EPJ Web of Conferences **323**, 11001 (2025) https://doi.org/10.1051/epjconf/202532311001
22nd International Metrology Congress

Low background facility for ionizing radiation at LNE LNHB: Design and traceability

J.M. Bordy *, O. Khattabi, C. Chardeur, K. Lahlal, J. Plangnard

Université Paris-Saclay, CEA, LIST, Laboratoire National Henri Becquerel (LNE-LNHB), F-91120, Palaiseau, France

Abstract. This paper presents the set up of a low background calibration facility aimed at calibrating environment survey meter. The facility is a lead box 100 cm x 100 cm x 125 cm with 2.5 cm thickness walls, the Caesium 137 source is located in a conical collimator including an internal cavity for the source. The ambient dose equivalent rate in the beam of this facility varies between 300 and 80 nSv/h. This quantity is traceable to the air kerma national references of LNE-LNHB. The standard uncertainty for the ambient dose equivalent rate is about 2% and the uncertainty of the calibration coefficient od a survey meter, depending meanly on the uncertainty if the background measure, is estimated between 5% and 10%.

1 Introduction.

The calibration coefficient of a survey meter is defined as the ratio between the reference value of the dosimetric quantity, in this case the ambient dose equivalent, and the corrected survey meter reading. Under conventional calibration conditions, the influence of background radiation on the value of the calibration coefficient and its associated uncertainty is negligible, since it is around 100 to 1000 times smaller than the reference value of the dosimetric quantity. This is no longer the case for low-rate calibrations, comparable to the level of radiation encountered in the environment. The uncertainty of the calibration coefficient increases drastically, reaching several tens of percents and the linearity of radiation meters at low ambient dose equivalent rates needs to be verified.

Radiative background consists mainly of two natural components (cosmic, telluric) and the possible influence of nearby or even distant nuclear facilities. In addition to underground or on boat calibration facilities, which largely eliminate natural components, ground-level calibration beams require shielding. The aim of this study is to set up a facility, similar to the National Metrological Institute of Japan one[1], for calibrating environmental dosimeters with very low ambient dose equivalent rates comparable to those encountered in the environment, i.e. a few tenth of nSv/h. In this publication, we present the design of the shielded facilty, and the study of the traceability of the measurements to the national references in terms of air kerma of the LNE-LNHB.

2 Design of the shielded facility.

Figure 1 shows the spectrum measured in air without a lead screen and without collimation using an ORTEC germanium detector model GMX 35P4-70-PLUS-1 cooled with liquid nitrogen. The origin of the peaks highlighted in orange is identified using the « Laraweb » website.[1]

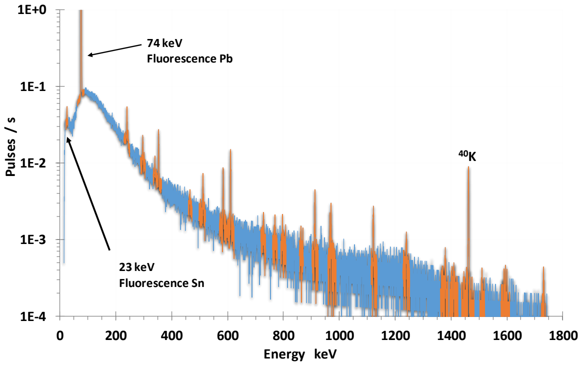

Fig. 1. Radiative background spectrum

The spectrum includes radionuclide's from the 4N (^{232}Th) and 4N+2 (^{238}U) natural decay families (^{224}Ra, ^{214}Pb, ^{228}Ac, ^{208}Tl, ^{214}Bi, ^{212}B, ^{226}Ra) and ^{40}K, plus a Kα lead fluorescence peak at 74 keV due to the measurement room environment, and a second fluorescence peak at 23 keV due to the presence of tin in the detector. The emission lines of these radionuclide's, identified on the spectrum, are used to choose the thickness of the walls through Monte Carlo modeling using the MCNP code [2]. The parallelepiped representing the enclosure is placed at the center of a sphere. Photons are emitted from the inner surface of this sphere, isotropically towards its center. The lead thickness is progressively increased by calculating the spectral fluence distribution for each thickness.

The analysis of the spectra reveals that the range of 25 to 30 mm of lead seems adequate. These results in terms

---

* Corresponding author: Jean-marc.bordy@cea.fr

[1] http://www.nucleide.org/Laraweb/index.php

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

of fluence are converted into ambient dose equivalent in order to quantify the influence of lead wall thickness in dosimetric terms. A 98.7% reduction in dose equivalent is observed across the entire background spectrum for a wall thickness of 25 mm. This performance is largely due to the drastic attenuation of low-energy photons (Table 1).

Table 1. Fraction of *H**(10) remaining at the center of the enclosure for a 2.5 cm lead wall.

Energy	10-100 keV	0.1-0.5 MeV	0.1-1 MeV	1-2 MeV	Total
Remaining fraction of *H**(10)	0.1%	2.4%	9.2%	18.7%	1.3%

To reduce the influence of lead fluorescence radiation, a copper layer is added inside the facility. Optimi-zation between attenuation of 74 keV photons and production of photons scattered in the copper led to the choice of a thickness of 0.25 mm. It also makes possible to avoid the photons emitted by lead 210 contamination (X rays at 12.56 keV (22%) and 46.54 keV (4.3%)) and their decay products.

Source collimation is the key to defining the beam profile and the proportion of the scattered component of the radiation field in terms of dose equivalent. We chose a conical collimator with an internal cavity for the source. The sources are produced by LNE-LNHB there are made of a 3 mm diameter solid deposit on a plastic support surrounded by a plastic ring.

The variation of the total ambient dose equivalent and its component due to scattered photons was calculated along the axis of the beam in the enclosure as a function of its depth. The best compromise between the internal dimensions of the detectors to be calibrated, the total mass of the enclosure and this initial assessment of the dosimetric characteristics of the calibration conditions, led to external dimension of 100 cm x 100 cm x 125 cm.

Calibration of the transfert standard.

According to ISO 4037 [3] specifications, the scattered component of the radiation field must not exceed 5% in terms of air kerma, and for dose equivalent rates below 1 µSy/h a correction for radiative background must be implemented. We determined these corrections in an attempt to extend the calibration range below 1 µSv/h.

The spectral distribution of fluence between 100 and 1500 cm from a Cesium 137 source is calculated. The model takes into account the dimensions of the room and the design of our irradiator, in order to account for the scattered part of the radiation field at the point of measurement. The spectral distributions show a scattered component about two decades below the direct component represented by the radionuclide emission peak at 662 keV. Table 2 shows the ambient dose equivalent and air kerma rates from the Cesium 137 photon source. This calculation does not take into account the scattered component of the radiation field. The air kerma per photon emitted by the source is calculated for each spectrum (Table 3).

Table 2. Air kerma rates in the collimated beam of the multi-source irradiator on July 10, 2024 as a function of distance from the source.

Distance (m)	K_a Gy/h	Distance (m)	K_a Gy/h
1.00	5.02E-05	9.00	5.74E-07
2.00	1.25E-05	10.00	4.60E-07
3.00	5.48E-06	11.00	3.77E-07
4.00	3.05E-06	12.00	3.14E-07
5.00	1.93E-06	13.00	2.64E-07
6.00	1.33E-06	14.00	2.26E-07
7.00	9.67E-07	14.95	1.97E-07
8.00	7.34E-07	-	-

Table 3. air kerma per photon emitted by the source calculated by Monte Carlo and conversion coefficient from fluence to air kerma as a function of distance from source.

Distance (m)	K_a (pGy)	h* (pGy cm²)	Distance (m)	K_a (pGy)	h* (pGy cm²)
1	2.37E-05	2.83	9	2.76E-07	2.73
2	5.88E-06	2.83	10	2.24E-07	2.66
3	2.59E-06	2.83	11	1.86E-07	2.56
4	1.44E-06	2.83	12	1.58E-07	2.44
5	9.19E-07	2.82	13	1.38E-07	2.31
6	6.34E-07	2.81	14	1.23E-07	2.13
7	4.63E-07	2.80	14.95	1.16E-07	1.93
8	3.51E-07	2.77	-	-	-

The operating range of LNE-LNHB's reference beams under COFRAC IOS 17025 accreditation stops at 7m; to extend this range beyond this, in order to achieve lower kerma flow rates, we need to establish a correction that takes scattered radiation into account. The data in Tables 2 and 3 enable us to quantify this correction named $k_{\mathrm{spectrum,diff,Ka,D}}$ as a function of the distance to the source, D. The air kerma at distance D is calculated according to the following equation.

$$k_{spectrum,diff,Ka,\mathrm{D}} = K_{a,MC,D} \Big/ K_{a,MC,D=100cm} = \int_E \emptyset_{E,D,MC}\, h_{E,K}\, dE \Big/ \int_E \emptyset_{E,D=100,MC}\, h_{E,K}\, dE$$

- ➢ $h_{\mathrm{E,K}}$ is the conversion coefficient from fluence to air kerma of ICRU 57, expressed in pGv cm²,
- ➢ $K_{a,MC,D}$ is the air kerma at distance D obtained from the fluence calculated by Monte Carlo,
- ➢ $K_{a,MC,D=100cm}$ is the air kerma at 100 cm from the source calculated by Monte Carlo,
- ➢ $\emptyset_{E,D,MC}$ is the photon fluence at distance D calculated by Monte Carlo,
- ➢ $\emptyset_{E,D,MC}$ is the photon fluence at distance D calculated by Monte Carlo.

The calibration coefficient of the transfer standard, $N_{Ka,d,534}$, is measured according to the following equation.

$$N_{Ka,d,534} = \frac{\begin{array}{c} K_{a,100cm}\ (100^2 / \mathrm{D}^2)\ \exp(\mu_{att}\ \mathrm{x}\ \rho\ (100 - \mathrm{D}) \\ k_{spectre,diff,Ka,D}\ k_{profil\ 534,ref,D} \end{array}}{G_{brut,d,Cs/Co\ 534,D} - G_{BdF,d,Cs/Co\ 534,D}}$$

- ➢ $K_{a,100cm}$ is the air kerma at 1 m from the source traceable to the LNE-LNHB primary reference,

- μ_{att} is the average attenuation coefficient of the photon spectrum,
- $k_{spectre,diff,Ka,D}$ is the correction factor for scattered photon fluence and its influence on the conversion coefficient to air kerma at distance D,
- $G_{brut,d,Cs/Co\ 534,D}$ is the raw indication of the transfer dosimeter, d, during calibration measurement,
- $G_{BdF,d,Cs/Co\ 534,D}$ is the transfer dosimeter indication, d, during background measurement,
- $k_{profil534,ref,D}$ is the correction factor allowing to pass from the reference value of the dosimetric quantity defined at a point to the value averaged over the part of the beam profile occupied by the transfer standard, taking into account the dimensions of this standard and the profile of the calibration beams, this factor is taken equal to 1.

The standard uncertainties are the following:

- $u(K_{a,D})$ is equal to 0.41 %,
- $u(k_{spectre,Ka,D})$ is estimated from the uncertainty on the calculated spectral fluence distribution and that on the polynomial regression equations. The values of the fluence-to-air kerma conversion coefficient in ICRU 57 are conventionally considered to be without uncertainty. On average, the uncertainty on fluence in each energy channel is equal to 0.7%, but that on emission lines is between 0.03 and 0.05%. As the spectral fluence distributions are dominated at least 2 decades by the fluences of the Cesium 137 emission lines, however, in order not to underestimate the uncertainty, a standard uncertainty on the spectrum equal to 0.5% is applied. The maximum deviation between the polynomial regression equations and the data used to calculate them is in all cases less than 0.4%. Considering this deviation as the maximum width of a rectangular distribution, the uncertainty on the polynomial regression equations is estimated to 0.4/2√3 = 0.115 %. The relative standard uncertainty on this correction factor is estimated at 0.513%.
- The standard uncertainty on the calibration distance, measured with a laser pointer, is a maximum of 0.1%.

The uncertainty budget for the calibration coefficient (excluding measurement fluctuation) in terms of air kerma therefore gives a standard uncertainty, whatever the distance, equal to 0.652%.

The study of radiative background leads us to choose a number of measurements greater than or equal to 60, in order to achieve an uncertainty of better than 10% on the distribution of measurements and better than 1% on the distribution of mean values.

Figure 2 shows the variation of the transfer standard response as a function of photon energy. These results were obtained from ISO 4037 N series. It can be seen that this variation is close to that claimed by the supplier in terms of dose equivalent, to within about 10%. The angular sensitivity variation is good and in line with the manufacturer's data.

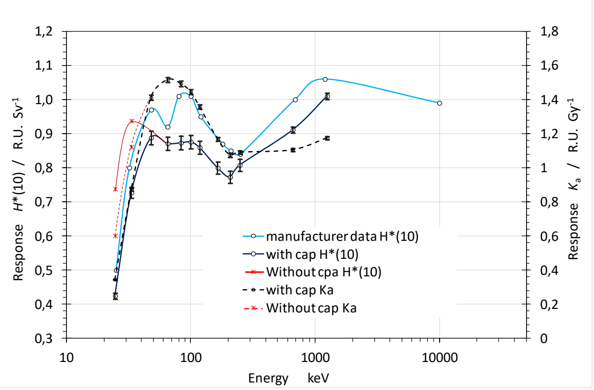

Fig. 2. $H^*(10)$ and K_a response of the transfer standard as a function of energy.

The transfer standard has been calibrated in terms of air kerma between 0.4 and 1 µGy/h. The calibration coefficient is equal to 0.897 µGy/h/ U.L. (U.L. = µSv/h), the standard deviation on these values is equal to 1.29%, we take this value for the uncertainty on the calibration coefficient of our transfer standard.

3 Establishment of the reference in terms of ambient dose equivalent in the shielded facility.

Prior to measuring the air kerma in the shielded facility using the transfer standard, the variation of the fluence spectrum along the axis of the beam and in the perpendicular plane is studied.

Figure 3 show the variation in ambient dose equivalent and the proportion of its scattered component as a function of distance from the source, with a 5% minimum between 60 and 80 cm. This range has been chosen as the calibration range in the shielded facility.

The value of the ambient dose equivalent, $H^*(10)_{BD}$, at the measurement point in the shielded enclosure beam is given by the following equation.

$$H^*(10)_{BD} = N_{Ka,d,534}\ G_{corr,d,BD}\ k_Q\ \overline{h^*}$$

- $N_{d,Cs/Co\ 534}$: Calibration coefficient of the transfer standard as determined in the previous section,
- $G_{corr,d,Cs/Co\ BD}$: Corrected indication of the transfer standard at the measurement point in the shielded facility,
- $\overline{h^*}$: Conversion factor from air kerma to ambient dose equivalent in the shielded facility,
- k_Q : Beam quality correction factor on the air kerma calibration coefficient of the transfer dosimeter.

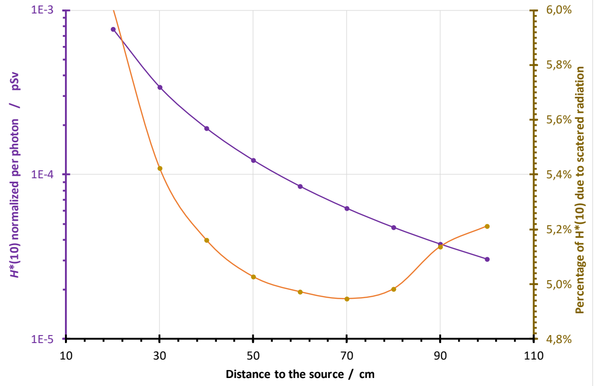

Fig. 3: Variation in ambient dose equivalent along the beam axis as a function of distance from the Cesium 137 source.

Te k_Q factor is the ratio of the calibration coefficients in the photon calibration beam (index "534") and in the shielded facility (index "BD").

$$k_Q = \frac{N_{d,Q,BD}}{N_{Ka,d,534}} = \frac{\left[\int_E \phi_{E,DB} h_{\phi,K}\, dE \Big/ \int_E \phi_{E,DB} h_{\phi,K}\, R_{E,d}\, dE\right]_{BD}}{\left[\int_E \phi_{E,534} h_{\phi,K}\, dE \Big/ \int_E \phi_{E,534} h_{\phi,K}\, R_{E,d}\, dE\right]_{534}}$$

- $h_{\phi,K}$ is the conversion coefficient from fluence to kerma in air,
- $\phi_{E,DB}$ is the spectral fluence calculated in the low-flow chamber,
- $\phi_{E,534}$ is the spectral fluence calculated in the calibration facility,
- $R_{E,d}$ is the energy response of the transfer standard.

The standard uncertainty of this correction factor is calculated by taking into account the uncertainty of the calculated spectra, estimated as before (0.5%), and that of the energy-dependent response as measured, i.e. 1%. The average conversion coefficient from air kerma to ambient dose equivalent $\overline{h}^*$ is calculated from ICRU 57 data, its standard uncertainty calculated in a similar way to that on $k_{spectre,Ka,D}$ but in the absence of polynomial regression.

The closed-beam radiative background is evaluated using the cone-of-shadow technique, by applying a kM measurement correction factor to evaluate the component due to radiation transmission through the shutter from the calculated spectra. The uncertainty of this correction factor therefore takes into account the uncertainty of the spectra (0.5%) and that of the background measurements (1.0%), i.e. a total of 1.12%.

Table 4. Calculation of reference values in terms of ambient dose equivalent rate in the shielded enclosure as a function of distance from the source.

Distance cm	k_Q	$\overline{h}^*$ Sv/Gy	$N_{Ka,d,534}$ µGy/h R.U.	Raw measure R.U.	k_M
40	0.9358	1.223	0.897	322.04	0.053
50	0.9354	1.223		217.50	0.053
60	0.9352	1.223		158.17	0.052
70	0.9354	1.224		115.07	0.052
80	0.9357	1.224		95.81	0.052

Distance cm	Backgrond R.U.	Corrected measure R.U.	$H^*(10)_{BD}$ nSv/h
40	33.91	303.40	311.5
50	28.03	199.52	204.7
60	26.04	139.13	142.8
70	20.96	99.09	101.7
80	21.87	77.85	80.0

Table 5. Uncertainty budget on the reference value of H*(10) in the shielded facility (an uncertainty of 0.4% on the calibration distance is added).

Distance cm	Standard deviation raw measure R.U.	Standard deviation background measure R.U.	Standard uncertainty on the corrected measure	
			R.U.	%
40	0.87	0.72	1.14	0.39%
50	0.54	1.26	1.37	0.63%
60	0.80	1.24	1.48	1.12%
70	0.70	0.91	1.14	1.22%
80	0.52	0.81	0.96	1.29%

Distance cm	u(k_Q)	u($\overline{h}^*$)	u(k_M)	u($N_{Ka,d,534}$)	u($H^*(10)_{BD}$)
40	1.0%	0.50%	1.12%	1.29%	2.1%
50	1.0%	0.50%	1.12%	1.29%	2.2%
60	1.0%	0.50%	1.12%	1.29%	2.4%
70	1.0%	0.50%	1.12%	1.29%	2.4%
80	1.0%	0.50%	1.12%	1.29%	2.5%

4 Conclusions.

The expression for the calibration coefficient of a calibrated survey meter in the shielded facility beam is

$$N_{H*,d,BD} = \frac{H^*_{BD,D}\, k_{profile}}{G_{corr,d,BD,D}}$$

A profile correction is calculated according to the dimensions of the device to be calibrated. Its purpose is to correct the dose equivalent value obtained with the transfer standard, $H^*(10)_{DB}$. This correction factor is calculated from 2D mapping in the plane perpendicular to the source axis according to the following equation:

$$k_{profile} = \frac{\iint_{x\,y} H^*(10)_{x,y}\, dx\, dy}{H^*(10)_{DB}}$$

The value of this correction factor is a maximum of 4%, depending on the x and y dimensions of the survey meter, and the beam aperture radius is 24 cm at 70 cm from the source.

This study has enabled us to install and characterize Cesium 137 photon beams in a shielded facility for radiameter calibration against ambient dose equivalent rates comparable to those encountered in the environment. The reference value of the ambient dose equivalent in the low dose rate facility is traceable to the national references of the LNE-LNHB in terms of air kerma. The uncertainty on the calibration coefficient of a survey meter on this facility is estimated at between 5 and 10%; this uncertainty budget remains dominated by the uncertainty on the measurement of the radiative background.

References.

[1]Tadahiro Kurosawa & al, poster at AOCRP-4 ; 12 may 2014, Kuala Lumpur, Malaisia

[2] J. A. Kulesza, T. R. Adams, J. C. Armstrong, S. R. Bolding, F. B. Brown, J. S. Bull, T. P. Burke, A. R. Clark, R. A. Forster III, J. F. Giron, T. S. Grieve, C. J. Josey, R. L. Martz, G. W. McKinney, E. J. Pearson, M. E. Rising, C. J. Solomon Jr., S. Swaminarayan, T. J. Trahan, S. C. Wilson, A. J. Zukaitis. MCNP® Code Version 6.3.0 Theory & User Manual. Los Alamos National Laboratory Tech. Rep. LA-UR-22-30006, Rev. 1. Los Alamos, NM, USA. September 2022.

[3] ISO 4037 Series; Radiological protection — X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy.

This study is made within the 21GRD02 **BIOSPHERE** (*Metrology for earth Biosphere: Cosmic rays, ultraviolet radiation and fragility of ozone shield*) research program. It has received funding from the European Partnership on Metrology, EPM, co-financed by the European Union's Horizon Europe Research and innovation Program and by Participating States. https://euramet-biosphere.eu/