSv C^{-1} A^{-1}	2.311E+04	mSv C^{-1}		
2	k(setup,tr)	1.000E+00		2.900E-03		0.29	Rectangular (TypeB)	3.668E+06	mSv C^{-1}	1.064E+04	mSv C^{-1}		
3	H(S-Cs)	9.963E-03	mSv h^{-1}	2.285E-04	mSv h^{-1}			3.682E+08	mSv C^{-1} mSv^{-1} h	8.413E+04	mSv C^{-1}		
	N(S-Cs)	1.320E+10	mSv (Ah)$^{-1}$										
	N(S-Cs)	3.668E+06	mSv C^{-1}	-			-	-		8.790E+04	mSv C^{-1}	2.40	standard uncertainty, k = 1
										1.758E+05	mSv C^{-1}	4.79	standard uncertainty, k = 2

*) used for the determination of the standard uncertainty

17/01/2014

Arvi Hakanen

H*(10)

Uncertainty budget according to GUM
STUK S-Cs; 1 mSv h^{-1}

Model function: H = Nk(std)*k(stab,std)*k(unif,std)*k(spect,std)*I(std)* k(pT)*h

No.	quantity or group of quantities	estimated value		standard uncertainty		%	probability distribution *)	sensitivity coefficient		contribution to the standard uncertainty		%	remarks
1	Nk(std)	3.132E+03	Gy C^{-1}	1.879E+01	Gy C^{-1}	0.60		3.197E-04	mSv h^{-1}Gy^{-1} C	6.008E-03	mSv h^{-1}		Air kerma calibration factor of ionisation chamber TM 32002 S/N 83 (standard) calibrated at PTB in 2012
2	k(stab,std)	1.000E+00		5.800E-03		0.58	Rectangular (TypeB)	1.001E+00	mSv h^{-1}	5.807E-03	mSv h^{-1}		
3	k(unif,std)	1.000E+00		2.900E-03		0.29	Rectangular (TypeB)	1.001E+00	mSv h^{-1}	2.904E-03	mSv h^{-1}		
4	k(spect,std)	1.000E+00		2.900E-03		0.29	Rectangular (TypeB)	1.001E+00	mSv h^{-1}	2.904E-03	mSv h^{-1}		
5	I(std)	7.400E-11	A	8.88E-14	A	0.12	(TypeA)	1.353E+10	mSv h^{-1}A^{-1}	1.202E-03	mSv h^{-1}		
6	k(pT)	1.000E+00		8.000E-04		0.08	Rectangular (TypeB)	1.001E+00	mSv h^{-1}	8.010E-04	mSv h^{-1}		
7	h(S-Cs)	1.200E+00	Sv Gy^{-1}	2.400E-02	Sv Gy^{-1}	2.00		8.344E-01	mSv h^{-1}Sv^{-1} Gy	2.003E-02	mSv h^{-1}		ISO 4037-3:1999
	H(S-Cs)	2.781E-07	Sv s^{-1}										
	H(S-Cs)	1.001E+00	mSv h^{-1}	-			-	-		2.213E-02	mSv h^{-1}	2.21	standard uncertainty, k = 1
										4.426E-02	mSv h^{-1}	4.42	standard uncertainty, k = 2

*) used for the determination of the standard uncertainty

Model function: N(S-Cs) = H(S-Cs)/[I(tr)*k(setup,tr)]

No.	quantity or group of quantities	estimated value		standard uncertainty		%	probability distribution *)	sensitivity coefficient		contribution to the standard uncertainty		%	remarks
1	I(tr)	7.623E-11	A	9.15E-14	A	0.12	(TypeA)	4.786E+16	mSv C^{-1} A^{-1}	4.378E+03	mSv C^{-1}		
2	k(setup,tr)	1.000E+00		2.900E-03		0.29	Rectangular (TypeB)	3.649E+06	mSv C^{-1}	1.058E+04	mSv C^{-1}		
3	H(S-Cs)	1.001E+00	mSv h^{-1}	2.213E-02	mSv h^{-1}			3.644E+06	mSv C^{-1} mSv^{-1} h	8.065E+04	mSv C^{-1}		
	N(S-Cs)	1.314E+10	mSv (Ah)$^{-1}$										
	N(S-Cs)	3.649E+06	mSv C^{-1}	-			-	-		8.145E+04	mSv C^{-1}	2.23	standard uncertainty, k = 1
										1.629E+05	mSv C^{-1}	4.46	standard uncertainty, k = 2

*) used for the determination of the standard uncertainty

17/01/2014

Arvi Hakanen

Ka

Uncertainty budget according to GUM

N-60; 1 mSv h^{-1}

Model function: K = Nk(std)*k(stab,std)*k(unif,std)*k(spect,std)*I(std)* k(pT)

No.	quantity or group of quantities	estimated value		standard uncertainty		%	probability distribution *)	sensitivity coefficient		contribution to the standard uncertainty		%	remarks
1	Nk(std)	4.293E+04	Gy C^{-1}	2.576E+02	Gy C^{-1}	0.60		1.610E-05	mGy h^{-1} Gy^{-1} C	4.148E-03	mGy h^{-1}		Air kerma calibration factor of ionisation chamber NE 2575 S/N 547 (standard) calibrated at PTB in 2009
2	k(stab,std)	1.000E+00		5.800E-03		0.58	Rectangular (TypeB)	6.914E-01	mGy h^{-1}	4.010E-03	mGy h^{-1}		Long-term stability of the standard
3	k(unif,std)	1.000E+00		5.800E-03		0.58	Rectangular (TypeB)	6.914E-01	mGy h^{-1}	4.010E-03	mGy h^{-1}		B type uncertainty due to differences in beam uniformity (Primary lab. vs. STUK)
4	k(spect,std)	1.000E+00		5.800E-03		0.58	Rectangular (TypeB)	6.914E-01	mGy h^{-1}	4.010E-03	mGy h^{-1}		B type uncertainty due to differences in beam spectra (Primary lab. vs. STUK).
5	I(std)	4.473E-12	A	1.21E-14	A	0.27	(TypeA)	1.546E+11	mGy h^{-1}A^{-1}	1.867E-03	mGy h^{-1}		
6	k(pT)	1.000E+00		8.000E-04		0.08	Rectangular (TypeB)	6.914E-01	mGy h^{-1}	5.531E-04	mGy h^{-1}		
	K(N-60)	1.921E-07	Gy s^{-1}										
	K(N-60)	6.914E-01	mGy h^{-1}	-			-	-		8.321E-03	mGy h^{-1}	1.20	standard uncertainty, k = 1
										1.664E-02	mGy h^{-1}	2.41	standard uncertainty, k = 2

*) used for the determination of the standard uncertainty

Model function: N(N-60) = K(N-60)/[I(tr)*k(setup,tr)*k(tube output)]

No.	quantity or group of quantities	estimated value		standard uncertainty		%	probability distribution *)	sensitivity coefficient		contribution to the standard uncertainty		%	remarks
1	I(tr)	8.618E-11	A	8.62E-14	A	0.10	(TypeA)	2.586E+16	mGy C^{-1} A^{-1}	2.229E+03	mGy h^{-1}		
2	k(setup,tr)	1.000E+00		2.900E-03		0.29	Rectangular (TypeB)	2.229E+06	mGy C^{-1}	6.463E+03	mGy h^{-1}		B type uncertainty due to setup differences between the measurements of the standard and the transfer instruments.
3	k(tube output)	1.000E+00		1.000E-03		0.10	Rectangular (TypeB)	2.229E+06	mGy C^{-1}	2.229E+03	mGy h^{-1}		B type uncertainty due to differences in tube output between the measurements of the standard and the transfer instruments.
4	K(N-60)	6.914E-01	mGy h^{-1}	8.321E-03	mGy h^{-1}			3.223E+06	mGy C^{-1} mGy^{-1} h	2.682E+04	mGy h^{-1}		
	N(N-60)	8.023E+09	mGy (Ah)$^{-1}$										
	N(N-60)	2.229E+06	mGy C^{-1}	-			-	-		2.777E+04	mGy C^{-1}	1.25	standard uncertainty, k = 1
										5.554E+04	mGy C^{-1}	2.49	standard uncertainty, k = 2

*) used for the determination of the standard uncertainty

17/01/2014

Arvi Hakanen

Ka

Uncertainty budget according to GUM
S-Cs; 0,01 mSv h^{-1}

Model function: K = Nk(std)*k(stab,std)*k(unif,std)*k(spect,std)*I(std)* k(pT)

No.	quantity or group of quantities	estimated value		standard uncertainty		%	probability distribution *)	sensitivity coefficient		contribution to the standard uncertainty		%	remarks
1	Nk(std)	3.138E+03	Gy C^{-1}	1.883E+01	Gy C^{-1}	0.60		2.646E-06	mGy h^{-1} Gy^{-1} C	4.982E-05	mGy h^{-1}		Air kerma calibration factor of ionisation chamber TM 32002 S/N 83 (standard) calibrated at PTB in 2012
2	k(stab,std)	1.000E+00		5.800E-03		0.58	Rectangular (TypeB)	8.303E-03	mGy h^{-1}	4.816E-05	mGy h^{-1}		
3	k(unif,std)	1.000E+00		2.900E-03		0.29	Rectangular (TypeB)	8.303E-03	mGy h^{-1}	2.408E-05	mGy h^{-1}		
4	k(spect,std)	1.000E+00		3.000E-03		0.30	Rectangular (TypeB)	8.303E-03	mGy h^{-1}	2.491E-05	mGy h^{-1}		Additional uncertainty due to higher contribution of background spectrum
5	I(std)	7.349E-13	A	4.56E-15	A	0.62	(TypeA)	1.130E+10	mGy $h^{-1}$$A^{-1}$	5.148E-05	mGy h^{-1}		
6	k(pT)	1.000E+00		8.000E-04		0.08	Rectangular (TypeB)	8.303E-03	mGy h^{-1}	6.642E-06	mGy h^{-1}		
	K(S-Cs)	2.306E-09	Gy s^{-1}										
	K(S-Cs)	8.303E-03	mGy h^{-1}	-			-	-		9.325E-05	mGy h^{-1}	1.12	standard uncertainty, k = 1
										1.865E-04	mGy h^{-1}	2.25	standard uncertainty, k = 2

*) used for the determination of the standard uncertainty

Model function: N(S-Cs) = K(S-Cs)/[I(tr)*k(setup,tr)]

No.	quantity or group of quantities	estimated value		standard uncertainty		%	probability distribution *)	sensitivity coefficient		contribution to the standard uncertainty		%	remarks
1	I(tr)	7.545E-13	A	4.75E-15	A	0.63	(TypeA)	4.051E+18	mGy C^{-1} A^{-1}	1.926E+04	mGy h^{-1}		
2	k(setup,tr)	1.000E+00		2.900E-03		0.29	Rectangular (TypeB)	3.057E+06	mGy C^{-1}	8.864E+03	mGy h^{-1}		
3	K(S-Cs)	8.303E-03	mGy h^{-1}	9.325E-05	mGy h^{-1}			3.682E+08	mGy C^{-1} mGy^{-1} h	3.433E+04	mGy h^{-1}		
	N(S-Cs)	1.100E+10	mGy $(Ah)^{-1}$										
	N(S-Cs)	3.057E+06	mGy C^{-1}	-			-	-		4.035E+04	mGy C^{-1}	1.32	standard uncertainty, k = 1
										8.069E+04	mGy C^{-1}	2.64	standard uncertainty, k = 2

*) used for the determination of the standard uncertainty

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Arvi Hakanen

Ka

Uncertainty budget according to GUM

S-Cs; 1 mSv h^{-1}

Model function: K = Nk(std)*k(stab,std)*k(unif,std)*k(spect,std)*I(std)* k(pT)

No.	quantity or group of quantities	estimated value		standard uncertainty		%	probability distribution *)	sensitivity coefficient		contribution to the standard uncertainty		%	remarks
1	Nk(std)	3.132E+03	Gy C^{-1}	1.879E+01	Gy C^{-1}	0.60		2.664E-04	mGy h^{-1} Gy^{-1} C	5.006E-03	mGy h^{-1}		Air kerma calibration factor of ionisation chamber TM 32002 S/N 83 (standard) calibrated at PTB in 2012
2	k(stab,std)	1.000E+00		5.800E-03		0.58	Rectangular (TypeB)	8.344E-01	mGy h^{-1}	4.840E-03	mGy h^{-1}		
3	k(unif,std)	1.000E+00		2.900E-03		0.29	Rectangular (TypeB)	8.344E-01	mGy h^{-1}	2.420E-03	mGy h^{-1}		
4	k(spect,std)	1.000E+00		2.900E-03		0.29	Rectangular (TypeB)	8.344E-01	mGy h^{-1}	2.420E-03	mGy h^{-1}		
5	I(std)	7.400E-11	A	8.88E-14	A	0.12	(TypeA)	1.128E+10	mGy h^{-1}A^{-1}	1.001E-03	mGy h^{-1}		
6	k(pT)	1.000E+00		8.000E-04		0.08	Rectangular (TypeB)	8.344E-01	mGy h^{-1}	6.675E-04	mGy h^{-1}		
	K(S-Cs)	2.318E-07	Gy s^{-1}										
	K(S-Cs)	8.344E-01	mGy h^{-1}	-			-	-		7.851E-03	mGy h^{-1}	0.94	standard uncertainty, k = 1
										1.570E-02	mGy h^{-1}	1.88	standard uncertainty, k = 2

*) used for the determination of the standard uncertainty

Model function: N(S-Cs) = K(S-Cs)/[I(tr)*k(setup,tr)]

No.	quantity or group of quantities	estimated value		standard uncertainty		%	probability distribution *)	sensitivity coefficient		contribution to the standard uncertainty		%	remarks
1	I(tr)	7.623E-11	A	9.15E-14	A	0.12	(TypeA)	3.989E+16	mGy C^{-1} A^{-1}	3.649E+03	mGy h^{-1}		
2	k(setup,tr)	1.000E+00		2.900E-03		0.29	Rectangular (TypeB)	3.041E+06	mGy C^{-1}	8.818E+03	mGy h^{-1}		
3	K(S-Cs)	8.344E-01	mGy h^{-1}	7.851E-03	mGy h^{-1}			3.644E+06	mGy C^{-1} mGy^{-1} h	2.861E+04	mGy h^{-1}		
	N(S-Cs)	1.095E+10	mGy (Ah)$^{-1}$										
	N(S-Cs)	3.041E+06	mGy C^{-1}	-			-	-		3.016E+04	mGy C^{-1}	0.99	standard uncertainty, k = 1
										6.032E+04	mGy C^{-1}	1.98	standard uncertainty, k = 2

*) used for the determination of the standard uncertainty

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Cs-137_1:

The uncertainty budget of the true value is presented in the table below,

UNCERTAINTY BUDGET OF TRUE VALUE							
Name of uncertainty component	*Estimation*	*Probability distribution*	*Standard uncertainty*	Sensitivity coefficient	Unit	Contribution to standard uncertainty	Unit
Calibration coefficient, N_{Ka} [Gy/C]	3,172E+03	*normal*	1,4E+01	5,482E-11	Sv.C/Gy	7,675E-10	Sv
Measurement, *M* [C]	4,593E-11	*normal*	6,771E-15	3,786E+03	Sv/C	2,564E-11	
Pressure, *P* [hPa]	1014,2	*rectangular*	0,05	-1,715E-10	Sv/hPa	-8,574E-12	
Temperature, *T* [ºC]	18,7	rectangular	0,03	5,959E-10	Sv/K	1,788E-11	
Dimension of radiation field, *a*	1,000	*rectangular*	0,0003	1,739E-07	Sv	5,217E-11	
Humidity, *H*	1,000	*rectangular*	0,0004	1,739E-07	Sv	6,956E-11	
Distance, *d*	200,000	*rectangular*	4,593E-14	3,786E+03	Sv/C	1,739E-10	
Conversion coefficient, CC [Sv/Gy]	1,20	*normal*	2,400E-02	1,449E-07	Gy	3,478E-09	
						3,567E-09	**Sv**

This implies an uncertainty of 2.1 % (k = 1) on the true value of ambient dose equivalent.

Cs-137_2:

The uncertainty budget of the true value is presented in the table below,

UNCERTAINTY BUDGET OF TRUE VALUE							
Name of uncertainty component	*Estimation*	*Probability distribution*	*Standard uncertainty*	Sensitivity coefficient	Unit	Contribution to standard uncertainty	Unit
Calibration coefficient, N_{Ka} [Gy/C]	2,576E+04	*normal*	7,5E+01	5,824E-10	Sv.C/Gy	4,368E-08	Sv
Measurement, *M* [C]	4,880E-10	*normal*	1,713E-14	3,074E+04	Sv/C	5,267E-10	
Pressure, *P* [hPa]	1018,3	*rectangular*	0,05	-1,473E-08	Sv/hPa	-7,366E-10	
Temperature, *T* [ºC]	19,8	rectangular	0,03	5,121E-08	Sv/K	1,536E-09	
Dimension of radiation field, *a*	1,000	*rectangular*	0,0003	1,500E-05	Sv	4,500E-09	
Humidity, *H*	1,000	*rectangular*	0,0004	1,500E-05	Sv	6,001E-09	
Distance, *d*	200,000	*rectangular*	4,880E-13	3,074E+04	Sv/C	1,500E-08	
Conversion coefficient, CC [Sv/Gy]	1,20	*normal*	2,400E-02	1,250E-05	Gy	3,000E-07	
						3,037E-07	**Sv**

This implies an uncertainty of 2.1 % (k = 2) on the true value of ambient dose equivalent.

N-60:

The uncertainty budget of the true value is presented in the table below. Due to the fact that the true value on X ray measurements are presented in the dosimetric quantity divided by the monitor units (MU), so it is presented always in Sv/UM, the uncertainty budget is in fact three, one for standard measurements, other for monitor unit measurements and on for the true value.

Uncertainty budget of standard measurements:

Quantity X_i	Estimation x_i	Probability distribution	Standard uncertainty	Sensitivity coefficient c_i	Contribution to standard uncertainty $u_i(y)$	Unit
Standard measurement, $M_{padrão}$ (C)	1,316E-08	normal	7,165E-12	0,98806	7,0798E-12	C
Pressure, *P* (hPa)	1024,45	rectangular	0,05	-1,26958E-11	-6,3479E-13	
Temperature, *T* (°C)	19,7	rectangular	0,03	4,44126E-11	1,3324E-12	
Distance, *d* (cm)	200	rectangular	3,949E-11	0,98806	3,9019E-11	
Humidity, *h*	1	rectangular	0,0004	1,30062E-08	5,2025E-12	
	y				*4,0023E-11*	

This implies an uncertainty of 0.61 % (k = 2) on the measurements with the standard.

Uncertainty budget of MU measurements:

Quantity X_i	Estimation x_i	Probability distribution	Standard uncertainty	Sensitivity coefficient c_i	Contribution to standard uncertainty $u_i(y)$	Unit
Measurements with monitor chamber, M_{UM} (V)	1,165	normal	5,977E-04	0,98806	5,9055E-04	V
Pressure, *P* (hPa)	1024,45	rectangular	0,05	-1,12324E-03	-5,6162E-05	
Temperature, *T* (°C)	19,7	rectangular	0,03	3,92933E-03	1,1788E-04	
Humidity, *h*	1	rectangular	0,0004	1,15070	4,6028E-04	
	y				*7,6004E-04*	

This implies an uncertainty of 0.13 % (k = 2) on the measurement of monitor units (MU).

Uncertainty budget of H true value:*

Quantity X_i	Estimation x_i	Probability distribution	Standard uncertainty	Sensitivity coefficient c_i	Contribution to standard uncertainty $u_i(y)$	Unit
Measurement (C/UM)	1,1303E-08	normal	3,5148E-11	4,00E+04	1,405E-06	Sv/UM
Calibration coefficient, N_K (Gy/C)	2,514E+04	normal	1,01E+02	1,7972E-08	1,807E-06	
Conversion coefficient CC (Sv/Gy)	1,59	normal	0,032	2,8412E-04	9,035E-06	
	y				*9,3204E-06*	

This implies an uncertainty of 4.2 % (k = 2) on the true value of ambient dose equivalent.

Cs-137_1:

Measurements with HS chamber:

Date of measurements: 21-10-2013

The uncertainty budget for the measurements with HS chamber at 2 meters distance is presented in the table below,

Uncertainty budget of HS chamber measurements

Unncertainty component	*estimation*	*Probability distribution*	*Standard uncertainty*	Sensitivity coefficient	unit	Contribution to standard uncertainty	unit
Measurement, *M* [C]	4,726E-11	*normal*	8,274E-14	9,968E-01	Gy/C	8,247E-14	
Pressure, *P* [hPa]	1011,0	*rectangular*	0,05	-4,659E-14	Gy/hPa	-2,330E-15	
Temperature, *T* [ºC]	18,4	rectangular	0,03	1,616E-13	Gy/K	4,847E-15	C/min
Radiation field dimension, *a*	1,000	*rectangular*	0,0003	4,711E-11	Gy	1,413E-14	
Humidity, *H*	1,000	*rectangular*	0,0003	4,711E-11	Gy	1,413E-14	
Distance, *d*	200,000	*rectangular*	4,726E-14	9,968E-01	Gy	4,711E-14	
						9,720E-14	**C/min**

This implies an uncertainty of 0.21 % (k = 1) on measurements with HS chamber.

The uncertainty of the calibration coefficient will be calculated in the following way,

Calibration coefficient	3.708E+03	Sv/C
Ambient dose equivalent	0.1790×10^{-06}	Sv/min
Uncertainty of ambient dose equivalent	3.759×10^{-09}	Sv/min
Measurement of HS chamber	48.272×10^{-12}	C/min
Uncertainty of measurement of HS chamber	1.014×10^{-13}	C/min
UNCERTAINTY OF CALIBRATION COEFFICIENT	**$7.826 \times 10^{+01}$**	**Sv/C**
RELATIVE UNCERTAINTY	**2.1**	**%**
EXPANDED UNCERTAINTY OF CALIBRATION COEFFICIENT	**$1.565 \times 10^{+02}$**	**Sv/C**
RELATIVE EXPANDED UNCERTAINTY	**4.2**	**%**

Cs-137_2:

The uncertainty budget for the measurements with HS chamber at 2.5 meters distance is presented in the table below,

Uncertainty budget of HS chamber measurements

Unncertainty component	*estimation*	*Probability distribution*	*Standard uncertainty*	Sensitivity coefficient	unit	Contribution to standard uncertainty	unit
Measurement, *M* [C]	2,645E-09	*normal*	1,314E-12	1,007E-00	Gy/C	1,323E-12	C/min
Pressure, *P* [hPa]	1005,8	*rectangular*	0,05	-2,649E-12	Gy/hPa	-1,324E-13	
Temperature, *T* [ºC]	19,9	rectangular	0,03	9,091E-12	Gy/K	2,727E-13	
Radiation field dimension, *a*	1,000	*rectangular*	0,0003	2,664E-09	Gy	7,992E-13	
Humidity, *H*	1,000	*rectangular*	0,0003	2,664E-09	Gy	7,992E-13	
Distance, *d*	250,000	*rectangular*	2,645E-12	1,007E-00	Gy	2,664E-12	
						3,197E-12	**C/min**

This implies an uncertainty of 0.12 % (k = 1) on measurements with HS chamber.

The uncertainty of the calibration coefficient will be calculated in the following way,

Calibration coefficient	3.680E+03	Sv/C
Ambient dose equivalent	0.01525×10^{-03}	Sv/min
Uncertainty of ambient dose equivalent	3.203×10^{-07}	Sv/min
Measurement of HS chamber	4.143×10^{-09}	C/min
Uncertainty of measurement of HS chamber	4.971×10^{-12}	C/min

UNCERTAINTY OF CALIBRATION COEFFICIENT	**7.744 x 10^{+01}**	**Sv/C**
RELATIVE UNCERTAINTY	**2.1**	**%**
EXPANDED UNCERTAINTY OF CALIBRATION COEFFICIENT	**1.549 x 10^{+02}**	**Sv/C**
RELATIVE EXPANDED UNCERTAINTY	**4.2**	**%**

N-60:

Measurements with HS chamber:

The uncertainty budgets associated with the measurements with HS chamber at 2 meters distance are presented in the tables below,

Uncertainty budget of HS chamber measurements:

Quantity X_i	Estimation x_i	Probability distribution	Standard uncertainty	Sensitivity coefficient c_i	Contribution to standard uncertainty $u_i(y)$
HS chamber measurement, M_{HS}	9,726E-09	normal	1,979E-12	1,00358	1,9863E-12
pressure, P	1005,85	rectangular	0,05	-9,70356E-12	-4,8518E-13
temperature, T	18,9	rectangular	0,03	3,34200E-11	1,0026E-12
distânce, d	200	rectangular	2,918E-11	1,00358	2,9281E-11
humidity, h	1	rectangular	0,0004	9,76033E-09	3,9041E-12
	y				*2,9628E-11*

This implies an uncertainty of 0.30 % (k = 1) on measurements with HS chamber.

Uncertainty budget of MU measurements:

Quantity X_i	Estimation x_i	Probability distribution	Standard uncertainty	Sensitivity coefficient c_i	Contribution to standard uncertainty $u_i(y)$
Measurements with monitor chamber, M_{UM}	0,779	normal	3,442E-04	1,00220	3,4500E-04
pressure, P	1005,85	rectangular	0,05	-7,76437E-04	-3,8822E-05
temperature, T	18,5	rectangular	0,03	2,67780E-03	8,0334E-05
humidity, h	1	rectangular	0,0004	0,78098	3,1239E-04
	y				*4,7389E-04*

This implies an uncertainty of 0.06 % (k = 1) on measurements with monitor chamber.

The measurements of HS chamber are normalized to the monitor units of the X radiation quality. The uncertainty of the measurements of HS chamber is,

M_{HS_X} =	**1,248E-08**	**C/UM**
Uncertainty of M_{HS_X}:	**3,877E-11**	**C/UM**

This implies an uncertainty of 0.31 % (k = 1) on measurements with HS chamber.

The uncertainty of the calibration coefficient will be calculated in the following way,

Calibration coefficient	3.531E+03	Sv/C
Ambient dose equivalent	0.044099 x 10^{-03}	Sv/UM
Uncertainty of ambient dose equivalent	9.261 x 10^{-07}	Sv/UM
Measurement of HS chamber	1.248 x 10^{-08}	C/UM
Uncertainty of measurement of HS chamber	3.877 x 10^{-11}	C/UM
UNCERTAINTY OF CALIBRATION COEFFICIENT	**7.501 x 10^{+01}**	**Sv/C**
RELATIVE UNCERTAINTY	**2.2**	**%**
EXPANDED UNCERTAINTY OF CALIBRATION COEFFICIENT	**1.500 x 10^{+02}**	**Sv/C**
RELATIVE EXPANDED UNCERTAINTY	**4.4**	**%**

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (LMRI-CIEMAT)

3.3 Conventional true values and its uncertainties

The conventional true values of the ambient dose equivalent rate, $\dot{H}^*(10)$, were determined using the following equations:

$$\dot{H}^*(10) = h_K^*(10,\mathrm{Q}) \cdot \dot{K}_\mathrm{a} \qquad (1),$$

$$\dot{K}_\mathrm{a} = I \cdot N_K \cdot \prod_\mathrm{i} k_\mathrm{i} \qquad (2),$$

where:

$h_K^*(10,\mathrm{Q})$	is the conversion coefficient from air kerma to ambient dose equivalent for S-Cs, $h_K^*(10,\text{S-Cs})$, or for X ray N-60, $h_K^*(10,\text{N-60})$.
$\dot{K}_\mathrm{a}$	is the reference value or conventional true value of the air kerma rate.
I	is the net ionization current (corrected for leakage currents), measured with the reference instrument.
N_K	is the air kerma calibration coefficient of the secondary standard (reference instrument), for a chamber air temperature of 20 °C, an ambient air pressure of 1013,25 hPa, and a relative humidity of 50%.
k_i	are the correction factors, described in 3.3.1 and 3.3.2.

3.3.1 Conventional true value for S-Cs quality

In the framework of this comparison, the following correction factors, k_i, in equation (2) have been considered:

k_TP	is the air density correction factor, for reference air temperature and pressure (293,15 K and 101,325 kPa, respectively),
k_h	is the air humidity correction to the reference relative humidity of 50 %,
k_stab	is the correction factor for the long term stability of the reference instrument,
k_s	is the correction factor for recombination losses,
k_pos	is the correction factor for the positioning of the secondary standard ionization chamber.

The values of the parameters that appear in equations (1) and (2) and the corresponding uncertainties are shown in table 3, according to the requirements of the GUM [3]. Because both the standard and the transfer instrument used the same current measurement system, including the thermometer and the barometer, some non-statistical components of uncertainty cancel. These components have not been included in the uncertainty budget.

Table 3: Parameters for the determination of ambient dose equivalent rates in ^{137}Cs beams and their estimated relative standard uncertainties.

Parameters	**Values**	**Uncertainties (k = 1)** 100 s_i	100 u_i
N_K (× 10^3 Gy/C)	3,163	-	0,75
$h_K^*(10,\text{S-Cs})$	1,20	-	2,00
k_{TP}		-	0,05
k_h	1,0000	-	0,04
k_{stab}	1,0000	0,24	-
k_{pos}	1,0000	-	0,04
k_s	0,9987	-	0,11
	0,9985	-	0,11
I		0,01	0,05
		0,06	0,14
Quadratic summation		0,24	2,14
		0,25	2,15
Combined relative standard uncertainty (in %)		2,15	
		2,16	

Notes:

- s_i represents the relative standard uncertainty estimated by statistical methods, type A
- u_i represents the relative standard uncertainty estimated by other means, type B
- The first row of "k_s", "I", "quadratic summation" and "combined relative standard uncertainty" corresponds to the comparison reference value of 1 mSv/h, while the second row corresponds to the comparison reference value of 10 μSv/h,

The reference values of the ambient dose equivalent rates, determined at ^{137}Cs beams of the CIEMAT, using the equations (1), and (2), are summarized in table 4, whereas the measured values of air kerma rates are summarized in table 5. The corresponding expanded uncertainties were calculated from the uncertainty budget in table 3. The standard uncertainties were multiplied by a coverage factor k = 2, providing a level of confidence of approximately 95%.

During the measurements with the standard chamber the air pressure was in the range from 94,71 kPa to 94,98 kPa, while the air temperature was in the range from 19,47 ^{o}C to 19,99 ^{o}C. The air relative humidity was 43 %.

Table 4: Reference values of $\dot{H}^*(10)$

$\dot{H}^*(10)$	Relative uncertainty (k = 2)
$9{,}970 \times 10^{-4}$ Sv/h	$4{,}30 \times 10^{-2}$
$9{,}994 \times 10^{-6}$ Sv/h	$4{,}32 \times 10^{-2}$

Table5: Reference values of $\dot{K}_a$

$\dot{K}_a$	Relative uncertainty (k = 2)
$8{,}308 \times 10^{-4}$ Gy/h	$1{,}60 \times 10^{-2}$
$8{,}329 \times 10^{-6}$ Gy/h	$1{,}62 \times 10^{-2}$

3.3.2 Conventional true value for N-60 quality

In the framework of this comparison, the following correction factors, $k_{i,}$ in equation (2) have been considered:

k_{TP}	is the air density correction factor, for reference air temperature and pressure (293,15 K and 101,325 kPa, respectively),
k_h	is the air humidity correction to the reference relative humidity of 50 %,
k_Q	is the correction factor applied to the calibration coefficient of the reference instrument, relative to the quality N-40,
k_{stab}	is the correction factor for the long term stability of the reference instrument.

The values of these parameters and the corresponding uncertainties are shown in table 6, according to the requirements of the GUM [3]. As in the case of S-Cs quality, the measurements with the standard chamber and the transfer instrument were carried out with the same electrometer, and with the same thermometer and barometer. For that reason some non-statistical components of uncertainty cancel and have not been included in the uncertainty budget.

The reference value of the ambient dose equivalent rate, determined at N-60 reference beam of the CIEMAT, using the equations (1) and (2), is given in table 7. The measured value of air kerma rate is presented in table 8. The corresponding expanded uncertainties were calculated from the uncertainty budget in table 6. The standard uncertainties were multiplied by a coverage factor k = 2, providing a level of confidence of approximately 95%.

During the measurements with the standard chamber the air pressure was stable in a value of 94,164 kPa, while the air temperature was in the range from 20,04 ^{o}C to 20,09 ^{o}C. The air relative humidity was 42 %.

Table 6: Parameters for the determination of ambient dose equivalent rates in X-Ray N-60 beam and their estimated relative standard uncertainties.

Parameters	**Values**	**Uncertainties (k = 1)** 100 s_i	100 u_i
N_K x k_Q ($\times$ 10^4 Gy/C)	4,322	-	0,60
$h_K^*(10, \text{N-60})$	1,59	-	2,00
k_{TP}		-	0,11
k_h	1,0000	-	0,05
k_{stab}	1,0000	0,21	-
I		0,03	0,10
Quadratic summation		0,21	2,09
Combined relative standard uncertainty (in %)		2,10	

Notes:

- s_i represents the relative standard uncertainty estimated by statistical methods, type A
- u_i represents the relative standard uncertainty estimated by other means, type B

Table 7: Reference value of $\dot{H}^*(10)$

$\dot{H}^*(10)$	Relative uncertainty (k = 2)
1,013 $\times$ 10^{-3} Sv/h	4,20 $\times$ 10^{-2}

Table 8: Reference value of $\dot{K}_a$

$\dot{K}_a$	Relative uncertainty (k = 2)
6,369 $\times$ 10^{-4} Gy/h	1,31 $\times$ 10^{-2}

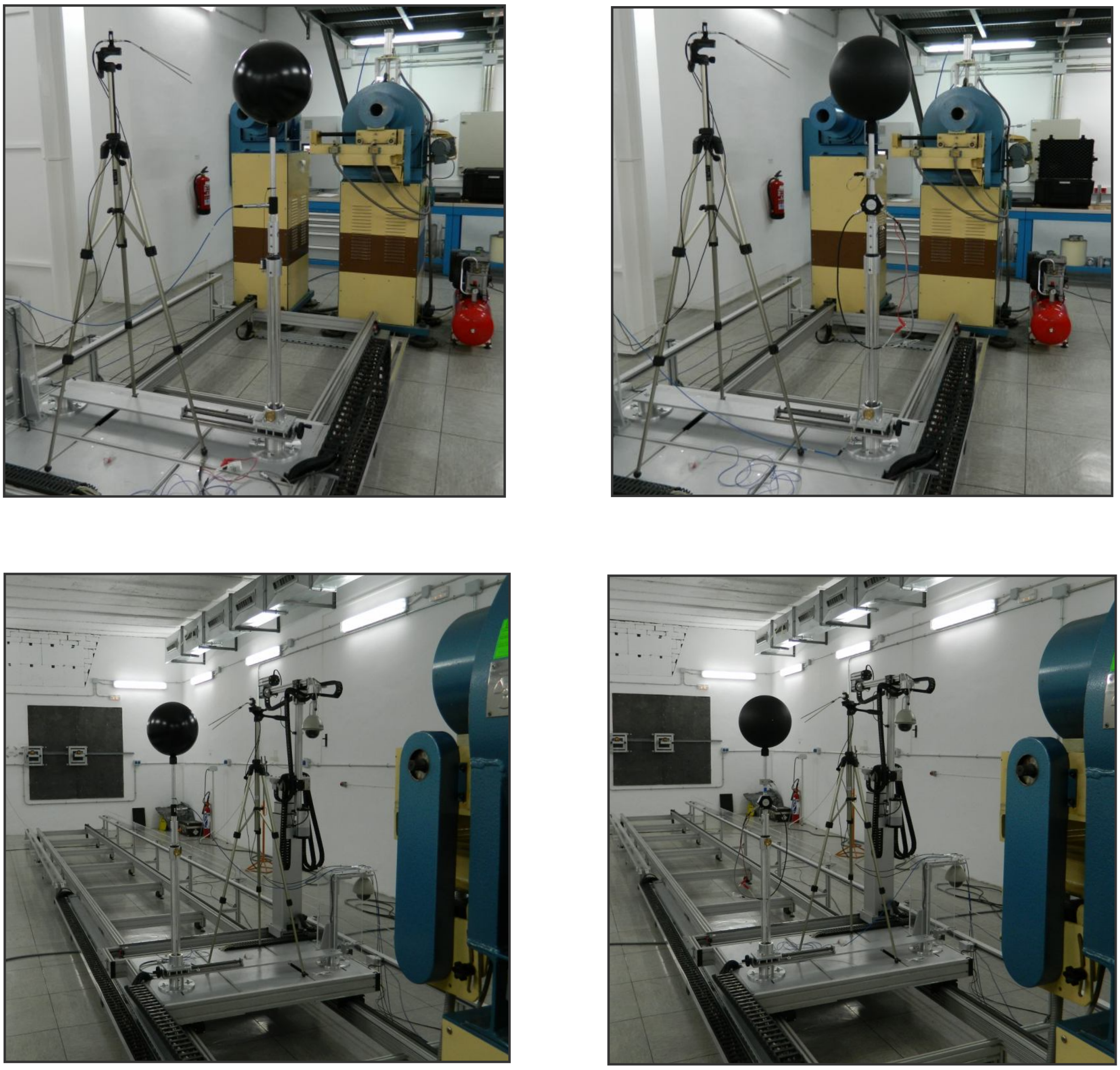
4. DESCRIPTION OF THE CALIBRATION MEASUREMENTS

The calibrations were made by using the sequential method, in which the standard chamber and the transfer chamber HS10 were placed alternately with their reference points of measurements at the same calibration point on the central axis of the beam (see figures 1 and 2). The measuring conditions were those specified in the technical protocol of the comparison [4].

The transfer chamber was positioned with the stem perpendicular to the beam axis and the white mark, on the chamber wall, oriented to the source. The reference point of measurements for positioning the chamber HS10 in the beams was taken as the geometrical centre of the spherical chamber cavity. The radiation fields used throughout the calibrations were circular in cross-section and their sizes were sufficient to irradiate the whole of the chamber. The chambers were placed at the reference points, with the collecting voltage applied, at least two hours before the beginning of measurements in order to guarantee the temperature equilibrium.

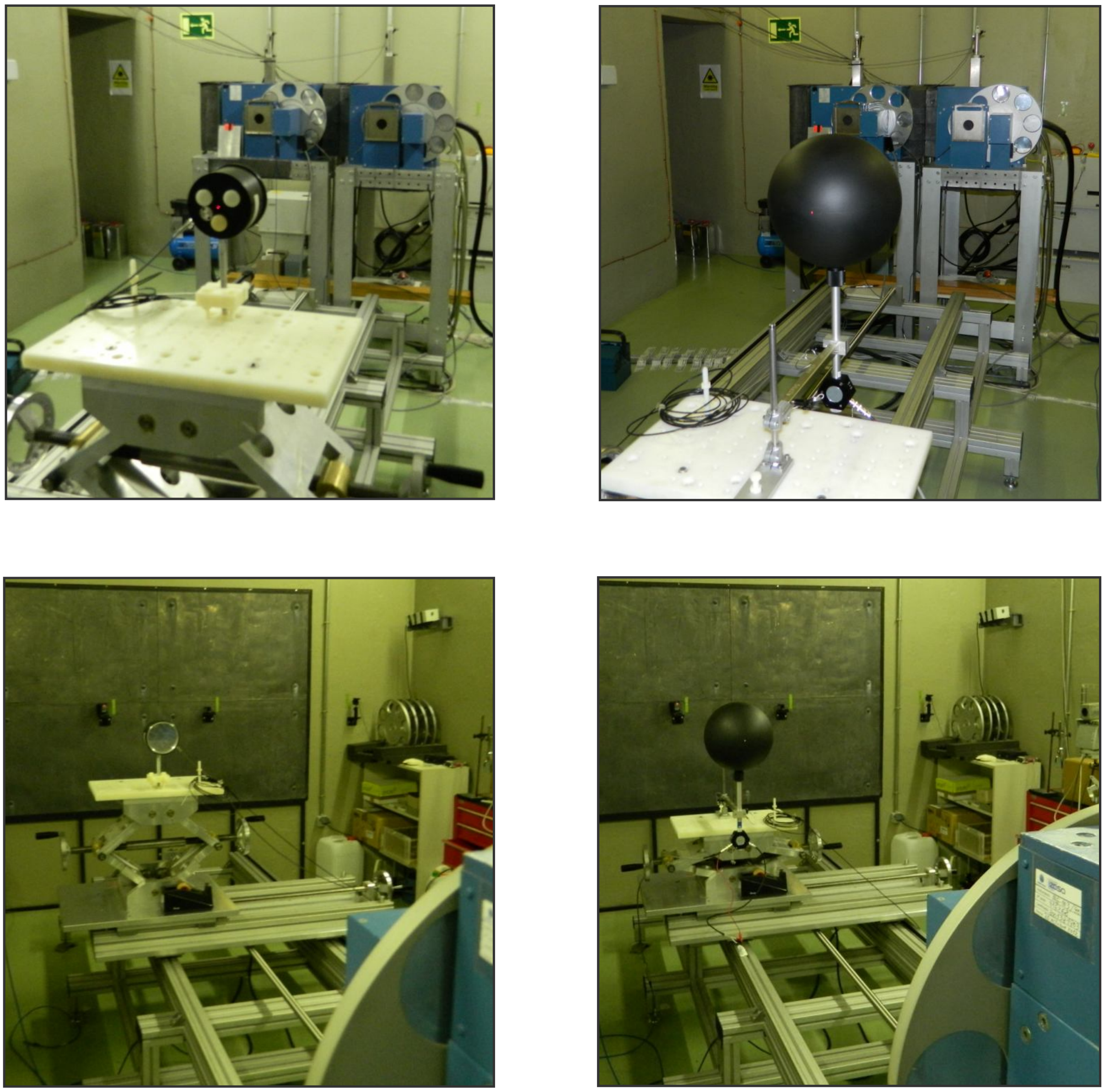
During calibrations the transfer chamber was operated at a polarising potential of 400 volts. This was applied to the chamber so that the chamber wall was positive with respect to the inner central electrode (the collecting electrode). The ionization current of the transfer chamber was determined using the same electrometer as was used with the standard chamber.

The chamber background current was measured before and after the chamber was exposed to the source of radiation. The average of background current was determined and subtracted from the measured ionization current produced in the chamber when exposed to the source of radiation. The measured ionization currents were normalized to the reference values of chamber air temperature and pressure (293,15 K and 101,325 kPa, respectively).



(a) *(b)*

Figure 1: Calibration arrangement in S-Cs beams at CIEMAT.
a) Standard chamber. b) Transfer chamber.



(a) *(b)*

Figure 2: Calibration arrangement in N-60 beam at CIEMAT.
a) Standard chamber. b) Transfer chamber.

5. DETERMINATION OF THE CALIBRATION COEFFICIENTS

The calibration coefficients, N_H (in Sv/C), were determined by evaluating the ratio:

$$N_H = \frac{\dot{H}^*(10)}{I} \qquad (3)$$

where

$\dot{H}^*(10)$ is the conventional true value of the ambient dose equivalent rate measured with the reference instrument (in Sv/s),

I is the ionization current measured with the transfer chamber, corrected for leakage current and the reference air pressure and temperature (101,325 kPa and 293,15 K, respectively), expressed in A.

The ionization current of the transfer chamber was determined with the electrometer used for the measurement of the conventional true value of the ambient dose equivalent rate with the secondary standard chamber. The environmental variables where measured also with the same instruments.

The current measured with the transfer chamber was not corrected for humidity, neither for lack of saturation.

5.1 ISO radiation quality: S-Cs

The table 9 lists the relevant values associated to the obtained calibration coefficients, N_H, for both ambient dose equivalent rates, at the stated reference conditions (293,15 K and 101,325 kPa), whereas the table 10 contains the information regarding the corresponding air kerma calibration coefficients, N_K. The uncertainty values were obtained from the uncertainty budget in table 11. The standard uncertainties were multiplied by a coverage factor k = 2, providing a level of confidence of approximately 95%.

Table 9: Ambient dose equivalent calibration coefficients, N_H, and their uncertainties

Reference comparison values $\dot{H}^*(10)$	N_H (Sv/C)	Uncertainty (k = 2) (Sv/C)	(%)
1 mSv/h	$3{,}704 \times 10^3$	$1{,}59 \times 10^2$	4,3
10 uSv/h	$3{,}716 \times 10^3$	$1{,}61 \times 10^2$	4,3

Table 10: Air kerma calibration coefficients, N_K, and their uncertainties

Reference values $\dot{H}^*(10)$	Air kerma rates $\dot{K}_a$	N_K (Gy/C)	Uncertainty (k = 2) (Gy/C)	(%)
1 mSv/h	$8{,}308 \times 10^{-4}$ Gy/h	$3{,}086 \times 10^{3}$	$5{,}0 \times 10^{1}$	1,6
10 uSv/h	$8{,}329 \times 10^{-6}$ Gy/h	$3{,}097 \times 10^{3}$	$5{,}1 \times 10^{1}$	1,7

Table 11: Estimated relative standard uncertainties of the calibration coefficients, N_H and N_K, for the two ambient dose equivalent rate values

Relative standard uncertainty (1)	**100 s_i** (2)	**100 u_i**
Positioning	-	0,09
Air density correction (temperature and pressure)	-	0,05
Ionization current of the transfer chamber	0,01	0,05
	0,07	0,12
Relative standard uncertainty of $\dot{H}^*(10)$ (3)	-	2,15
	-	2,16
Relative standard uncertainty of $\dot{K}_a$ (3)	-	0,80
	-	0,81
Relative standard uncertainty of N_H *(in %)*	2,15	
	2,17	
Relative standard uncertainty of N_K *(in %)*	0,81	
	0,83	

(1) The first row of "Ionization current of the transfer chamber", "Relative standard uncertainty of $\dot{H}^*(10)$ ", "Relative standard uncertainty of $\dot{K}_a$ ", "Relative standard uncertainty of N_H", and "Relative standard uncertainty of N_K" corresponds to the comparison reference value of 1 mSv/h, while the second row corresponds to the comparison reference value of 10 µSv/h.

(2) s_i represents the relative standard uncertainty estimated by statistical methods, type A
u_i represents the relative standard uncertainty estimated by other means, type B

(3) Values obtained from tables 4 and 5.

During the measurements with the transfer chamber the air temperature, pressure and relative humidity were in the following ranges:

$\dot{H}^*(10)$	Temperature (°C)	Pressure (kPa)	Relative humidity (%)
1 mSv/h	19,60 – 19,88	94,88 – 94,91	43
10 uSv/h	19,44 – 19,70	94,68 – 94,69	44

5.2 ISO radiation quality: N-60

The table 12 lists the relevant values associated to the obtained calibration coefficient, N_H, at the stated reference conditions (293,15 K and 101,325 kPa), whereas the table 13 contains the information regarding the corresponding air kerma calibration coefficient, N_K. The uncertainty values were obtained from the uncertainty budget in table 14. The standard uncertainties were multiplied by a coverage factor k = 2, providing a level of confidence of approximately 95%.

Table 12: Ambient dose equivalent calibration coefficient, N_H, and its uncertainty

Reference comparison value $\dot{H}^*(10)$	N_H (Sv/C)	Uncertainty (k = 2) (Sv/C)	(%)
1 mSv/h	$3{,}488 \times 10^3$	$1{,}47 \times 10^2$	4,2

Table 13: Air kerma calibration coefficient, N_K, and its uncertainty

Reference value $\dot{H}^*(10)$	Air kerma rate $\dot{K}_a$	N_K (Gy/C)	Uncertainty (k = 2) (Gy/C)	(%)
1 mSv/h	$6{,}369 \times 10^{-4}$Gy/h	$2{,}194 \times 10^3$	$2{,}9 \times 10^1$	1,3

During the measurements with the transfer chamber the air temperature, pressure and relative humidity were in the following ranges:

$\dot{H}^*(10)$	Temperature (°C)	Pressure (kPa)	Relative humidity (%)
1 mSv/h	19,91 – 19,94	94,164 – 94,168	42

Table 14: Estimated relative standard uncertainties of the calibration coefficients, N_H and N_K,

Relative standard uncertainty	**100 s_i**(1)	**100 u_i**
Positioning	-	0,03
Air density correction (temperature and pressure)	-	0,11
Ionization current of the transfer chamber	0,01	0,01
Relative standard uncertainty of $\dot{H}^*(10)^{(2)}$	-	2,10
Relative standard uncertainty of $\dot{K}_a$ (2)	-	0,66
Relative standard uncertainty of N_H *(in %)*	2,10	
Relative standard uncertainty of N_K *(in %)*	0,67	

(1) s_i represents the relative standard uncertainty estimated by statistical methods, type A
u_i represents the relative standard uncertainty estimated by other means, type B
(2) Values obtained from tables 7 and 8.

6. REFERENCES

[1] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION: X and gamma reference radiation for calibrating dosemeters and dose rate 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 4037-03 (1999).

[2] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION: X and gamma reference radiation for calibrating dosemeters and dose rate meters and for determining their response as a function of photon energy. Part 1: Radiation characteristics and production methods. ISO 4037-01 (1996).

[3] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION: Uncertainty of measurement - Part 3: Guide to the Expression of Uncertainty in Measurement (GUM:1995) (Geneva: ISO), BIPM JCGM 100:2008; Guide to the Expression of Uncertainty in Measurement (GUM) ISO/IEC Guide 98-3 (2008).

[4] HUPE, O.: EURAMET supplementary comparison of the ambient dose equivalent rate for photon radiation. Technical Protocol. EURAMET project No. 1132, BIPM KCDB: EURAMET.R(I)-S11 (2013).

Czech Metrology Institute (CMI)

Annex: Uncertainty budget

N60, 1 mSv/h

a) Determination of a reference value of H*(10)

No.	Quantity or group of quantities	Estimated value	Standard uncertainty	Contribution to the resulting standard uncertainty	Remarks
1	Calibration coeff.	1.041E6 Gy/C	0.6 %	0.6 %	
2	Ionization current	1.839E-13 A	0.47 %	0.47 %	
3	Leakage current	4E-16 A	63 %	0.14 %	
4	Air temperature	20.3°C	0.15 %	0.15 %	
5	Air pressure	996.2 hPa	0.1 %	0.1 %	
6	Air humidity	22 %	0.1 %	0.1 %	
7	Distance F-D	2.125 m	0.05 %	0.1 %	
8	Effective energy	47.2 keV	0.5 %	0.45 %	C_{ICRU} = 1.616
	$\dot{H}*(10)$	3.094E-7 Sv/s	---	0.92 %	k=1
				1.85 %	k=2

b) Calibration of a transfer chamber HS(10)

No.	Quantity or group of quantities	Estimated value	Standard uncertainty	Contribution to the resulting standard uncertainty	Remarks
1	$\dot{H}*(10)$	3.094E-7 Sv/s	0.92 %	0.92 %	
2	Ionization current	8.475E-11 A	0.40 %	0.40 %	
3	Leakage current	3.88E-14 A	13.5 %	0.06 %	
4	Air temperature	20.4 °C	0.15 %	0.15 %	
5	Air pressure	996.3 hPa	0.1 %	0.1 %	
6	Air humidity	22 %	0.1 %	0.1 %	
7	Distance F-D	2.125 m	0.1 %	0.2 %	
	N_H	3.645E3 Sv/C	---	1.05 %	k=1
				2.10 %	k=2

^{137}Cs, 1 mSv/h

a) Determination of a reference value of H*(10)

No.	Quantity or group of quantities	Estimated value	Standard uncertainty	Contribution to the resulting standard uncertainty	Remarks
1	Calibration coeff.	1.077E6 Gy/C	0.6 %	0.6 %	
2	Ionization current	2.161E-13 A	0.47 %	0.47 %	
3	Leakage current	-4.3E-15 A	10 %	0.2 %	
4	Air temperature	21.6°C	0.15 %	0.15 %	
5	Air pressure	978.8 hPa	0.1 %	0.1 %	
6	Air humidity	22 %	0.1 %	0.1 %	
7	Distance F-D	6.385 m	0.01 %	0.02 %	
8	Effective energy	661 keV	---	---	C_{ICRU} = 1.204
	$\dot{H}*(10)$	2.799E-7 Sv/s	---	0.82 %	k=1
				1.63 %	k=2

b) Calibration of a transfer chamber HS(10)

No.	Quantity or group of quantities	Estimated value	Standard uncertainty	Contribution to the resulting standard uncertainty	Remarks
1	$\dot{H}*(10)$	2.799E-7 Sv/s	0.82 %	0.82 %	
2	Ionization current	7.710E-11 A	0.40 %	0.40 %	
3	Leakage current	1.05E-14 A	35 %	0.05 %	
4	Air temperature	21.6 °C	0.15 %	0.15 %	
5	Air pressure	979.2 hPa	0.1 %	0.1 %	
6	Air humidity	22 %	0.1 %	0.1 %	
7	Distance F-D	6.385 m	0.03 %	0.06 %	
	N_H	3.631E3 Sv/C	---	0.94 %	k=1
				1.88 %	k=2

^{137}Cs, 10 µSv/h:

a) Determination of a reference value of air kerma rate

No.	Quantity or group of quantities	Estimated value	Standard uncertainty	Contribution to the resulting standard uncertainty	Remarks
1	Calibration coeff.	1.077E6 Gy/C	0.6 %	0.6 %	
2	Ionization current	2.154E-12 A	0.40 %	0.40 %	
3	Leakage current	-7.6E-15 A	6.8 %	0.02 %	
4	Air temperature	21.7°C	0.15 %	0.15 %	
5	Air pressure	982.2 hPa	0.1 %	0.1 %	
6	Air humidity	23 %	0.1 %	0.1 %	
7	Distance F-D	2.037 m	0.05 %	0.1 %	
	$\dot{K}$	2.328E-6 Gy/s	---	0.76 %	k=1
				1.51 %	k=2

b) Calibration of the comparator

No.	Quantity or group of quantities	Estimated value	Standard uncertainty	Contribution to the resulting standard uncertainty	Remarks
1	$\dot{K}$	2.328E-6 Gy/s	0.76 %	0.76 %	
2	Ionization current	7.801E-10 A	0.40 %	0.40 %	
3	Leakage current	3.0E-14 A	15 %	0 %	
4	Air temperature	21.0 °C	0.15 %	0.15 %	
5	Air pressure	985.2 hPa	0.1 %	0.1 %	
6	Air humidity	23 %	0.1 %	0.1 %	
7	Distance F-D	2.037 m	0.05 %	0.1 %	
	N_K	2.985E3 Gy/C	---	0.89 %	k=1
				1.78 %	k=2

c) Determination of a reference value of H*(10)

No.	Quantity or group of quantities	Estimated value	Standard uncertainty	Contribution to the resulting standard uncertainty	Remarks
1	Calibration coeff.	2.985E3 Gy/C	0.89 %	0.89 %	
2	Ionization current	8.087E-13 A	0.50 %	0.50 %	
3	Leakage current	3.33E-14 A	8 %	0.33 %	
4	Air temperature	21.6°C	0.15 %	0.15 %	
5	Air pressure	985.2 hPa	0.1 %	0.1 %	
6	Air humidity	23 %	0.1 %	0.1 %	
7	Distance F-D	4.016 m	0.025 %	0.05 %	
8	Effective energy	661 keV	---	---	C_{ICRU} = 1.204
	$\dot{H}*(10)$	2.787E-9 Sv/s	---	1.09 %	k=1
				2.19 %	k=2

d) Calibration of a transfer chamber HS(10)

No.	Quantity or group of quantities	Estimated value	Standard uncertainty	Contribution to the resulting standard uncertainty	Remarks
1	$\dot{H}*(10)$	2.787E-9 Sv/s	1.09 %	1.09 %	
2	Ionization current	7.717E-13 A	0.50 %	0.50 %	
3	Leakage current	6.2E-15 A	50 %	0.40 %	
4	Air temperature	20.5 °C	0.15 %	0.15 %	
5	Air pressure	978.8 hPa	0.1 %	0.1 %	
6	Air humidity	23 %	0.1 %	0.1 %	
7	Distance F-D	4.016 m	0.025 %	0.05 %	
	N_H	3.650E3 Sv/C	---	1.28 %	k=1
				2.56 %	k=2

Horia Hulubei National Institute of R&D for Physics and Nuclear Engineering (IFIN-HH)

The standard instrument

A) The standard instrument

The standard instrument used for this comparison is an UNIDOS T 10021 electrometer with the TM 32003 ionization chamber (Volume= 10 l) (See fig. 2). Using this standard instrument, the reference value is obtained.

The IFIN-HH standard instrument traceability is assured by calibration at PTB (Calibration Certificate No PTB-6.3-4065479/10.09.2013 and 6.25-40/13K/17.09.2013).

According it`s Calibration Certificate, for the ambient dose equivalent rate (at 10 mm depth) (H*(10)), the relative expanded uncertainty is of 3% for k=2.

For the air kerma rate ($\dot{K}_a$), the relative expanded uncertainty is of 1.2 % for k=2.

For Quality radiation N-60, the relative expanded uncertainty is of 0.8 % for k=2 (for Gy) and 3% for k=2 (for Sv)

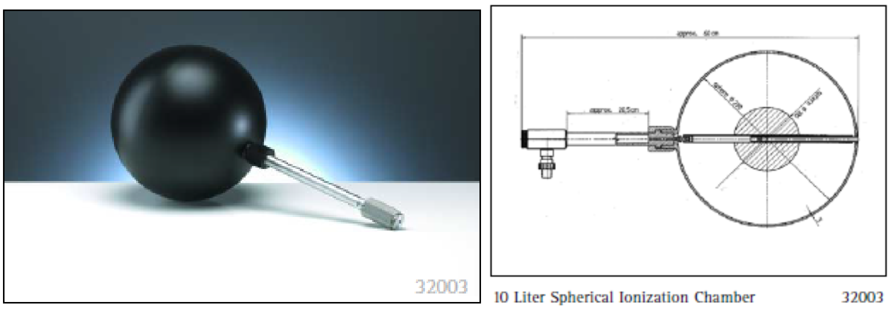


Fig. 2 Ionisation chamber type TM 32003

Results

The irradiations were performed on the irradiation bench, using a collimated beam produced by a 137-Cs radioactive source (serial number 337).

Reference point of the ionization chamber: Geometrical centre of the chamber.
The radioactive source-detector distance (SDD) is the distance between the radioactive source and the geometrical center of the spherical chamber.
The alignment of the chamber in the gamma beam was performed by using the mark point (MP) on the exterior surface of the chamber

Climatic conditions:

- Temperature: 20.1 to 20.9^{0}C
- Air pressure: 1013.2 to 1016 hPa
- Rel. humidity: 44 to 55%

For the irradiations, the position of the geometrical center of the chamber was established on the bench, as the intersection of the three laser beams.

Then, the ionization chamber was placed on the bench, in such a manner that it`s geometrical center was in the intersection of the three laser beams.
The focal spot of horizontal laser beam was on the MP of the chamber.

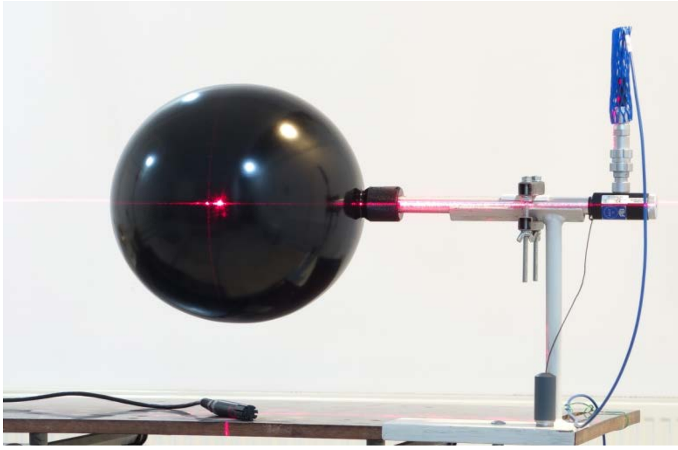


Fig. 3 Ionisation chamber type TM 32003

During these measurements, a good reproducibility of the values of the measured quantity was obtained, which means that the positioning of the source was reproducible and that the ionization chamber was placed, each time, at the same SDD.

The air temperature and pressure were measured, at the beginning and at the end of each $\dot{H}*(10)$ measurement. For each variation of the values of the temperature and pressure, the suitable corrections are applied; the corresponding uncertainties, of the measurement were calculated for k=2.

For each value of $\dot{H}$ (equivalent dose rate) 10 values (statistically independent) were recorded and the mean value ($\bar{\dot{H}}$) was calculated,

$$\dot{H} = \frac{\sum_{i=1}^{n} \dot{H}_i}{n} \cdot k_{TP} \qquad (1)$$

Were: $\dot{H}_i$ – the recorded values of the equivalent dose rate
n – numbers of the recorder values
k_{TP} - correction factor for temperature and pressure

k_{TP} correction factor was calculated using eq. (2):

$$k_{TP} = \frac{1013.25}{P} * \frac{(273.15+T)}{293.15} \qquad (2)$$

Where: T – temperature
P – Pressures

The components of the measurement uncertainty are:

a) The standard uncertainty (s_n) of the measurements made using the standard instrument (s_n):

$$s_n = \frac{1}{\overline{H}}\sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}(H_i - \overline{H})^2} \qquad (3)$$

Where: - $\dot{H}_i$ the recorded value of $\dot{H}$
- n the number of the recorded values for each measurement
- $\bar{\dot{H}}$ the mean value of the recorded values for each measurement

b) The calibration uncertainty of the standard instrument used for comparison, (u_{cc}) according the Calibration Certificate:

$$u_{cc} = \frac{1}{2}\, U_{calib} \qquad (4)$$

Where: - U_{calib} the uncertainty of the standard instrument, according the Calibration Certificate, for k=2.

c) The uncertainty due to the electrometer: 0.2 % for k=2

d) The uncertainty due to the resolution of the displayed values of the standard instrument (u_{res}):

$$u_{res} = \frac{1}{\sqrt{3}}\frac{R_{et}}{\overline{H}} \qquad (5)$$

Where: R_{et} – the resolution of the displayed values of the standard instrument;
$\dot{H}$*(10) - the mean value of the ambient dose equivalent rate

e) The uncertainty due to the instruments used for the measurement of the air temperature and pressure ($u_{kTP\ CE}$):

$$u_{kTP\ CE} = k_{TP,m} * \sqrt{\frac{u_P^2}{P_m^2} + \frac{u_T^2}{(273.15+T_m)^2}} \qquad (6)$$

Where:
$K_{T,P,m}$ - the correction factor for T and P, calculated for the measured values
u_T - the measurement uncertainty for the temperature, from the calibration certificate of the instrument for k=1;
u_P - the measurement uncertainty for the pressure, from the calibration certificate of the instrument, for k=1
P_m - he measured value of the pressure (hPa)
T_m - the measured value of the temperature (^{0}C)

f) The uncertainty due to the display resolution of the instruments used for the measurement of the temperature and the pressure (u_{kTPrez})

$$u_{kTP\ rez} = k_{TP,m} * \sqrt{\frac{\delta_P^2}{P_m^2} + \frac{\delta_T^2}{(273.15+T_m)^2}} \qquad (7)$$

Where:

- $K_{TP,m}$ – the correction factor for T and P, calculated for the measured values of T and P
- δ_P – the resolution for displaying the pressure value,
- δ_T – the resolution for displaying the temperature value,
- P_m – the measured value of the pressure (hPa)
- T_m – the measured value of the temperature (^{0}C)

g) The uncertainty due to the variation of the ambient temperature and the pressure during the measurements (u_{varTP}),

$$u_{var\ TP} = k_{TP,m} * \sqrt{\frac{\Delta_p^2}{P_m^2} + \frac{\Delta_T^2}{(273.15+T_m)^2}} \qquad (8)$$

Where:

- $K_{T,P,m}$ - the correction factor for T and P, calculated for the measured values
- Δp - pressure variation during the measurements of H;
- ΔT - temperature variation during measurements
- P_m - the measured value of P (hPa)
- T_m - the measured value of T(^{0}C)

h) When the ionization chamber is placed on the irradiation bench, a maximum positioning error (ε) is assumed; the value of this error was of 2 mm
The uncertainty due to the positioning of the standard instrument ($u_{distance}$):

$$u_{distance} = \frac{d^2}{\sqrt{3}} * \left(\frac{1}{(d-\varepsilon)^2} - \frac{1}{(d+\varepsilon)^2}\right) \qquad (9)$$

Where:

- d= the distance (SDD)
- ε = the error for the positioning

i) The uncertainty for to the positioning of the standard instrument due to the calibration of the instrument for the distance (according the Calibration Certificate):

$$u_{distanta\ CC} = \frac{d^2}{\sqrt{3}} * \left(\frac{1}{(d-u_d)^2} - \frac{1}{(d+u_d)^2}\right) \qquad (10)$$

Where:

- d – distance (m)
- u_d - the uncertainty of the calibration of the instrument (as give in the calibration certificate) for k=1 according the Calibration Certificate,

The expanded uncertainty of the measurements results obtained with the standard instrument is:

$$u_{SSD} = \sqrt{s_n^2 + u_{cc}^2 + u_{rez}^2 + u_{kTPCC}^2 + u_{kTPrez}^2 + u_{varTP}^2 + u_d^2 + u_{dCC}^2} \qquad (11)$$

B. Ionization chamber type HS 10

In the picture below the ionization chamber type HS 10 in the laser beams for alignment is presented.
The ionization chamber type HS 10 was connected to the 10021UNIDOS Webline electrometer.

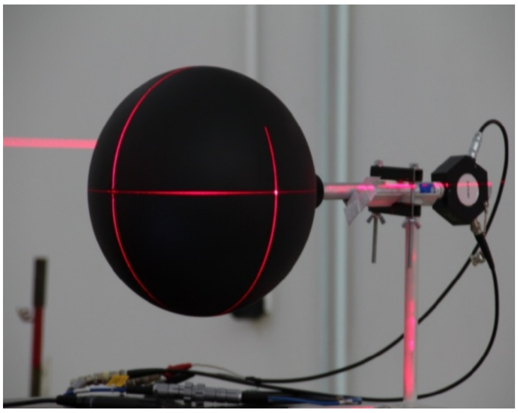


Fig. 4 Ionisation chamber type HS 10, in the laser beams for positioning

The calibration factor (in Sv/C) given by:

$$N_H = \frac{H^*(10)}{I} \qquad (12)$$

Where:

- I – the ionization current measured by the ionisation chamber with the UNIDOS Webline type 10021
- $\dot{H}^*(10)$ – the reference value of the ambient dose equivalent rate conventional quantity value of the ambient dose equivalent rate

Leackage current (I_{leack}) -
For each value of I_{leack} 10 values (statistically independent) were recorded and the mean value was calculated:

$$\bar{I}_{leack} = \frac{\sum_1^{10} I_{leack}}{10} \qquad (13)$$

Measurement current, $I_{meas(net)}$
The net ionization current is calculated from the mean measured current (I_{mas}), by substracting the mean leackage current

$$I_{meas(net)} = \bar{I}_{meas} - \bar{I}_{leack} \qquad (14)$$

I_{mas}, the mean measured current is calculated as the mean of 10 statistically independent dispayes values.
The components of the measurement uncertainty are:

a) The standard uncertainty of the measurements performed using the standard instrument (s_n):

$$s_n = \frac{1}{\bar{I}} \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} (I_i - \bar{I}\,)^2} \qquad (15)$$

Where:

- $\bar{I}$ is the mean value of the recorded values for each measurement
- I_i is measurement of the ionization current
- n - numbers of the measurements

b) The uncertainty due to the electrometer: 0.2 % for k=2

c) The uncertainty due to the resolution of the displayer values of the standard instrument (u_{res}):

$$u_{res} = \frac{1}{\sqrt{3}} \frac{R_{elec}}{\bar{I}} \qquad (16)$$

Where: R_{elec} – the resolution of the displayed values of the electrometer (instrument);
$\dot{\bar{I}}$ the mean value of the ionization current

d) The uncertainty due to the instruments used for the measurement of the air temperature and pressure ($u_{kTP\,CE}$):

$$u_{kTP\,CE} = k_{TP,m} * \sqrt{\frac{u_P^2}{P_m^2} + \frac{u_T^2}{(273.15+T_m)^2}} \qquad (17)$$

Where:

$K_{T,P,m}$ the correction factor for T and P, calculated for the measured values

u_T the measurement uncertainty for the temperature, from the calibration certificate of the instrument for k=1;

u_P the measurement uncertainty for the pressure, from the calibration certificate of the instrument, for k=1

P_m the measured value of the pressure (hPa)

T_m the measured value of the temperature (^{0}C)

e) The uncertainty due to the display resolution of the instruments used for the measurement of the temperature and the pressure (u_{kTPrez})

$$u_{kTP\,rez} = k_{TP,m} * \sqrt{\frac{\delta_P^2}{P_m^2} + \frac{\delta_T^2}{(273.15+T_m)^2}} \qquad (18)$$

Where:

- $K_{TP,m}$ – the correction factor for T and P, calculated for the measured values of T and P
- δ_P – the resolution for displaying the pressure value,
- δ_T – the resolution for displaying the temperature value,
- P_m – the measured value of the pressure (hPa)
- T_m – the measured value of the temperature (^{0}C)

-

f) The uncertainty due to the variation of the ambient temperature and the pressure- during the measurements (u_{varTP}),

$$u_{var\,TP} = k_{TP,m} * \sqrt{\frac{\Delta_p^2}{P_m^2} + \frac{\Delta_T^2}{(273.15+T_m)^2}} \qquad (19)$$

Where:

- $K_{T,P,m}$ - the correction factor for T and P, calculated for the measured values
- Δp – the pressure variation during the measurements of D;
- ΔT – the temperature variation during measurements
- P_m - the measured value of P (hPa)
- T_m - the measured value of T(^{0}C)

g) The uncertainty due to the positioning of the standard instrument ($u_{distance}$):

$$u_{distance} = \frac{d^2}{\sqrt{3}} * \left(\frac{1}{(d-\varepsilon)^2} - \frac{1}{(d+\varepsilon)^2}\right) \qquad (20)$$

Where:

- d= distance (SDD)
- ε = the error for the positioning

h) The uncertainty due to the positioning of the standard instrument due to the calibration of the instrument for the distance measurement (according the Calibration Certificate):

$$u_{distanta\,CC} = \frac{d^2}{\sqrt{3}} * \left(\frac{1}{(d-u_d)^2} - \frac{1}{(d+u_d)^2}\right) \qquad (21)$$

Where:

- d – distance (m)
- u_d - the uncertainty of the calibration of the instrument (as give in the calibration certificate) for k=1 according the Calibration Certificate,

The uncertainty is the expanded measurement for ionization chamber HS10

$$u_{HS10} = \sqrt{s_n^2 + u_{electr}^2 + u_{rez}^2 + u_{kTPCC}^2 + u_{kTPrez}^2 + u_{varTP}^2 + u_d^2 + u_{dCC}^2} \quad (22)$$

The extended uncertainty

$$U = k * \sqrt{u_{SSD}^2 + u_{HS10}^2}$$

VSL (VSL)

Table 1: Relative uncertainty in the ambient dose equivalent calibration coefficient for radiation quality N-60 (1 mSv/h).

Quantity or group of quantities	Estimate	Standard uncertainty	Probability distribution	Uncertainty contribution
Realization of air-Kerma with primary standard		0.48 %	rectangular	0.48 %
Reference measurement with primary standard (statistical)		0.70 %	normal	0.70 %
- Electrometer	20 nC	0.10 %	rectangular	0.10 %
- Temperature	20 °C	0.05 %	rectangular	0.05 %
- Atmospheric pressure	101.3 kPa	0.10 %	rectangular	0.10 %
SDD set-up for calibration of transfer ion-chamber	100 cm	1 mm	rectangular	0.12 %
Calibration measurement with transfer ion-chamber (statistical)		0.15 %	normal	0.15 %
- Recombination	1.000	0.05 %	rectangular	0.05 %
- Electrometer	20 nC	0.10 %	rectangular	0.10 %
- Temperature	20 °C	0.05 %	rectangular	0.05 %
- Atmospheric pressure	101.3 kPa	0.10 %	rectangular	0.10 %
Reference measurement with Exradin A5 (statistical)		0.50 %	normal	0.50 %
- Recombination	1.000	0.05 %	rectangular	0.05 %
- Electrometer	2 nC	0.10 %	rectangular	0.10 %
- Temperature	20 °C	0.05 %	rectangular	0.05 %
- Atmospheric pressure	101.3 kPa	0.10 %	rectangular	0.10 %
ISO 4037-3 conversion coefficient	1.59	2.0 %	rectangular	2.0 %
SDD set-up for calibration of HS10	420 cm	3 mm	rectangular	0.10 %
Measurement with HS10 (statistical)		0.05 %	normal	0.05 %
- Beam homogeneity	100 %	0.10 %	rectangular	0.10 %
- Scattered radiation	1.000	0.10 %	rectangular	0.10 %
- Recombination	1.000	0.05 %	rectangular	0.05 %
- Electrometer	20 nC	0.10 %	rectangular	0.10 %
- Temperature	20 °C	0.05 %	rectangular	0.05 %
- Pressure	101.3 kPa	0.10 %	rectangular	0.10 %
Combined uncertainty (k=1)				2.27 %
Expanded uncertainty (k=2)				**4.6 %**

Table 2: Relative uncertainty in the ambient dose equivalent calibration coefficient for radiation quality S-Cs (1 mSv/h).

Quantity or group of quantities	Estimate	Standard uncertainty	Probability distribution	Uncertainty contribution
Realization of reference air-Kerma		1.50 %	rectangular	1.50 %
Correction for decay of Cs-137 ($T_{½}$)	30.05 y	0.08 y	rectangular	0.18 %
Correction for air absorption, μ	0.01002/m	0.001	rectangular	0.11 %
ISO 4037-3 conversion coefficient	1.20	2.0 %	rectangular	2.0 %
SDD set-up for calibration of HS-10	450 cm	3 mm	rectangular	0.10 %
Measurement with HS-10 (statistical)		0.05 %	normal	0.05 %
- Beam homogeneity	100 %	0.10 %	rectangular	0.10 %
- Scattered radiation	1.000	0.10 %	rectangular	0.10 %
- Recombination	1.000	0.05 %	rectangular	0.05 %
- Electrometer	20 nC	0.10 %	rectangular	0.10 %
- Temperature	20 °C	0.05 %	rectangular	0.05 %
- Pressure	101.3 kPa	0.10 %	rectangular	0.10 %
Combined uncertainty (*k*=1)				2.52 %
Expanded uncertainty (*k*=2)				**5.1 %**

Table 2: Relative uncertainty in the ambient dose equivalent calibration coefficient for radiation quality S-Cs (10 µSv/h).

Quantity or group of quantities	Estimate	Standard uncertainty	Probability distribution	Uncertainty contribution
Realization of reference air-Kerma		1.50 %	rectangular	1.50 %
Correction for decay of Cs-137 ($T_{½}$)	30.05 y	0.08 y	rectangular	0.18 %
Correction for air absorption, μ	0.01002/m	0.001	rectangular	0.11 %
ISO 4037-3 conversion coefficient	1.20	2.0 %	rectangular	2.0 %
SDD set-up for calibration of HS-10	470 cm	3 mm	rectangular	0.10 %
Measurement with HS-10 (statistical)		0.05 %	normal	0.05 %
- Beam homogeneity	100 %	0.10 %	rectangular	0.10 %
- Scattered radiation	1.000	0.10 %	rectangular	0.10 %
- Recombination	1.000	0.05 %	rectangular	0.05 %
- Electrometer	2 nC	0.15 %	rectangular	0.15 %
- Temperature	20 °C	0.05 %	rectangular	0.05 %
- Pressure	101.3 kPa	0.10 %	rectangular	0.10 %
Combined uncertainty (*k*=1)				2.52 %
Expanded uncertainty (*k*=2)				**5.1 %**

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M – ionization chamber current in radiation field
M(b) – background ionization chamber current
N_{Kair} – calibration factor for LS-01 ionization chamber (Gy/As)
F_{ad} – air density correction
$F_{l.t.s.}$ – long term stability
$F_{s.t.s.}$ – short term stability (X-ray)
$h^*_K(10)$ – conversion coefficient (Sv/Gy)

The secondary standard ionization chamber LS-01 was placed in the central beam of radiation to be measured, at the distance D from the centre of the source in order to achieve the required geometry and dose rates.

In the case of S-Cs source the beam was attenuated with lead absorbers.

The Pb absorber thicknes, ambient dose rate $\dot{H}*(10)$ and distance D from focus of the source for the three radiation qualities are shown in table 1.

Table 1: Absorber thicknes, ambient dose rate and distance from focus of the source for the three radiation qualities.

Source	Absorber thicknes (mm Pb)	$\dot{H}*(10)$ (µSv/h)	Distance (cm)
S-Cs	7	997	186
S-Cs	46	9,9	203
N-60	/	1031	270

The principal components of the uncertainty are listed in Tables 2 to 4.

Table 2: The uncertainty components for determination of $\dot{H}*(10)$ for S-Cs, 1 mSv.

Quantity	Estimated value	Absolute uncertainty	Unit	Probability distribution	Relative standard uncertainty	Sensitivity coeficcient	Contribution to combined standard uncertainty
M-M(b)	831	0,4	µGy/h	normal	0.0005	1	0,0005
N_{Kair}	24970	12	Gy/As	normal	0,005	1	0,005
F_{ad}	297	1	°K	square	0,0019	1	0,0019
$F_{l.t.s.}$	1	0,005	/	square	0,0029	1	0,0029
$h^*_K(10)$	1,2	0,024	/	square	0,02	1	0,02
distance	1,86	0,003	m	square	0,0009	2	0,0019

Table 3: The uncertainty components for determination of $\dot{H}^*(10)$ for S-Cs, 10 µSv/h.

Quantity	Estimated value	Absolute uncertainty	Unit	Probability distribution	Relative standard uncertainty	Sensitivity coeficcient	Contribution to combined standard uncertainty
M-M(b)	8,26	0,004	µGy/h	normal	0.0005	1	0,0005
N_{Kair}	24970	12	Gy/As	normal	0,005	1	0,005
F_{ad}	297	1	^oK	square	0,0019	1	0,0019
$F_{l.t.s.}$	1	0,005	/	square	0,0029	1	0,0029
$h^*_K(10)$	1,2	0,024	/	square	0,02	1	0,02
distance	2,03	0,003	m	square	0,0008	2	0,0017

Table 4: The uncertainty components for determination of $\dot{H}^*(10)$ for N-60, 1 mSv/h

Quantity	Estimated value	Absolute uncertainty	Unit	Probability distribution	Relative standard uncertainty	Sensitivity coeficcient	Contribution to combined standard uncertainty
M-M(b)	649	0,3	µGy/h	normal	0.0005	1	0,0005
N_{Kair}	24970	12	Gy/As	normal	0,005	1	0,005
F_{ad}	297	1	^oK	square	0,0019	1	0,0019
$F_{l.t.s.}$	1	0,005	/	square	0,0029	1	0,0029
$F_{s.t.s.}$	1	0,005	/	square	0,0029	1	0,0029
$h^*_K(10)$	1,2	0,024	/	square	0,02	1	0,02
distance	2,70	0,003	m	square	0,0006	2	0,0013

The resulting conventional quantity values of $\dot{H}^*(10)$ are:

S-Cs, 1 mSv/h: $\dot{H}^*(10) = 997 \cdot (1 \pm 0{,}0210)$ µSv/h
S-Cs, 10 µSv/h: $\dot{H}^*(10) = 9{,}91 \cdot (1 \pm 0{,}0211)$ µSv/h
N-60, 1 mSv/h: $\dot{H}^*(10) = 1031 \cdot (1 \pm 0{,}0214)$ µSv/h

2.3 Description of calibration measurements

After the determination of the conventional quantity value of $\dot{H}^*(10)$ for the three radiation qualities, the HS10 secondary standard chamber was placed to the same geometrical points as the LS-01 chamber in the first place.

The geometries of experimental setups are shown in Figures 1 and 2.

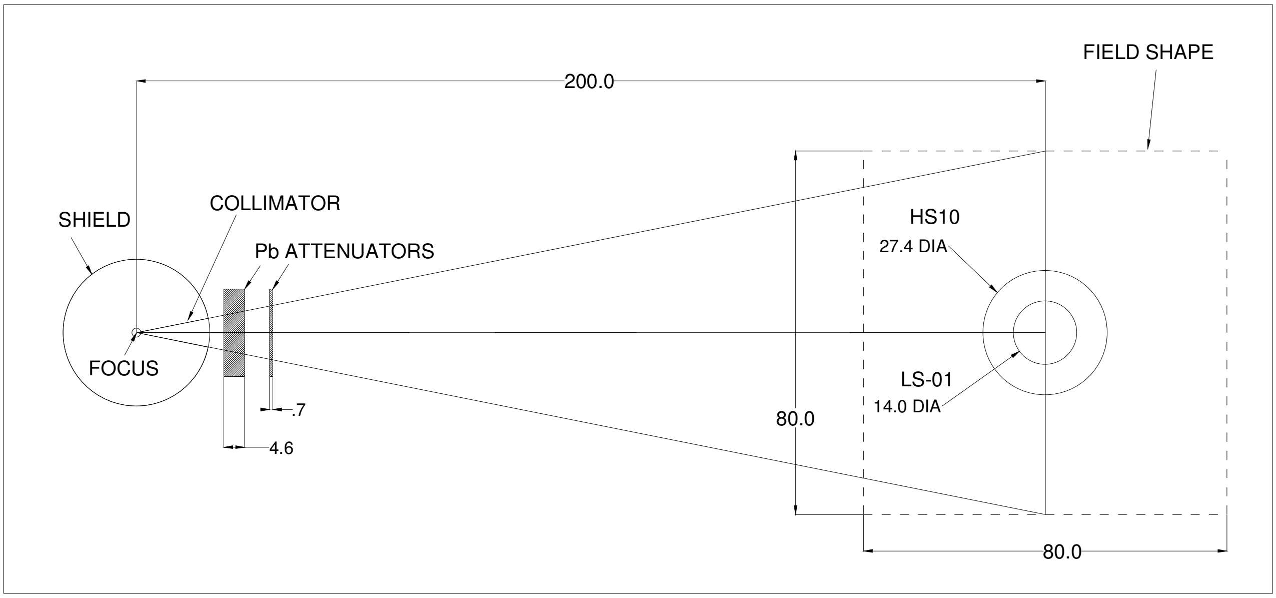

Figure 1: Geometry for the measurements of the S-Cs at the distance 2 m.

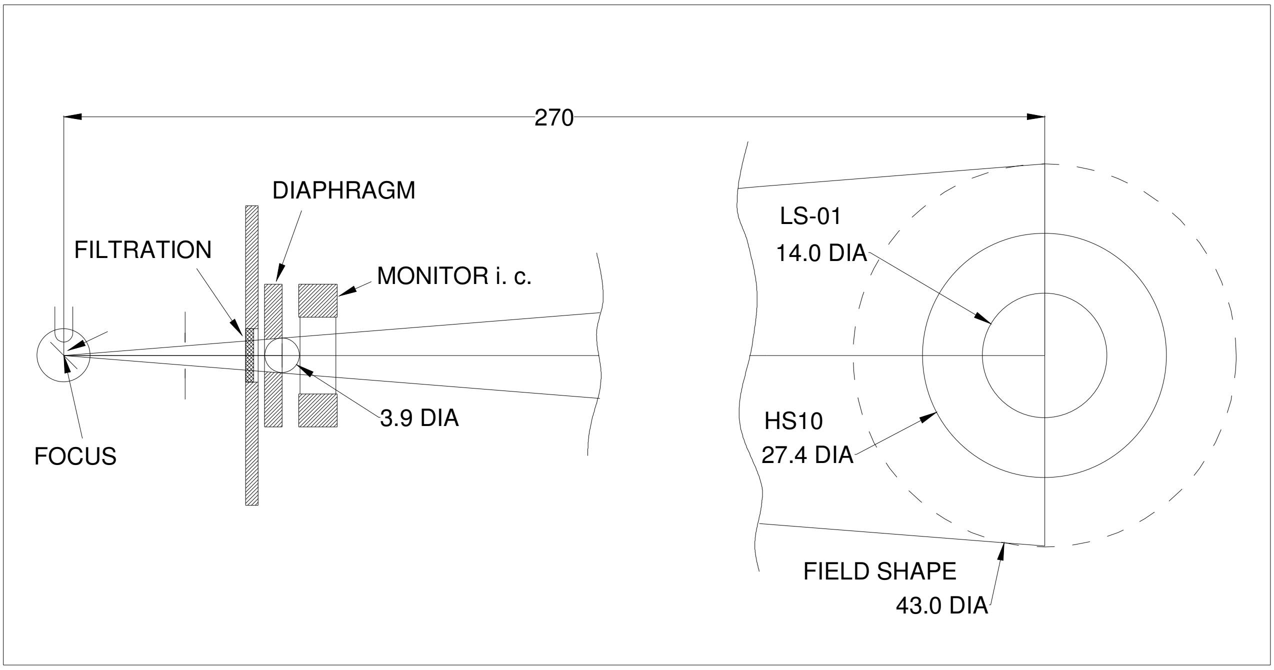

Figure 2: Geometry for the measurements of the narrow spectra N-60 at the distance 2.7 m.

The conventional quantity value of $\dot{H}*(10)$ was measured with the HS10 secondary standard chamber for the three radiation qualities.

The same N_{Kair} as with the LS-01 in equation Eq. 1 was used.

The ratio of dose rates calculated with both chambers is also the ratio of calibration factors of both ionization chambers.

2.4 Determination of the calibration factor

The principal components of the uncertainty for determination of the calibration factors for the three radiation quality are listed in Tables 5 to 7.

Table 5: The principal components of the uncertainty for determination of calibration factor for S-Cs, 1 mSv/h.

Quantity	Estimated value	Absolute uncertainty	Unit	Probability distribution	Relative standard uncertainty	Sensitivity coeficcient	Contribution to combined standard uncertainty
M-M(b)	8136	1	µSv/h	normal	0.0001	1	0,0001
F_{ad}	297	1	°K	square	0,0019	1	0,0019
distance	1,86	0,003	m	square	0,0009	2	0,0019
$\dot{H}*(10)$	997	21	µSv/h	normal	0,0210	1	0,0210

Table 6: The principal components of the uncertainty for determination of calibration factor for S-Cs, 10 µSv/h.

Quantity	Estimated value	Absolute uncertainty	Unit	Probability distribution	Relative standard uncertainty	Sensitivity coeficcient	Contribution to combined standard uncertainty
M-M(b)	80,7	0,03	µSv/h	normal	0.0004	1	0,0004
F_{ad}	297	1	°K	square	0,0019	1	0,0019
distance	2,03	0,003	m	square	0,0008	2	0,0017
$\dot{H}*(10)$	9,91	0,21	µSv/h	normal	0,0211	1	0,0211

Table 7: The principal components of the uncertainty for determination of calibration factor for N-60, 1 mSv/h.

Quantity	**Estimated value**	**Absolute uncertainty**	**Unit**	**Probability distribution**	**Relative standard uncertainty**	**Sensitivity coeficcient**	**Contribution to combined standard uncertainty**
M-M(b)	11186	8	µsv/h	normal	0.0007	1	0,0007
F_{ad}	297	1	^{o}K	square	0,0019	1	0,0019
distance	1,86	0,003	m	square	0,0009	2	0,0013
$\dot{H}*(10)$	1031	22	µSv/h	normal	0,0214	1	0,0214

Calibration factors for the three radiation qualities with expaned relative standard uncertainties (with coverage factor k = 2).

Table 8: Calibration factors with expanded relative standard uncertainties (coverage factor k = 2)

Source	$\dot{H}*(10)$ **(mSv/h)**	$\mathbf{N_{H*(10)}}$	**Relative standard uncertainty (k = 2)**
S-Cs	1,00	3670	0,042
	0,010	3681	0,042
N-60	1,03	3562	0,043

Calibration factors for the three radiation qualities with expanded standard uncertainties (coverage factor k = 2).

Calibration factor for S-Cs, 1 mSv/h: $N_{H*(10)}$ = (3670 ± 155) Sv/As
Calibration factor for S-Cs, 10 µSv/h: $N_{H*(10)}$ = (3681 ± 156) Sv/As
Calibration factor for N-60, 1 mSv/h: $N_{H*(10)}$ = (3562 ± 153) Sv/As

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Table 4 - Uncertainty budget for the corrected current I_{corr} according to GUM (S-Cs ;1 mSv/h)

Model function (see equations (5) and (6)): $I_{corr} = \left[\left(\frac{\Delta V}{\Delta t} \right)_{slope}^{meas} - \left(\frac{\Delta V}{\Delta t} \right)_{slope}^{leak} \right] \cdot C_{fb} \cdot k_\rho \cdot k_{sat} \cdot k_{geom} \cdot k_{att} \cdot k_{omog} \cdot k_{dec}$

No.	quantity or group of quantities	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty /A	Type	Remarks
1	$(\Delta V/\Delta t)_{slope}^{meas}$ / V s^{-1}	1.42E-02	1.4E-07	normal	5,26E-09	7,47E-16	A	Linear regression of series of experimental data
2	$(\Delta V/\Delta t)_{slope}^{meas}$ / V s^{-1}	1.42E-02	2.1E-05	rectangular	5,26E-09	1,12E-13	B	Characteristics of measuring instrument
3	$(\Delta V/\Delta t)_{slope}^{leak}$ / V s^{-1}	-6.91E-07	7.6E-07	normal	5,26E-09	3,99E-15	A	Linear regression of series of experimental data
4	$(\Delta V/\Delta t)_{slope}^{leak}$ / V s^{-1}	-6.91E-07	1.0E-09	rectangular	5,26E-09	5,45E-18	B	Characteristics of measuring instrument
5	C_{fb} / F	5.02E-09	2.5E-12	normal	1,49E-02	3,74E-14	B	Calibration certificate issued by INRIM (IT)
6	k_ρ	1.0140	2.0E-04	normal	7,37E-11	1,49E-14	A	Standard deviation of the mean of series of experimental data
7	k_ρ	1.0140	3.5E-04	rectangular	7,37E-11	2,61E-14	B	Characteristics of measuring instrument
8	k_{sat}	1.0010	1.0E-03	rectangular	7,46E-11	7,47E-14	B	Previous measurements
9	k_{geom}	0.9980	5.0E-03	rectangular	7,48E-11	3,74E-13	B	Previous measurements and literature data
10	k_{att}	0.9990	1.0E-03	rectangular	7,48E-11	7,47E-14	B	Previous measurements and literature data
11	k_{omog}	1.0208	3.1E-03	rectangular	7,32E-11	2,24E-13	B	Previous measurements
12	k_{dec}	1.0005	5.0E-06	rectangular	7,47E-11	3,74E-16	B	Literature data
quantity to be determined	I_{corr} / A	7.47E-11				4.64E-13 0.62% 9.29E-13 1.24%	Overall uncertainty	standard uncertainty k=1 expanded uncertainty k=2
						1.57E-13 0.21% 3.14E-13 0.42%	Reduced uncertainty applied for the comparison 2)	standard uncertainty k=1 expanded uncertainty k=2

1) in reference attenuation conditions
2) accounting for common uncertainty components among the measurement with the ENEA-INMRI standard and the HS10 transfer chambers (capacity value of the feedback capacitor, beam inhomogeneity and chamber finite dimensions).

Table 5 - - Uncertainty budget for the corrected current I_{corr} according to GUM (S-Cs; 10 μSv/h)

Model function (see equations (5) and (6)): $I_{corr} = \left[\left(\frac{\Delta V}{\Delta t}\right)_{slope}^{meas} - \left(\frac{\Delta V}{\Delta t}\right)_{slope}^{leak}\right] \cdot C_{fb} \cdot k_\rho \cdot k_{sat} \cdot k_{geom} \cdot k_{att} \cdot k_{omog} \cdot k_{dec}$

No.	quantity or group of quantities	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty /A	Type	Remarks
1	$(\Delta V/\Delta t)_{slope}^{meas}$ / V s^{-1}	7.98E-04	8.0E-09	normal	1,04E-09	8,26E-18	A	Linear regression of series of experimental data
2	$(\Delta V/\Delta t)_{slope}^{meas}$ / V s^{-1}	7.98E-04	1.2E-06	rectangular	1,04E-09	1,24E-15	B	Characteristics of measuring instrument
3	$(\Delta V/\Delta t)_{slope}^{leak}$ / V s^{-1}	4.16E-06	1.3E-07	normal	1,04E-09	1,33E-16	A	Linear regression of series of experimental data
4	$(\Delta V/\Delta t)_{slope}^{leak}$ / V s^{-1}	4.16E-06	6.2E-09	rectangular	1,04E-09	6,46E-18	B	Characteristics of measuring instrument
5	C_{fb} / F	9.97E-10	2.0E-13	normal	8,25E-04	1,64E-16	B	Calibration certificate issued by INRIM (IT)
6	k_ρ	1.0115	1.3E-03	normal	8,13E-13	1,09E-15	A	Standard deviation of the mean of series of experimental data
7	k_ρ	1.0115	3.5E-04	rectangular	8,13E-13	2,88E-16	B	Characteristics of measuring instrument
8	k_{sat}	1.0007	1.0E-03	rectangular	8,22E-13	8,22E-16	B	Previous measurements
9	k_{geom}	0.9960	5.0E-03	rectangular	8,25E-13	4,11E-15	B	Previous measurements and literature data
10	k_{att}	0.9990	1.0E-03	rectangular	8,23E-13	8,22E-16	B	Previous measurements and literature data
11	k_{omog}	1.0195	3.1E-03	rectangular	8,06E-13	2,47E-15	B	Previous measurements
12	k_{dec}	1.0004	5.0E-06	rectangular	8,22E-13	4,11E-18	B	Literature data
quantity to be determined	I_{corr} / A	8.22E-13				5.21E-15 0.63% 1.04E-14 1.27%	Overall uncertainty	standard uncertainty k=1 expanded uncertainty k=2
						2.05E-15 0.25% 4.09E-15 0.50%	Reduced uncertainty applied for the comparison 2)	standard uncertainty k=1 expanded uncertainty k=2

1) in reference attenuation conditions
2) accounting for common uncertainty components among the measurement with the ENEA-INMRI standard and the HS10 transfer chambers (capacity value of the feedback capacitor, beam inhomogeneity and chamber finite dimensions).

Table 6- - Uncertainty budget for the corrected current I_{corr} according to GUM (S-Cs; 0.5 µSv/h)

Model function (see equations (5) and (6)): $I_{corr} = \left[\left(\frac{\Delta V}{\Delta t} \right)_{slope}^{meas} - \left(\frac{\Delta V}{\Delta t} \right)_{slope}^{leak} \right] \cdot C_{fb} \cdot k_\rho \cdot k_{sat} \cdot k_{geom} \cdot k_{att} \cdot k_{omog} \cdot k_{dec}$

No.	quantity or group of quantities	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty /A	Type	Remarks
1	$(\Delta V/\Delta t)_{slope}^{meas}$ / V s^{-1}	3.58E-05	3.6E-10	normal	1,03E-09	3,69E-19	A	Linear regression of series of experimental data
2	$(\Delta V/\Delta t)_{slope}^{meas}$ / V s^{-1}	3.58E-05	5.4E-08	rectangular	1,03E-09	5,53E-17	B	Characteristics of measuring instrument
3	$(\Delta V/\Delta t)_{slope}^{leak}$ / V s^{-1}	1.71E-06	2.9E-07	normal	1,03E-09	3,00E-16	A	Linear regression of series of experimental data
4	$(\Delta V/\Delta t)_{slope}^{leak}$ / V s^{-1}	1.71E-06	2.6E-09	rectangular	1,03E-09	2,65E-18	B	Characteristics of measuring instrument
5	C_{fb} / F	9.97E-10	2.0E-13	normal	3,52E-05	7,02E-18	B	Calibration certificate issued by INRIM (IT)
6	k_ρ	1.0130	2.0E-04	normal	3,46E-14	7,02E-18	A	Standard deviation of the mean of series of experimental data
7	k_ρ	1.0130	3.5E-04	rectangular	3,46E-14	1,23E-17	B	Characteristics of measuring instrument
8	k_{sat}	1.0007	1.0E-03	rectangular	3,51E-14	3,51E-17	B	Previous measurements
9	k_{geom}	0.9990	5.0E-03	rectangular	3,51E-14	1,75E-16	B	Previous measurements and literature data
10	k_{att}	0.9990	1.0E-03	rectangular	3,51E-14	3,51E-17	B	Previous measurements and literature data
11	k_{omog}	1.0068	3.0E-03	rectangular	3,49E-14	1,05E-16	B	Previous measurements
12	k_{dec}	1.0006	5.0E-06	rectangular	3,51E-14	1,75E-19	B	Literature data
quantity to be determined	I_{corr} / A	3.51E-14				3.71E-16 1.06% 7.42E-16 2.11%	Overall uncertainty	standard uncertainty k=1 expanded uncertainty k=2
						3.09E-16 0.88% 6.18E-16 1.76%	Reduced uncertainty applied for the comparison 2)	standard uncertainty k=1 expanded uncertainty k=2

1) in reference attenuation conditions
2) accounting for common uncertainty components among the measurement with the ENEA-INMRI standard and the HS10 transfer chambers (capacity value of the feedback capacitor, beam inhomogeneity and chamber finite dimensions).

Table 7- - Uncertainty budget for the corrected current I_{corr} according to GUM (N-60; 1 mSv/h)

Model function (see equations (5) and (6)): $I_{corr} = \left[\left(\frac{\Delta V}{\Delta t} \right)^{meas}_{slope} - \left(\frac{\Delta V}{\Delta t} \right)^{leak}_{slope} \right] \cdot C_{fb} \cdot k_{\rho} \cdot k_{sat} \cdot k_{geom} \cdot k_{att} \cdot k_{omog} \cdot k_{dec}$

No.	quantity or group of quantities	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty /A	Type	Remarks
1	$(\Delta V/\Delta t)^{meas}_{slope}$ / V s^{-1}	2.74E-03	2.7E-08	normal	3,07E-08	8,41E-16	A	Linear regression of series of experimental data
2	$(\Delta V/\Delta t)^{meas}_{slope}$ / V s^{-1}	2.74E-03	4.1E-06	rectangular	3,07E-08	1,26E-13	B	Characteristics of measuring instrument
3	$(\Delta V/\Delta t)^{leak}_{slope}$ / V s^{-1}	1.61E-06	8.8E-09	normal	3,07E-08	2,71E-16	A	Linear regression of series of experimental data
4	$(\Delta V/\Delta t)^{leak}_{slope}$ / V s^{-1}	1.61E-06	2.4E-09	rectangular	3,07E-08	7,40E-17	B	Characteristics of measuring instrument
5	C_{fb} / F	2.99E-08	3.0E-12	normal	2,81E-03	8,40E-15	B	Calibration certificate issued by INRIM (IT)
6	k_{ρ}	1.0090	2.0E-04	normal	8,33E-11	1,68E-14	A	Standard deviation of the mean of series of experimental data
7	k_{ρ}	1.0090	3.5E-04	rectangular	8,33E-11	2,94E-14	B	Characteristics of measuring instrument
8	k_{sat}	1.0011	1.0E-03	rectangular	8,40E-11	8,40E-14	B	Previous measurements
9	k_{geom}	0.9990	5.0E-03	rectangular	8,41E-11	4,20E-13	B	Previous measurements and literature data
10	k_{att}	0.9990	1.0E-03	rectangular	8,41E-11	8,40E-14	B	Previous measurements and literature data
11	k_{omog}	1.0080	3.0E-03	rectangular	8,34E-11	2,52E-13	B	Previous measurements
quantity to be determined	I_{corr} / A	8.40E-11				5.21E-13 0.62% 1.04E-12 1.24%	Overall uncertainty	standard uncertainty k=1 expanded uncertainty k=2
						1.77E-13 0.21% 3.53E-13 0.42%	Reduced uncertainty applied for the comparison [2)]	standard uncertainty k=1 expanded uncertainty k=2

1) in reference attenuation conditions
2) accounting for common uncertainty components among the measurement with the ENEA-INMRI standard and the HS10 transfer chambers (capacity value of the feedback capacitor, beam inhomogeneity and chamber finite dimensions).

Table 8 - Uncertainty budget for the calibration coefficients N_k and N_{H^*} according to GUM (S-Cs; 1 mSv/h)

Model functions: **A)** $N_k = \frac{\dot{K}_a}{I_{corr} \cdot k_{dist}}$ and **B)** $N_{H^*} = \frac{\dot{H}^*(10)}{I_{corr} \cdot k_{dist}}$

A)

No.	quantity or group of quantities	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty / A	Remarks
1	K_a / mGy h^{-1}	8.00E-01	1.1E-02	normal	3,72E+03	3,95E+01	previous measurements
2	I_{corr} / A	7.47E-11	1.6E-13	normal	3,98E+13	6,24E+00	Linear regression of series of experimental data
3	dist / cm	2.00E+02	1.0E-01	rectangular	2,97E+01	2,97E+00	
quantity to be determined	N_k / Gy C^{-1}	2.97E+03				4.01E+01	standard uncertainty
						1.35E-02	k=1
						8.03E+01	expanded uncertainty
						2.70E-02	k=2

B)

No.	quantity or group of quantities	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty / A	Remarks
1	H^* / mSv h^{-1}	9.73E-01	1.3E-02	normal	3,72E+03	5,00E+01	previous measurements
2	I_{corr} / A	7.47E-11	1.6E-13	normal	4,85E+13	7,60E+00	Linear regression of series of experimental data
3	dist / cm	2.00E+02	1.0E-01	rectangular	3,62E+01	3,62E+00	
quantity to be determined	N_H / Sv C^{-1}	3.62E+03				5.07E+01	standard uncertainty
						1.40E-02	k=1
						1.01E+02	expanded uncertainty
						2.80E-02	k=2

Table 9- Uncertainty budget for the calibration coefficients N_k and N_{H*} according to GUM (S-Cs; 10 µSv/h).

Model functions: **A)** $N_k = \frac{\dot{K}_a}{I_{corr} \cdot k_{dist}}$ and **B)** $N_{H*} = \frac{\dot{H}^*(10)}{I_{corr} \cdot k_{dist}}$

A)

No.	quantity or group of quantities	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty / A	Remarks
1	K_a / µGy h^{-1}	8.93E+00	1.6E-01	normal	3,34E+02	5,19E+01	previous measurements
2	I_{corr} / A	8.22E-13	2.1E-15	normal	3,62E+15	7,45E+00	Linear regression of series of experimental data
3	dist / cm	1.20E+02	1.0E-01	rectangular	4,97E+01	4,97E+00	
quantity to be determined	N_k / Gy C^{-1}	2.98E+03				5.26E+01	standard uncertainty
						1.77E-02	k=1
						1.05E+02	expanded uncertainty
						3.53E-02	k=2

B)

No.	quantity or group of quantities	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty / A	Remarks
1	H^* / µSv h^{-1}	1.09E+01	1.9E-01	normal	3,34E+02	6,50E+01	previous measurements
2	I_{corr} / A	8.22E-13	2.1E-15	normal	4,42E+15	9,08E+00	Linear regression of series of experimental data
3	dist / cm	1.20E+02	1.0E-01	rectangular	6,05E+01	6,05E+00	
quantity to be determined	N_H / Sv C^{-1}	3.63E+03				6.59E+01	standard uncertainty
						1.82E-02	k=1
						1.32E+02	expanded uncertainty
						3.63E-02	k=2

Table 10 - Uncertainty budget for the calibration coefficients N_k and N_{H*} according to GUM (S-Cs; 0.5 μSv/h).

functions: **A)** $N_k = \frac{\dot{K}_a}{I_{corr} \cdot k_{dist}}$ and **B)** $N_{H*} = \frac{\dot{H}^*(10)}{I_{corr} \cdot k_{dist}}$

A)

No.	quantity or group of quantities	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty / A	Remarks
1	K_a / μGy h^{-1}	3.83E-01	1.3E-02	normal	7,91E+03	1,00E+02	previous measurements
2	I_{corr} / A	3.51E-14	3.1E-16	normal	8,63E+16	2,67E+01	Linear regression of series of experimental data
3	dist / cm	2.80E+02	1.0E-01	rectangular	2,16E+01	2,16E+00	
quantity to be determined	N_k / Gy C^{-1}	3.03E+03				1.04E+02	standard uncertainty
						3.43E-02	k=1
						2.08E+02	expanded uncertainty
						6.85E-02	k=2

B)

No.	quantity or group of quantities	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty / A	Remarks
1	H^* / μSv h^{-1}	4.66E-01	1.6E-02	normal	7,92E+03	1,24E+02	Linear regression of series of experimental data
2	I_{corr} / A	3.51E-14	3.1E-16	normal	1,05E+17	3,25E+01	Linear regression of series of experimental data
3	dist / cm	2.80E+02	1.0E-01	rectangular	2,64E+01	2,64E+00	Linear regression of series of experimental data
quantity to be determined	N_H / Sv C^{-1}	3.69E+03				1.28E+02	standard uncertainty
						3.46E-02	k=1
						2.56E+02	expanded uncertainty
						6.93E-02	k=2

Table 11 - Uncertainty budget for the calibration coefficients N_k and N_{H*} according to GUM (N-60 1 mSv/h).

Model functions: **A)** $N_k = \frac{\dot{K}_a}{I_{corr} \cdot k_{dist}}$ and **B)** $N_{H^*} = \frac{\dot{H}^*(10)}{I_{corr} \cdot k_{dist}}$

A)

No.	quantity or group of quantities	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty / A	Remarks
1	K_a / mGy h^{-1}	6.39E-01	3.77E-03	normal	3.31E+03	1.25E+01	previous measurements
2	I_{corr} / A	8.40E-11	1.76E-13	normal	2.51E+13	4.43E+00	Linear regression of series of experimental data
3	dist / cm	3.17E+02	1.00E-01	rectangular	1.33E+01	1.33E+00	
quantity to be determined	N_k / Gy C^{-1}	2.11E+03				1.33E+01	standard uncertainty
						0.63%	k=1
						2.66E+01	expanded uncertainty
						1.26%	k=2

B)

No.	quantity or group of quantities	estimated value	standard uncertainty	probability distribution	sensitivity coefficient	contribution to the standard uncertainty / A	Remarks
1	K_a / mGy h^{-1}	6.39E-01	3.77E-03	normal	5.26E+03	1.98E+01	Linear regression of series of experimental data
2	I_{corr} / A	8.40E-11	1.76E-13	normal	4.00E+13	7.06E+00	Linear regression of series of experimental data
3	dist / cm	3.17E+02	1.00E-01	rectangular	2.12E+01	2.12E+00	Linear regression of series of experimental data
4	h / Sv Gy^{-1}	1.59	3.18E-02	normal	2.11E+03	6.72E+01	Linear regression of series of experimental data
quantity to be determined	N_H / Sv C^{-1}	3.36E+03				7.04E+01	standard uncertainty
						2.10%	k=1
						1.41E+02	expanded uncertainty
						4.19%	k=2

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Uncertainties

Uncertainty budget of calibration in terms of H*(10) in Cs-137 beam			
Determination of ambient dose equivalent rate by HS01 #102	Type A	Type B	
	Uncertainty (%)		
Calibration from PSDL in terms of H*(10)		0.50	
Long term stability of the secondary standard		0.06	
Temperature measurements		0.03	
Pressure measurements		0.01	
Current measurements including range and time base corrections	0.05	0.05	
Chamber positioning		0.03	
Repeatability (QA measurements of output)	0.1		
Uncertainty in step 1	**0.11**	**0.51**	
Transfer chamber	*Uncertainty (%)*		
Beam non-uniformity difference (3.0- 4.5) m SDD.		0.20	
Temperature measurements		0.03	
Pressure measurements		0.01	
Chamber positioning		0.03	
Current measurements including range and time base corrections	0.03	0.05	
Uncertainty in step 2	**0.00**	**0.21**	
Uncertainty (steps 1 + 2)	**0.11**	**0.55**	
Combined relative uncertainty	**0.56**		
Expanded relative uncertainty		**1.12**	**%**

Uncertainty budget of calibration in terms of H*(10) in Cs-137 beam			
Determination of ambient dose equivalent rate by LS01 #115	Type A	Type B	
	Uncertainty (%)		
Calibration from PSDL in terms of K_{air}		0.20	
Long term stability of the secondary standard		0.05	
Temperature measurements		0.03	
Pressure measurements		0.01	
Current measurements including range and time base corrections	0.4	0.05	
Chamber positioning		0.03	
Repeatability (QA measurements of output)	0.1		
H*(10)/Kair conversion coefficient (ISO 4037 Part 3)		2.00	
Uncertainty in step 1	**0.41**	**2.01**	
Transfer chamber	*Uncertainty (%)*		
Beam non-uniformity difference (3.0- 4.5) m SDD.		0.20	
Temperature measurements		0.03	
Pressure measurements		0.01	
Chamber positioning		0.03	
Current measurements including range and time base corrections	0.4	0.05	
Uncertainty in step 2	**0.40**	**0.21**	
Uncertainty (steps 1 + 2)	**0.57**	**2.02**	
Combined relative uncertainty	**2.10**		
Expanded relative uncertainty		**4.21**	**%**

Uncertainty budget of dosimeter irradiation free in air in terms of H*(10) in ISO N series X-ray beams from 40 kV to 300 kV			
Determination of ambient dose equivalent rate by HS01 #102	Type A	Type B	
	Uncertainty (%)		
Calibration from PSDL in terms of H*(10)		1.50	
Long term stability of the secondary standard		0.60	
Beam non uniformity difference PTB-DOL		0.20	
Pressure measurements		0.01	
Temperature measurements		0.03	
Ionization current	0.10	0.05	
Uncertainty in step 1	**0.10**	**1.63**	
Transfer chamber	*Uncertainty (%)*		
Beam non uniformity difference (4.0- 4.5) m SDD.		0.20	
Temperature measurements		0.03	
Pressure measurements		0.01	
Chamber positioning		0.03	
Current measurements including range and time base corrections	0.03	0.05	
Uncertainty in step 2	**0.03**	**0.21**	
Uncertainty (steps 1 + 2)	**0.10**	**1.64**	
Combined relative uncertainty	**1.65**		
Expanded relative uncertainty		**3.3**	**%**

Uncertainty budget of dosimeter irradiation free in air in terms of H*(10) in ISO N series X-ray beams from 40 kV to 300 kV			
Determination of ambient dose equivalent rate by LS01 #114	Type A	Type B	
	Uncertainty (%)		
Calibration from PSDL in terms of K_{air}		0.40	
Long term stability of the secondary standard		0.70	
Beam non uniformity difference PTB-DOL		0.20	
Temperature measurements		0.03	
Pressure measurements		0.01	
Current measurements including range and time base corrections	0.40	0.05	
Chamber positioning		0.03	
Repeatability (QA measurements of output)	0.10		
H*(10)/Kair conversion coefficient (ISO 4037 Part 3)		2.00	
Uncertainty in step 1	**0.41**	**2.17**	
Transfer chamber	*Uncertainty (%)*		
Beam non uniformity difference (4.0- 4.5) m SDD.		0.20	
Temperature measurements		0.03	
Pressure measurements		0.01	
Chamber positioning		0.03	
Current measurements including range and time base corrections	0.40	0.05	
Uncertainty in step 2	**0.40**	**0.21**	
Uncertainty (steps 1 + 2)	**0.57**	**2.18**	
Combined relative uncertainty	**2.25**		
Expanded relative uncertainty		**4.50**	**%**

Uncertainty budget of calibration in terms of H*(10) in Cs-137 beam with two lead attenuators			
Determination of ambient dose equivalent rate by LS10 #130 calibrated in terms of air kerma	Type A	Type B	
	Uncertainty (%)		
Calibration from PSDL in terms of K_{air}		0.23	
Long term stability of the secondary standard		0.06	
Beam nonuniformity difference BIPM-DOL		0.20	
Temperature measurements		0.03	
Pressure measurements		0.01	
Current measurements including range and time base corrections	0.4	0.05	
Chamber positioning		0.03	
Repeatability (QA measurements of output)	0.1		
H*(10)/Kair conversion coefficient (ISO 4037 Part 3)		**2.00**	
Uncertainty in step 1	**0.41**	**2.03**	
Transfer chamber	*Uncertainty (%)*		
Temperature measurements		0.03	
Pressure measurements		0.01	
Chamber positioning		0.03	
Current measurements including range and time base corrections	0.4	0.05	
Uncertainty in step 2	**0.40**	**0.07**	
Uncertainty (steps 1 + 2)	**0.57**	**2.03**	
Combined relative uncertainty	**2.11**		
Expanded relative uncertainty		**4.21**	**%**