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Long-Term Stability and Performance Assessment of ^{137}Cs Gamma Beams for Calibration of Radiation Protection Instruments According to ISO 4037 and IAEA Standards

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ABSTRACT

This study presents the experimental characterization of gamma radiation beams generated by a collimated irradiator equipped with two ^{137}Cs sources at the Gamma and X-ray Calibration Laboratory of CNESTEN. The facility is mainly used for calibrating radiation protection instruments and supporting dosimetric assessments. The irradiator provides air kerma rates (K_{air}) from 60 µGy/h to 60 mGy/h at distances up to three meters. Calibrations were performed in terms of ambient dose equivalent using K_{air} measurements and appropriate conversion coefficients, with corrections applied for source decay to maintain accuracy over time. A long-term evaluation of the irradiator's stability over 16 years showed consistent performance, with Kair rate deviations within 5% after decay correction. This confirms the reliability of the reference beams and supports extending calibration intervals. To ensure calibration validity, a beam homogeneity study was also conducted by measuring the transversal profile at various distances from the source. The results showed a uniform beam width of approximately ±8 cm at 1 meter and up to ±21 cm at 3 meters from the central axis, confirming the homogeneity of the irradiator for precise and reliable measurements across different distances. Finally, the system's performance meets the requirements of ISO 4037:2019 and IAEA SRS-16 standards. The expanded uncertainty of ±3.7% (k = 2) reflects the high reliability of dosimetric evaluations at the laboratory.

INTRODUCTION

Gamma rays are a form of high-energy electromagnetic radiation, similar to X-rays. However, X-rays typically have a lower average effective energy and require the establishment of well-defined beams through the use of additional filtration systems [1-3]. Both reference beams must be characterized in compliance with the ISO 4037 standard. These reference beams are widely used in industrial, medical, and research applications, as illustrated by this study, which focuses on the calibration of radiation protection instruments.

The main purposes of calibration are to confirm that an instrument is operating correctly, is appropriate for its intended monitoring use, and to evaluate its performance under controlled standard conditions. The instrument's readings in relation to the quantity's value it is designed to measure. This process must be performed across the entire range of the instrument's readings to ensure accurate calibration [4].

The calibration processes have been established by the International Organization for Standardization (ISO). Additionally, the International

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Electrotechnical Commission (IEC) has developed numerous standards regarding performance specifications and testing methods for radiation protection monitoring instruments.

The Gamma and X Calibration Laboratory at the National Center for Nuclear Energy, Science and Technology (CNESTEN) is responsible for calibrating all CNESTEN radiation protection measuring instruments, as well as external instruments provided as part of its external services. These calibrations are conducted in accordance with the requirements of ISO 4037 and IAEA SRS 16 standards. Dosimetry equipment is used to evaluate the amount of ionizing radiation delivered during techniques that rely on ionizing radiation for diagnosis and patient treatment [5,6]. Additionally, in measurements related to the radiation protection of workers and the public, it is crucial to ensure that the measurements are conducted in compliance with the recommendations of the International Organization for Standardization [4,7]. The high quality of calibration measurements conducted at the Gamma and X Calibration Laboratory, as well as the dosimetry equipment used at CNESTEN, is ensured by their precision, accuracy, and long-term stability.

This investigation presents an experimental study on the characterization of gamma-ray radiation beams using the secondary standard ionization chamber PTW 23361, which is utilized for the calibration of radiation protection instruments [2,8]. This study was conducted six times over an extended period from 2008 to 2024.

The influence of scattering from various facility components and the homogeneity of gamma radiation beams were evaluated at distances of 100 cm, 200 cm, and 300 cm from the gamma ray source [4,7,9].

METHODOLOGY

The Gamma and X Calibration Laboratory at the National Center for Nuclear Energy, Science and Technology (CNESTEN) uses a horizontal irradiator IMPROMAT model NUCOMAT equipped with three ^{137}Cs and three ^{60}Co sources. The initial activities of the sources were 20 Ci, 2 Ci, and 0.2 Ci for ^{137}Cs and 5.45 Ci, 0.52 Ci, and 0.05 Ci for ^{60}Co, respectively. This configuration allows coverage of a wide range of instrument calibration needs at various designated distances (Table 1).

Installed in 2003, the NUCOMAT irradiator consists primarily of an internal shielded cylinder housing the radioactive sources. The sources can be remotely moved from their storage position to the irradiation position, allowing precise control of the air kerma rate required for calibration at specific distances. The irradiator is collimated with an angle of incidence of 16°, in accordance with the requirements of ISO 4037, as shown in Fig. 1.

The collimator systems used with the ^{60}Co and ^{137}Cs sources are shown in Fig. 1. The collimator has a conical shape, with the source positioned at the apex. The collimator is composed of six rings featuring conical openings (diaphragms) made of lead alloy, with an overall thickness of approximately 90 mm, and each ring is separated by 20 mm thick spacers. The collimator includes nine diaphragms. The design and construction of the system are in full compliance with ISO 4037 and IAEA SRS 16 standards, ensuring accurate beam definition and adequate radiation shielding during calibration procedures.

The laboratory is equipped with one secondary standard ionization chamber, PTW 23361 (Fig. 2), with a volume of 30 cm^3. It is specifically designed as a reference chamber for absolute dosimetry and used by secondary standard laboratories (Table 2). This chamber is calibrated at the German National Laboratory PTB (Physikalisch-Technische Bundesanstalt) and is constructed with a long, rigid stem to allow easy positioning in the radiation field. It has a nominal useful energy range of 30 keV to 50 MeV.

Table 1. Characteristics of radioactive sources of irradiation.

Type source	Source Number	Activity (Ci)	Reference date	Energy (keV)	Half life (Years) [7]
^{60}Co	02	5.45	01/09/2008	1173.3 1332.5	5.271 ± 0.0008
^{60}Co	03	0.52	01/09/2008		
^{60}Co	04	0.05	01/09/2008		
^{137}Cs	08	0.2	02/04/2008	661.6	30.05 ± 0.08
^{137}Cs	09	2	02/01/2005		
^{137}Cs	10	20	10/01/2007		

Table 2. Technical details of a 23361-type cylindrical chamber.

Symbol	Manuf-acturer	Active volume (cm^3)	Wall material	Wall thickness (mm)	Wall density (g/cm^3)	Area density	Electrode
23361	PTW	30	PMMA ($C_5H_8O_2$)n	1.0	1.19	120	Aluminum, graphite coated

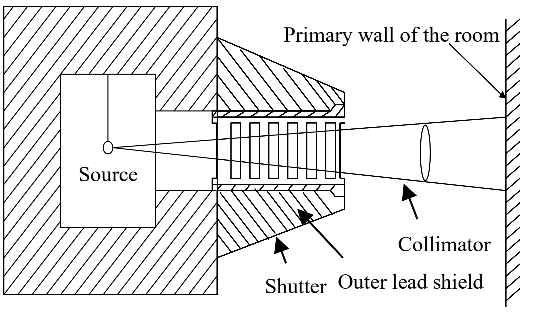

Fig. 1. Collimator and shutter assembly of a collimated source system [10].

Fig. 2. Secondary Standard Ionization Chamber PTW 23361.

Fig. 3. Electrometer Unidos PTW.

Table 3. Calibration coefficients of PTW 23361 for a period of 20 years.

Calibration coefficients Gy/C					
Nuclide	**2004**	**2014**	**2017**	**2020**	**2024**
^{137}Cs	/	942000	938300	944000	942400
^{60}Co	929400	928100	927600	928400	928200

The transfer standard system was used with the PTW UNIDOS T10001 electrometer (Fig. 3). The secondary standard system (chamber + electrometer) was last calibrated together at PTB-DAkkS-DKD in January 2024, with a calibration coefficient k_{elec} = 1 as documented in the calibration certificate. The calibration was performed for the following beam qualities: ^{60}Co, ^{137}Cs, and X-rays. Both devices are calibrated once every three years (Table 3).

All measurements were carried out under controlled conditions of temperature, pressure, and humidity in accordance with the requirements of ISO 4037. Monitoring of ambient conditions was performed using calibrated sensors compliant with ISO 17025 standards.

The laboratory is also equipped with a laser beam device that indicates the center of the beam, facilitating the precise positioning of the reference instrument. The reference point of the instrument must be accurately aligned with the laser beam axis.

The SCD (Source - Chamber Distance) used in this work is measured using a positioning bench, which is calibrated every two years. The bench is equipped with a platform that can support a maximum load of 50 kg, and it allows the source-to-detector distance to be adjusted from 0.7 m to 3.5 m [10].

A characterization of the gamma ray beams has already been made. This process consists of determining the air kerma rate at different points of the beams using a dosimetric assembly, a PTW 23361 ionization chamber, and an electrometer calibrated at a German primary standards laboratory, according to the requirements of ISO 4037 [7,11,12].

The air kerma rate at the measurement point and on the selected reference date is obtained from the measurement of the net ionization current I delivered by the ionization chamber using the following expression Eq. (1) [4]:

$$k_{air} = I \times N_K \times k_{TP} \times k_Q \times k_{ot} \tag{1}$$

Where I is the net current measured by the ionization chamber, N_K is the calibration factor of the reference chamber in terms of air kerma, k_{TP} is the correction factor for ambient temperature and pressure, k_Q is the correction factor for beam quality, and k_{ot} is the additional correction factor accounting for other influences.

The results of the air kerma rate measurements were then used to calculate the ambient dose equivalent $H^*(10)$ at a specific calibration point, using the air kerma to ambient dose equivalent conversion coefficient (h_k^*) provided in the ISO 4037-3 Eq. (2).

$$H^*(10) = k_{air} \times h_k^* \tag{2}$$

Based on Eqs. (1) & (2), it can be deduced that:

$$H^*(10) = (I_i - I_B) \times N_K \times k_{TP} \times k_Q \times k_{ot} \times h_k^* \tag{3}$$

Hence, the calibration coefficient N_C is given by Eq. (4) [4]:

$$N_C = \frac{H^*(10)}{(M_i - M_B)} \tag{4}$$

Where I_i, I_B are the ionization current in the presence and in the absence of the source respectively, h^*_k is the conversion coefficient used to obtain the ambient dose equivalent, $H^*(10)$ is the ambient dose equivalent, M_i is the indication of the instrument under calibration and M_B is the indication of the instrument when the source is removed (background).

Table 4. Gamma sources with beam output and calibration distances.

Nuclide	Activity range (GBq)	No. Of source	Range of covered air kerma rates (mGy/h)	Measurement date
^{137}Cs	499.0	10	4.52 – 40.88	10/31/2024
^{137}Cs	46.9	9	0.42 – 3.79	11/11/2024

The PTW 23367 chamber used in this work has been verified over the years using two reference sources ^{137}Cs (No. 10 and 9). The characteristics of these sources, including beam output and calibration distances, are given in Table 4.

For each measurement point, five repeated measurements were performed with a counting time of 100 seconds per measurement.

RESULTS AND DISCUSSION

In this research 152 radiation protection area monitoring instruments were calibrated in the Gamma and X Calibration Laboratory over two years. The calibration factors for all the instruments calibrated during this period were determined using Eqs. (3) and (4). The results obtained are presented in Fig. 4.

An analysis, as shown in Fig. 4, explains that more than 90% of the radiation protection instruments exhibit a relative indication error within the recommended limit of 30% [13].

From these results, we can conclude that the Gamma and X Calibration Laboratory meets international safety requirements.

The characterization of the gamma ray beam from the two ^{137}Cs sources, No. 10 and No. 9, at different beam distances was studied and is plotted in Figs. 5 and 6, respectively.

It can be observed that the air kerma rate over a six-year period at a distance of 100 cm varies between (59.2 mGy/h and 40.88 mGy/h) for ^{137}Cs No. 10 and between (5.51 mGy/h and 3.79 mGy/h) for ^{137}Cs No. 9.

Furthermore, the curves in both figures illustrate the decrease in the air kerma rate over time and at different distances following the exponential decay law of the radioactive decay of ^{137}Cs sources.

The measurements carried out to evaluate the stability of the dosimetry quantity K_{air} rate for the ^{137}Cs reference beams over a 16- year period for each source (No. 10 and No. 9) are presented in Figs. 7 and 8, respectively. The analysis of the results indicates that the radiation beams have remained highly stable throughout the 16-year period.

The results highlight the differences observed in the predicted K_{air} rate values over several years, after applying the appropriate decay correction, for both sources.

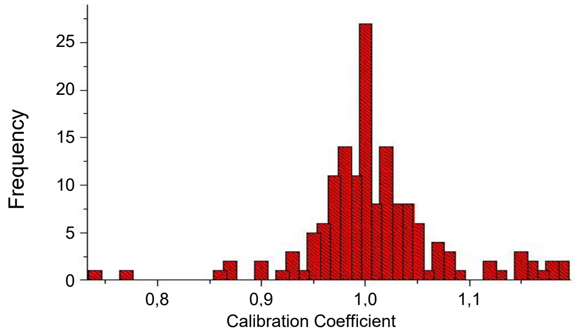

Fig. 4. Histogram of calibration coefficients for 152 instruments.

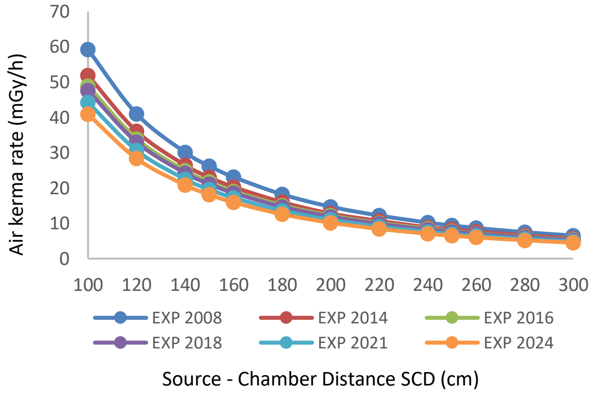

Fig. 5. Air-kerma rate values measured at different source-chamber distances - Source ^{137}Cs No. 10.

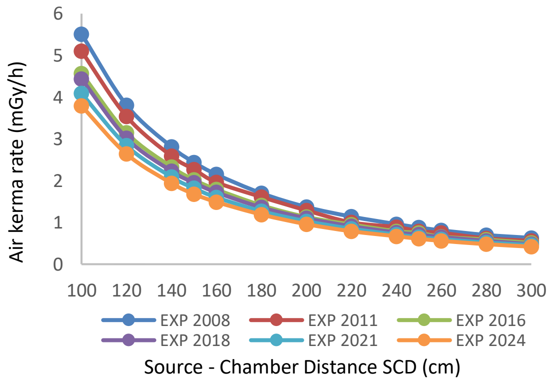

Fig. 6. Air-kerma rate values measured at different source-chamber distances - Source ^{137}Cs No. 9.

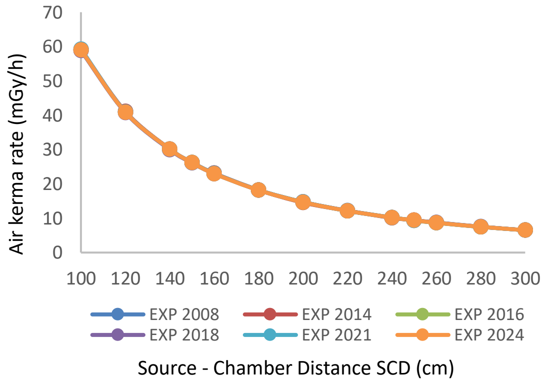

Fig. 7. Air-kerma rates predicted for subsequent dates may be obtained by applying the corresponding decay correction - Source ^{137}Cs No. 10).

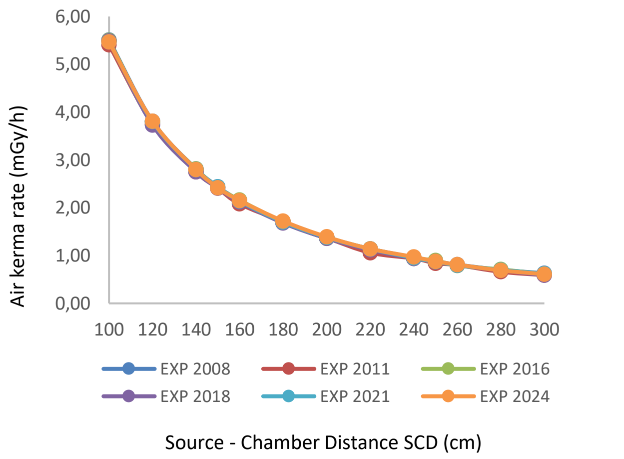

Fig. 8. Air-kerma rates predicted for subsequent dates may be obtained by applying the corresponding decay correction - Source ^{137}Cs No. 9.

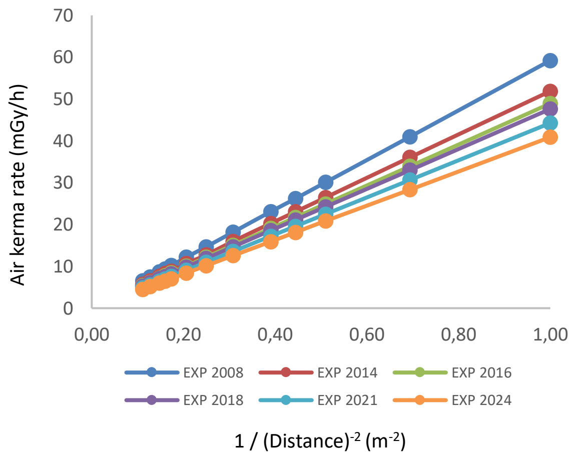

Fig. 9. Output of calibration source contained Nucomat gamma irradiator - Source ^{137}Cs No. 10.

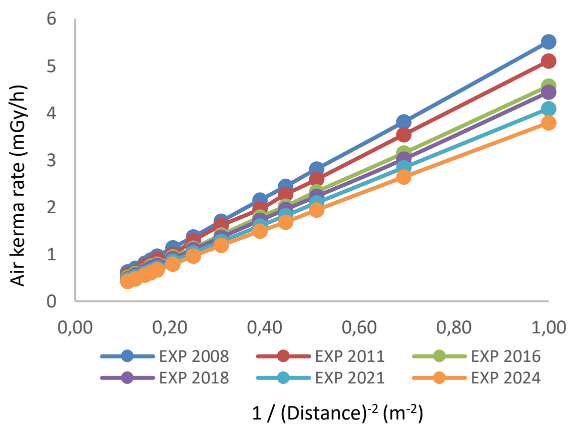

Fig. 10. Output of calibration source contained Nucomat gamma irradiator - Source ^{137}Cs No. 9.

For the ^{137}Cs source No. 10, the relative deviations range from 0% to a maximum of 0.69%. These deviations are minimal and do not exceed 1%, which meets the standard ISO-4037 recommendations. The applied correction is considered negligible when applied to the reference radiation fields used in radiation protection dosimetry [7,8].

For ^{137}Cs No. 9, the relative deviation rate is 3.4%. All results are below the 5%, fully complying with the [4,7] recommendations.

However, validating the reference beam characterization results requires verifying the validity of the inverse square law, with the deviation remaining below 5%. To this end, we developed a method to ensure compliance with this requirement [14]. The relationship between the K_{air} rate and the inverse square of the distance, from the center of the reference source to the reference point of the secondary standard ionization chamber, was investigated and is presented in Figs. 9 and 10 for ^{137}Cs sources No. 10 and No. 9, respectively.

Figures 9 and 10 show that the K_{air} rate increases with the inverse square of the distance. Over a six-year period, the correlation coefficients ranged from 0.999989 to 0.999999 for source No. 10 and from 0.99986 to 0.99999 for source No. 9. These high correlation values confirm that the K_{air} rate varies linearly with the inverse square of the distance. Table 5 summarizes the correlation coefficients over the six-year period for both ^{137}Cs sources (No. 10 and No. 9). The findings demonstrate that the K_{air} rates at different positions within the beam remain proportional, within 5%, to the inverse square of the distance from the center of the reference source to the reference point of the detector, in accordance with ISO 4037 (2019) and IAEA (2000) recommendations. As indicated, the results fall well within 5% deviation, which is internationally considered as acceptable [4,7].

The K_{air} rates along the central axis for each point of the beam were measured by applying the corresponding decay correction over six years for each source, ^{137}Cs No. 10 and 9. These measurements are plotted in Figs. 11 and 12. The applied correction, which remained below 1%, was considered negligible when applied to reference radiation fields used in radiation protection dosimetry [11].

Table 5. Correlation coefficient of ^{137}Cs No. 10 and 9 sources.

Nuclide	Source N°	2008	2011	2014	2016	2018	2021	2024
^{137}Cs	10	0.999998	/	0.999989	0.999999	0.999998	0.999999	0.999999
^{137}Cs	9	0.999990	0.99986	/	0.999960	0.999910	0.999990	0.999974

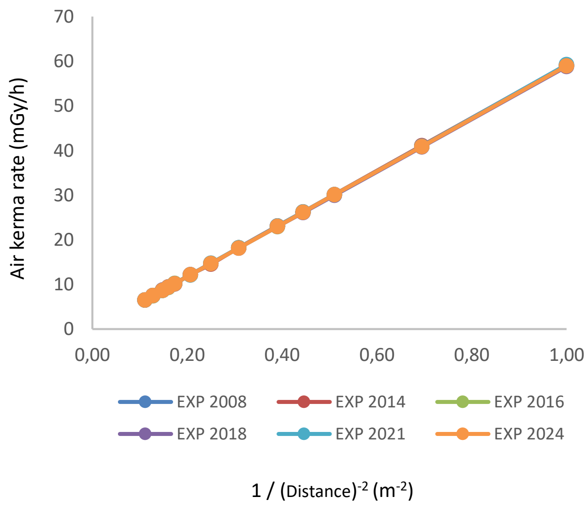

Fig. 11. Output of ^{137}Cs No. 10 calibration source irradiator obtained by applying the corresponding decay correction.

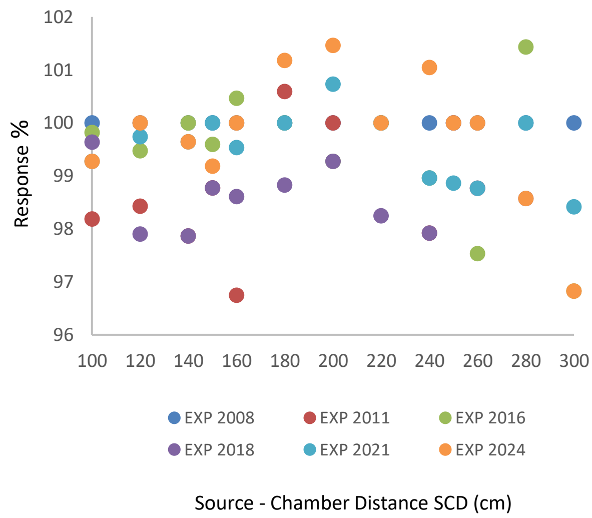

Fig. 14. Long-term stability of gamma irradiator (Source ^{137}Cs No. 9).

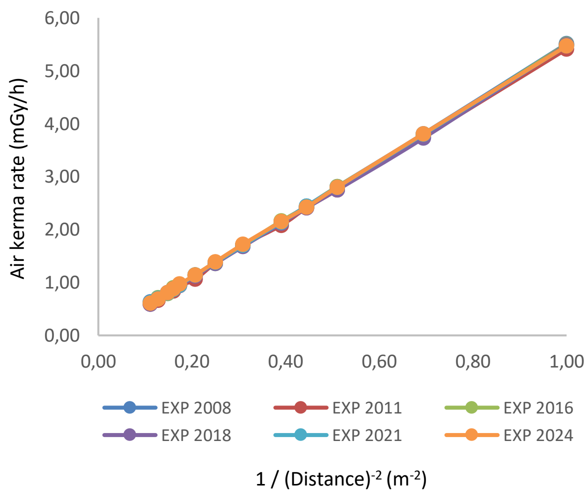

Fig. 12. Output of ^{137}Cs No. 9 calibration source irradiator obtained by applying the corresponding decay correction.

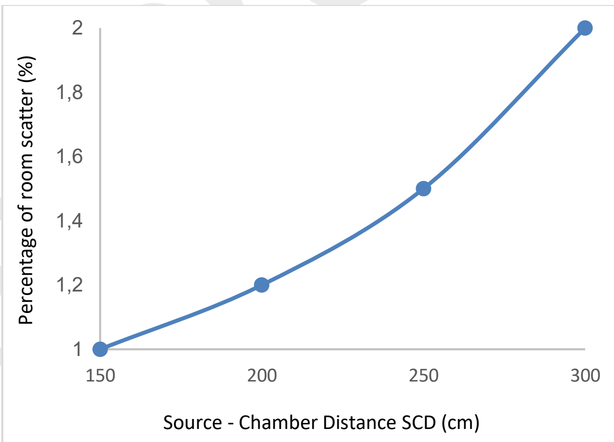

Fig. 15. Room scatter contribution to the measured signal for different source–chamber distances (Source ^{137}Cs No. 10).

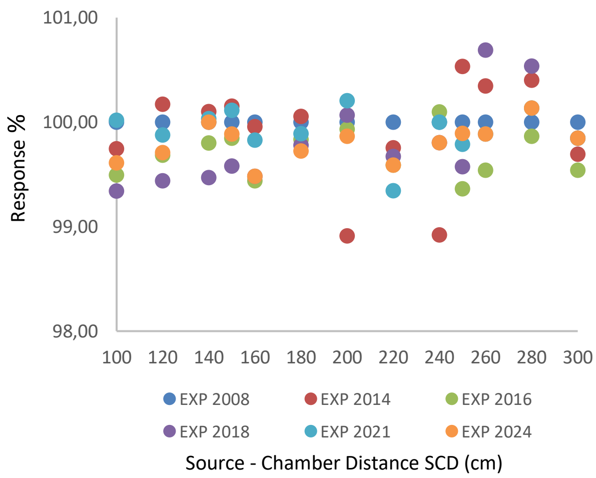

Fig. 13. Long-term stability of gamma irradiator (Source ^{137}Cs No. 10).

Figures 13 and 14 illustrate a comparison of the air kerma rate values over 6 years, corrected for radioactive decay, with the reference values measured in 2008. The k_{air} values shown in Figs. 13 and 14 were obtained using the ^{137}Cs sources N°10 and 9, respectively. The relative percentage deviations fluctuate between a minimum of 0.5% and a peak of 0.7% for source No. 10 and are very small, not exceed 1%, which complies with the ISO 4037 recommendations. This correction is considered negligible when applied to reference radiation fields used in dosimetry for radiation protection [7,8]. On the other hand, the k_{air} deviations vary between 0.5% and 2.5% for ^{137}Cs No. 9. All the results obtained are less than 5% that is recommended by [4,7].

The contribution of room scattering was measured using the PTW 23361 secondary standard ionization chamber. A shadow-shield with a 10 cm diameter was placed between the source and the secondary standard ionization chamber to completely protect the ionization chambers from radiation during the measurement. The analysis of the data presented in Fig. 15 reveals that the contribution of room scattering varies from 1% to 2% at source-to-chamber distances of 150 cm to 300 cm, respectively, using reference source ^{137}Cs N°10. These results, which do not exceed the 5%, are in accordance with the requirements of ISO 4037 and IAEA SRS 16 standards.

The uncertainty was determined and estimated in accordance with the ISO Guide to the expression of measurement uncertainties [15]. The principal relative uncertainty components are shown in Table 6. All measurement results and corresponding uncertainty budgets were calculated using the Excel software.

Table 6. Relative uncertainties budget for air kerma rate (Source ^{137}Cs No. 10 – SCD 100 cm).

Relative uncertainty components	Type (%)	Type B (%)
Reference kair measurements		
Ion chamber calibration coefficient N_k	-	1.250
Ion chamber stability	-	1.250
Electrometer calibration coefficient	-	0.250
Electrometer stability	-	0.250
Repetability	0.001	-
Resolution	-	0.0003
Air temperature	-	0.120
Pressure	-	0.115
Positioning secondary standard	-	0.3
Combined uncertainty K_{air}	-	1.8
U_{Kair}		3.7(k=2)

Table 7. Homogeneity of gamma beams.

SCD (cm)	Maximum deviation	Maximum radiation field diameter
100	3.3%	16 cm (between -8 to 8 cm)
200	1.3%	24 cm (between -12 to 12 cm)
300	1.7%	42 cm (between -21 cm to 21 cm)

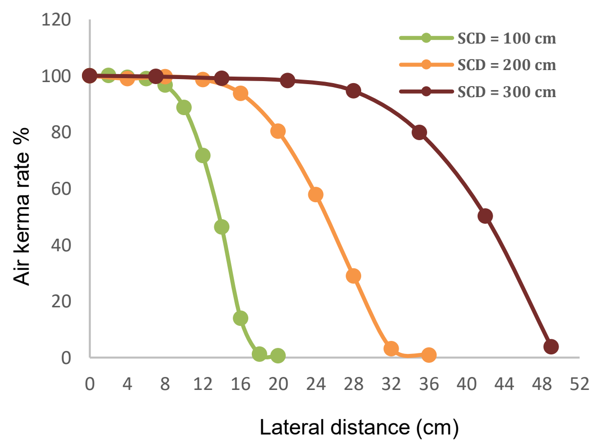

Fig. 16. Transverse profile of gamma radiation beams.

As shown in Fig. 16, the lateral air-kerma profiles were measured at SCD (Source–Chamber Distances) 100 cm, 200 cm, and 300cm. These measurements were carried out using the ^{137}Cs No. 10 and the PTW 23361 secondary standard ionization chamber to characterize the radiation field in terms of field shape, field size, homogeneity, and to detect air kerma rate values beyond the primary beam due to the scattering [9]. The measured percentages of air kerma, relative to the maximum value obtained along the horizontal axis, are presented in Table 7 as a function of the distance from the center of the radiation field. Beyond the primary beam, experimental air kerma rate at SCDs of 100 cm, at 200 cm and 300 cm showed maximum deviations of 3.3%, 1.3% and 1.7% at lateral off axis positions of 300 cm, within radiation field diameter of 16 cm (-8 to 8 cm), 24 cm (-12 to 12 cm) and 42 cm (-21 to 21 cm), respectively. All the results are below the 5% and thereby reply to the [4,7] recommendations**.**

CONCLUSION

The ionization chamber response to gamma radiation beams is linear (R^2 = 0.9999), and the measured air kerma rates follow the inverse square law within 5% accuracy. The long-term stability of the gamma irradiator with two ^{137}Cs sources was evaluated over 16 years using a PTW 23361 ionization chamber, confirming that reference air kerma values remained stable and ensuring reliable dose delivery for dosimetric instrument calibration. The study also evaluated the homogeneity of the gamma radiation beams, confirming compliance with ISO 4037 and IAEA SRS No. 16 standards, with scattered radiation remaining within acceptable limits. These findings demonstrate the high performance and reliability of CNESTEN's Gamma and X-ray Calibration Laboratory in accurately calibrating radiation protection instruments. The study confirms that the laboratory's practices comply with ISO recommendations and that the gamma irradiator meets international safety and quality standards.

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