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Commissioning of the Radiation Monitor Calibration Laboratory (LabCal) of IDQBRN for cesium-137 irradiation system

SILVA[a,b], T. M. S., AMORIM[a], A. S., BALTHAR[a], M.C. V., SANTOS[a], A., CURZIO[a], R. C. CARDOSO[b], D. D. O., NUNES[b], W. V.

[a] *Instituto de Defesa Química, Biológica, Radiológica e Nuclear (IDQBRN) / Seção de Defesa Radiológica e Nuclear (SDRN). Avenida das Américas, 28.705 - Guaratiba. 23020-470. Rio de Janeiro - RJ - Brasil.*

[b] *Instituto Militar de Engenharia (IME) / Seção de Engenharia Nuclear (SE/7). Praça General Tibúrcio, 80 – Praia Vermelha - Urca. 22290-270. Rio de Janeiro - RJ - Brasil.*

thiago.medeiros@eb.mil.br

ABSTRACT

The provision for the Brazilian Army of equipment that provides reliable and safe measurements, enabling decision-making based on radioprotection parameters, leads to the need to investigate the metrology of the calibration system used in the Radiation Monitor Calibration Laboratory (LabCal) of the Institute of Chemical, Biological, Radiological and Nuclear Defense (IDQBRN). To this end, the commissioning in cesium-137 is of primary importance in this process. In order to check the conformity of the radiator system, in this work, the ambient dose equivalent rate, $\dot{H}^{*}(10)$, was obtained experimentally for several configurations to compare them with the appropriate theoretical concepts. For this, the distance between the source of cesium-137 (36.9 GBq in 01/22/2015) and the ionization chamber was varied from 500 to 3000 mm at 250mm intervals. To obtain lower ambient dose equivalent rates, 15 and 32 mm thick lead attenuators were used. The mathematical model that best fit the experimental values was analyzed. In all cases, the potential function offers better fit, since the coefficients of determination obtained are approximately equal to 1, obeying the Law of the Inverse Square of the Distance, according to theoretical foundation. Moreover, it was evaluated that the relative deviations are below the limits established by the relevant standard.

Keywords: Commissioning, Calibration, DQBRN, Cs-137.

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1. INTRODUCTION

The Radiation Monitor Calibration Laboratory (*Laboratório de Calibração de Monitores de Radiação - LabCal*) of the Chemical, Biological, Radiological and Nuclear Defense Insitute (*Instituto de Defesa Química, Biológica, Radiológica e Nuclear do Exército - IDQBRN*) was created in 2016 with a focus on meeting the demands of the Earth Force, as a result of Science and System Transformation Project. Since then, it has operated in the fields of scientific advice and technical support in measuring monitors and radiological identifiers used by specialized troops of the Brazilian Army (*Exército Brasileiro - EB*), both in large-scale events and in specific demands in the health, safety and scientific research sectors [1].

Aiming to meet the needs of the Army's Chemical, Biological, Radiological and Nuclear Defense System (*Sistema de Defesa Química, Biológica, Radiológica e Nuclear do Exército - SisDQBRNEx)* in expanding the EB's operational capacity to act in the protection of society, the aim is to provide radiological monitors and identifiers with reliable and safe measurements [2] for prompt use in prevention and security actions against terrorist threats; illegal storage; use, transfer and trafficking of radioactive and nuclear substances and materials [3].

As a preliminary way to guarantee the quality of calibration tests at the magnitude of the ambient dose equivalent rate, $H^*(10)$, this study seeks to detail and validate the commissioning of the LabCal cesium-137 source irradiator system. Arrangements involving distance variations between the detector and the radiation source and the use (or not) of lead attenuators were proposed to provide an extensive continuous range of the magnitude under study. To validate this commissioning, the mathematical treatment of the experimental data, the comparison with the related theoretical basis and, finally, the analysis of the conformity of the system according to the set of standards of ISO 4037-1, which deals with radiological protection, is envisaged for reference gamma radiation for calibrating dosimeters and dose rate meters [4].

1.1. Commissioning

Commissioning is the process of ensuring that the system and components of a facility or industrial unit are designed, installed, tested, operated, and maintained in accordance with the appropriate operational requirements. That is, the commissioning aims to verify its conformity with the design characteristics and performance criteria [5]. It can be used both in new ventures and in units and systems in the process of expansion, modernization or adequacy [6]. In practice, commissioning is defined as the integrated application of a set of techniques and procedures to verify, inspect and test the system under analysis [7].

As an integral part of commissioning, this study carried out a conference on the conformity of the cesium-137 radiator system, which aims to analyze whether the variation in the ambient dose equivalent rate is in accordance with the theoretical behavior believed with minor variations than the normative upper limit [4].

1.2. Inverse Square Law

The Inverse Square Law (ISL) is a mathematical law commonly applicable in wide areas of knowledge and refers to the behavior of a magnitude, proportional to the emission of a beam equally in all directions by a point source, measured (or estimated) at different distances from the issuing source and the detector [8]. In the area of ionizing radiation, this Law applies, without restrictions, to cases of point radioactive sources emitting isotropically in the vacuum [9].

For a point source emitting radiation in all directions, the flow is inversely proportional to the square of this distance. It should be noted that this mathematical model is only true for a point source, a punctiform detector and negligible absorption between the source and the detector [10].

Applied to the ambient dose equivalent operational quantity, the ISL is expressed by Equation 1:

$$\frac{H^*(10)_1}{H^*(10)_2} = \frac{(r_2)^2}{(r_1)^2} \tag{1}$$

where $H^*(10)_1$ is the ambient dose equivalent at distance r_1 of the source and $H^*(10)_2$, at distance r_2 of the source.

Through mathematical manipulations and making the distance $r_1 = 1$ m. So, $H^*(10)_1$ represents the ambient dose equivalent at a point away from one meter from the source. Thus, we obtain Equation 2.

$$H^*(10)_2 = \frac{H^*(10)_1}{(r_2)^2} \tag{2}$$

Since $H^*(10)_2$ can be the equivalent of the ambient dose at any point whose distance from the source is r and that $H^*(10)_1$ is equal to a constant B, we can generalize to Equation 3:

$$H^*(10)_2 = \frac{B}{r^2} \tag{3}$$

where *B* is the ambient dose equivalent at a point 1 m away from the radioactive source.

In specific cases of real sources with small dimensions in relation to detector distance, the ISL lacks experimental approval [11], as will be developed in this study.

1.3. Correction for air temperature and pressure variation for an unsealed ionization chamber

For adverse environmental conditions, it is necessary to introduce a correction factor for air temperature and atmospheric pressure (Equation 4) between the measurement and the reference calibration conditions [12]:

$$C_{T,p} = \frac{p_0 \times T}{p \times T_0} \tag{4}$$

where p is atmospheric pressure during the test in in kPa; T is the ambient temperature during the test in K; p_0 is the reference atmospheric pressure (101.3 kPa) and T_0 is the reference ambient temperature (293.15 K).

1.4. Air kerma and ambient dose equivalent quantities

Radioprotection is a set of legal, technical and administrative measures that aim to reduce the exposure of living beings to ionizing radiation, to levels as low as reasonably achievable. In this area, the fundamental magnitude on which national gamma radiation standards are calibrated is air kerma, K_a [in Gray = Gy =J kg^{-1}]. In theoretical terms, the air kerma is the dE_{tr} quotient per dm, where dE_{tr}

is the sum of all the initial kinetic energies of all charged particles released by neutral particles or photons, incident on a *dm* mass of air [6].

According to CNEN NN 3.01-2011 [13], for strongly penetrating external radiation, the magnitude adopted for defined area monitoring is the ambient dose equivalent, $H^*(10)$ [in Sievert = Sv = J Kg-1], in a tissue equivalent phantom known as the ICRU sphere (International Commission on Radiation Units & Measurements). This magnitude refers to the value of the dose equivalent that would be produced by the corresponding expanded field and aligned in the ICRU sphere at depth d, in the radius that opposes the aligned field [5]. The recommended depth is 10 mm [9].

From the air kerma it is possible to determine all the operational quantities of current use in radioprotection, whose definitions and conversion factors are found in the literature. According to ISO 4037-3, the ambient dose equivalent rate, $H^*\dot{(10)}$, is measured indirectly and calculated from the air kerma rate, $\dot{K_a}$, according to Equation 5 [14].

$$H^*\dot{(10)} = h_K^*(10) \times \dot{K_a} \tag{5}$$

Specifically for a monoenergetic beam of cesium-137 (whose main gamma energy is defined as 662 keV) [4], the conversion factor $h^*_K(10)$ is equal to 1.21 Sv/Gy [14].

1.5. Time correction of quantities

Similar to the exponential decay of the activity of a radioactive source [9], the air kerma rate (and hence the ambient dose equivalent rate) must be corrected according to the lapse of time between the date of the initial measurement and the reference date (Equation 6). For comparative purposes in this study, the reference date was set as 04/06/2021, performing the radioactive decay between the original test date and the reference date:

$$\dot{K_a} = \dot{K_{a_0}} \times \exp\left[-\frac{\ln(2)}{t_{1/2}} \times \Delta t\right] \tag{6}$$

where $\dot{K_{a_0}}$ the initially measured air kerma rate, $\dot{K_a}$ the corrected air kerma rate after a period Δt between the reference date and the start date and $t_{1/2}$ the half-life time of Cs-137 (11018.3 days) [15].

2. MATERIALS AND METHODS

2.1. Materials

To perform the experimental analyses, a reference set previously calibrated in a competent laboratory was used, consisting of:

- 1 L ionization chamber (Manufacturer: PTW, model: TW32002, series nº: 528); and
- Electrometer (Manufacturer: PTW UNIDOS, model : Webline, series nº: T10022-999452).

To control environmental conditions, the temperature, humidity and pressure meter (Manufacturer: VAISALA, model: PTU 303, series nº: P1440563) was used.

Furthermore, the equipment and infrastructure of the IDQBRN itself (Figure 1) were used, such as an irradiation table and bench, laser positioning system, computers, among others. The use of the LabCal cesium-137 source irradiator (Manufacturer: VF NUCLEAR, model: IG-13)stands out, whose initial activity was 36.9 GBq on 01/22/2015. This source has an active ceramic core under double encapsulation with cylindrical geometry with dimensions of 8.0 mm in diameter and 12 mm in length [16].

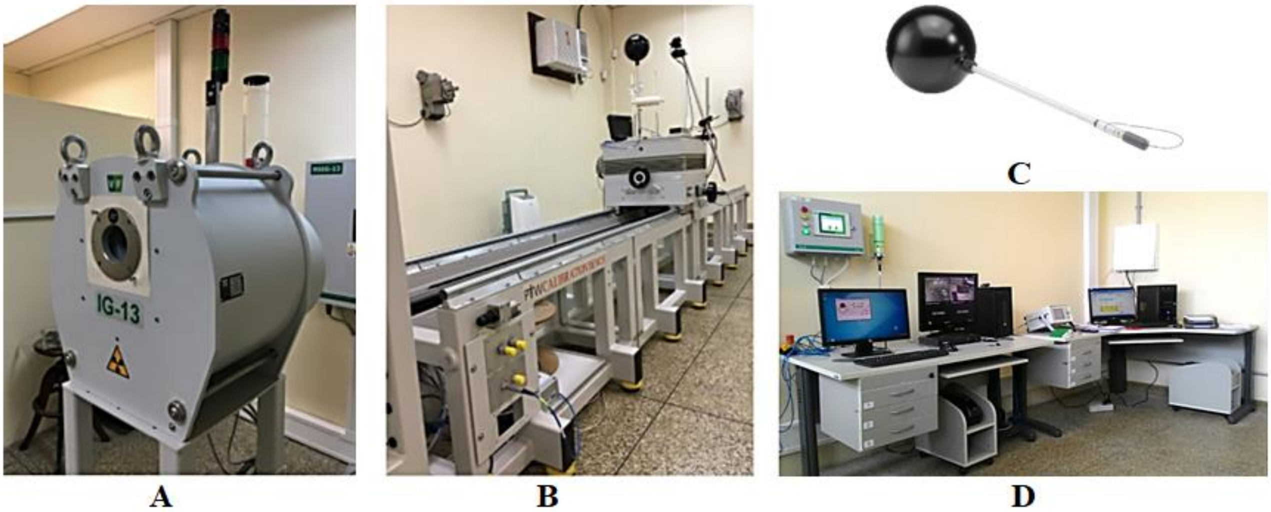

Figure 1: *LabCal infrastructure, being (A) Cs-137 radiator, (B) 3-axis manual positioning system and set of lasers for centralization, (C) calibrated measurement sets and (D) control system for source exposure.*
Source: Authors.

2.1.1 Measurement chamber assembly

The measure set (ionization chamber and electrometer) must be calibrated by a competent laboratory linked to the Brazilian Calibration Network (*Rede Brasileira de Calibração - RBC*).

The ionization chamber is one of the main dosimeters used for precision measurements, being considered a reference instrument for radiometric survey. They consist of a volume filled with an electrical and radiation-sensitive insulating gas and two collecting electrodes. The radiation incident in the chamber ionizes atoms in the sensitive volume of gas creating electrons and ions pairs. The electric field attracts these charged particles, generating a deposited electrical charge. Thus, the resulting electric current (related to the intensity of incident radiation) is measured by means of an electrical measurement device (electrometer) [17].

The electrometer quantifies the integrated electrical load during a certain period of irradiation of the ionization chamber [18]. Specifically, at LabCal, these devices are pre-programmed to account for the electrical charge over a period of 60 s.

The reference set used in this study was calibrated at the National Laboratory of Ionizing Radiation Metrology (*Laboratório Nacional de Metrologia das Radiações Ionizantes - LNMRI*) on 10/26/2020, resulting in an air kerma calibration factor (N_K) equal to 2.4987E+04 (Gy/C), obtained with average energy photons corresponding to cesium-137 [19].

2.1.2 Temperature, humidity and pressure meter

The equipment has thermometer, hygrometer and barometer integrated as measuring instruments for the control environmental conditions (temperature, relative humidity and atmospheric pressure, respectively). The parameters obtained in the meter are used to correct the test conditions (temperature and air pressure) in relation to the reference conditions. The equipment is periodically calibrated at each of these quantities by a laboratory designated by RBC [20].

2.2. Methods

Initially, the ionization chamber was fixed to the irradiation table at the reference point. In LabCal, the default position is 2000 mm distance between the dosimeter and the radioactive source (Figure 2).

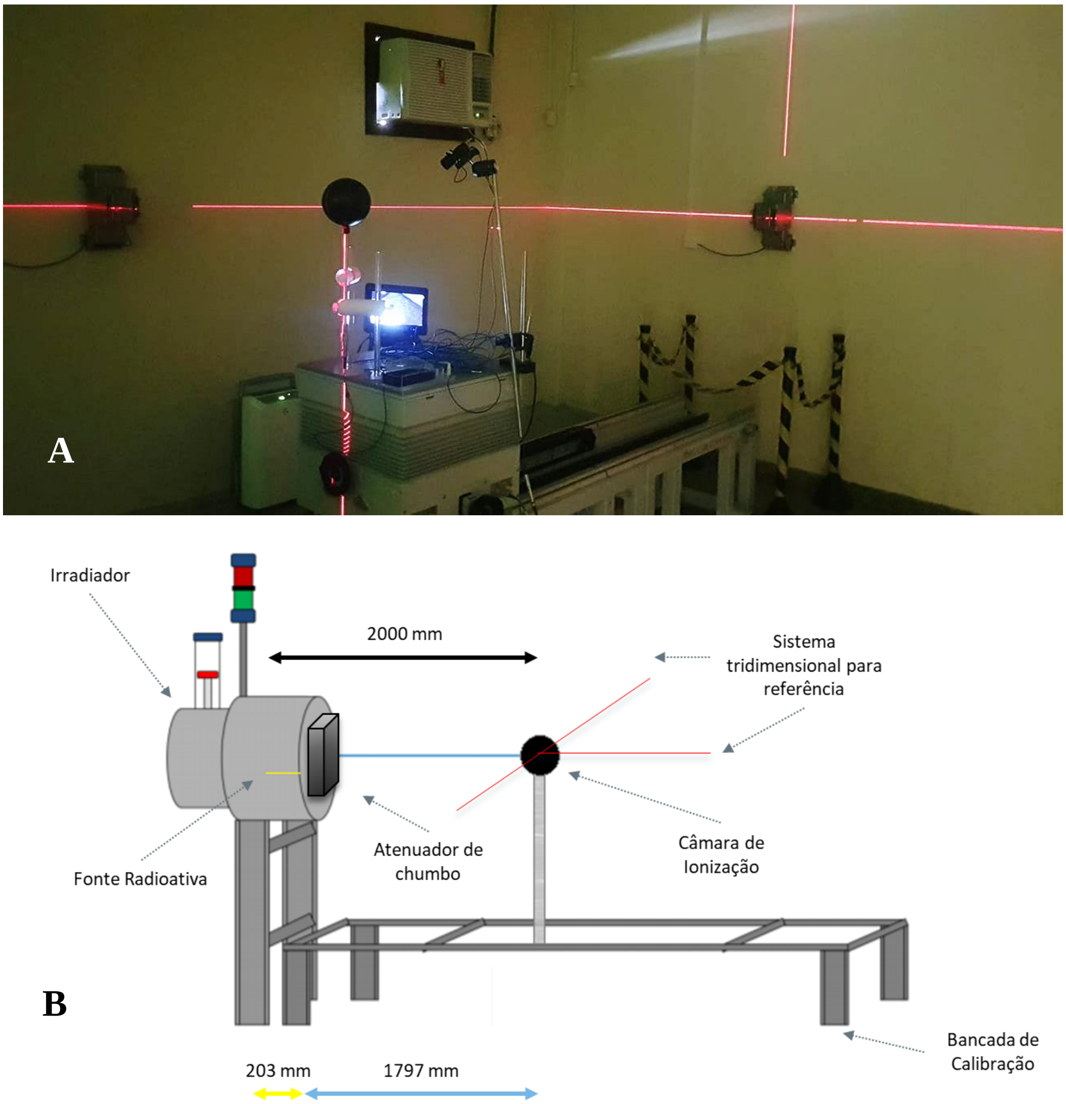

Figure 2: LabCal *experimental arrangement, highlighting the laser positioning system and the ionization chamber, photographed before exposure of the radioactive source in one of the tests performed (A). Scheme with distances of interest and the components presented and indicated (B).*
Source: Authors

Then, the distance between the detector and the irradiator was varied, moving the ionization chamber at the test points along the calibration bench (reference direction), at intervals of 250 mm from 500 to 3000 mm.

To decrease the upper and lower limits of the air kerma rate (compared to the case where there is no attenuator), lead attenuators with known thicknesses are used, thus seeking to obtain a wider and continuous range. Exposure without attenuator is represented by code A0. Lead attenuators with 15 mm and 32 mm are portrayed by code A15 and A32, respectively. Thus, 33 arrangements are defined, by varying the distances and attenuators, formed by 11 distance possibilities for each of the 3 attenuator possibilities. For each distance configuration and attenuators, the cesium-137 source is exposed in the irradiator according to internal protocols, measuring the electrical load collected in the ionization chamber for 60 s (pre-programmed in the electrometer), as well as the simultaneous conditions temperature, pressure and relative humidity during the test.

In the continuation, the average corrected current (Equation 7) is calculated at the end of ten replicates for each measuring point. The electrometer measures the Q_n value, referring to the electrical charge collected by the ionization chamber during the 60 s of the nth exposure. For each replicate, the temperature and pressure correction factor $(C_{T,p})_n$ (Equation 4) is applied based on the information provided by the temperature, humidity and pressure meter at the time of measuring Q_n [9].

$$\overline{I_c} = \frac{1}{10}\sum_{n=1}^{10}\left[\frac{Q_n}{60\ s} \times \left(C_{T,p}\right)_n\right] \tag{7}$$

In possession of the average corrected current value ($\overline{I_c}$), the respective air kerma rates explained in Equation 8 [9] are calculated, using the N_K value of the reference assembly [16], and the corresponding ambient dose equivalent rates, using the conversion factor (Equation 5) [11].

$$\dot{K_a} = N_K \times \overline{I_c} \tag{8}$$

For comparative purposes, the air kerma rates and the corresponding ambient dose equivalent rates for the reference date are corrected using radioactive decay (Equation 6).

Finally, it is mathematically treated the numerical values obtained experimentally in order to investigate if the real behavior resembles the ISL, thus being able to be validated the adopted premises[6]. In addition, there is the reproducibility of commissioning in accordance with normative instructions [4].

3. RESULTS AND DISCUSSION

3.1. Calculation of air kerma rate and ambient dose equivalent rate

For better exemplifying and understanding, the experimental measurements performed at 500 mm from the radiative source without the use of attenuator (A0) in Table 1 and the respective calculations of the air kerma rate and the ambient dose equivalent rate were explained in this study.

Table 1: Experimental data for 500 mm and A0 and calculation of quantities.

Repetition	**Electric Charge (nC)**	**Temperature (°C)**	**Pressure (kPa)**	**Currents Corrected (nC/s)**
1	7.482	18.85	101.312	1.242E-01
2	7.482	18.80	101.313	1.242E-01
3	7.478	18.89	101.315	1.242E-01
4	7.481	19.00	101.317	1.243E-01
5	7.477	19.14	101.318	1.243E-01
6	7.474	19.31	101.318	1.243E-01
7	7.470	19.46	101.311	1.243E-01
8	7.469	19.64	101.308	1.244E-01
9	7.466	19.68	101.308	1.243E-01
10	7.468	19.61	101.306	1.243E-01
Average corrected current (nC/s)				**1.242E-01**
Corrected current standard deviation (nC/s):			5.573E-05	
Coefficient of variation (%):			4.484E-02	
Standard deviation of the mean (nC/s):			1.762E-05	
Date of measurement (MM/DD/YYYY):			11/09/2020	
N_K (Gy/C):			2.4987E+04	
Conversion factor (Sv/Gy):			1.21	
Air kerma rate measured (mGy/h)				**11.178**
Ambient dose equivalent rate measured (mSv/h)				**13.526**
Reference date (MM/DD/YYYY):			04/06/2021	
Days elapsed:			148	
Half-life Cs-137 (days):			1.10183E+04	
Radioactive decay:			0.9907	
Air kerma rate corrected (mGy/h)				**11.075**
Ambient dose equivalent rate corrected (mSv/h)				**13.401**

Similarly, the same detailed procedure was performed for the other test points selected with exposures without attenuator. Data from 500 to 3000 mm with attenuator A0 are expressed in Table 2.

Table 2: Ambient dose equivalent rates for exposures without attenuator (A0).

Distance (mm)	Measurement Date (MM/DD/YYYY)	Measured ambient dose equivalent rate (mSv/h)	Reference Date (MM/DD/YYYY)	Corrected ambient dose equivalent rate (mSv/h)
500	11/09/2020	13.526	04/06/2021	13.401
750	11/10/2020	5.820		5.767
1000	11/10/2020	3.223		3.193
1250	11/11/2020	2.045		2.026
1500	11/11/2020	1.410		1.397
1750	11/12/2020	1.029		1.020
2000	11/12/2020	0.786		0.779
2250	11/12/2020	0.620		0.614
2500	11/12/2020	0.501		0.497
2750	11/12/2020	0.414		0.410
3000	11/12/2020	0.347		0.344

Similarly, the same procedure was performed with A15 and A32 for distance from 500 mm to 3000 mm, whose data are presented in Tables 3 and 4, respectively.

Table 3: Ambient dose equivalent rates for exposures with A15 attenuator.

Distance (mm)	Measurement Date (MM/DD/YYYY)	Measured ambient dose equivalent rate (mSv/h)	Reference Date (MM/DD/YYYY)	Corrected ambient dose equivalent rate (mSv/h)
500	11/09/2020	2.333	04/06/2021	2.311
750	11/10/2020	0.981		0.972
1000	11/10/2020	0.538		0.533
1250	11/11/2020	0.340		0.337
1500	11/11/2020	0.234		0.232
1750	11/12/2020	0.170		0.169
2000	11/12/2020	0.130		0.129
2250	11/12/2020	0.102		0.101
2500	11/12/2020	0.083		0.082
2750	11/12/2020	0.068		0.067
3000	11/12/2020	0.057		0.057

Table 4: Ambient dose equivalent rates for exposures with A32 attenuator.

Distance (mm)	Measurement Date (MM/DD/YYYY)	Measured ambient dose equivalent rate (mSv/h)	Reference Date (MM/DD/YYYY)	Corrected ambient dose equivalent rate (mSv/h)
500	11/09/2020	0.354	04/06/2021	0.350
750	11/10/2020	0.145		0.144
1000	11/10/2020	0.079		0.078
1250	11/11/2020	0.049		0.049
1500	11/11/2020	0.034		0.033
1750	11/12/2020	0.025		0.024
2000	11/12/2020	0.019		0.019
2250	11/12/2020	0.015		0.015
2500	11/12/2020	0.012		0.012
2750	11/12/2020	0.010		0.010
3000	11/12/2020	0.008		0.008

3.2. Plot of graphics

With tables 2, 3 and 4, and with the help of Excel software, in Figures 3, 4 and 5 are qualitatively represented the results referring to the methodology adopted in this study, in order to define the mathematical model that best describes the behavior of LabCal's cesium-137 irradiator system.

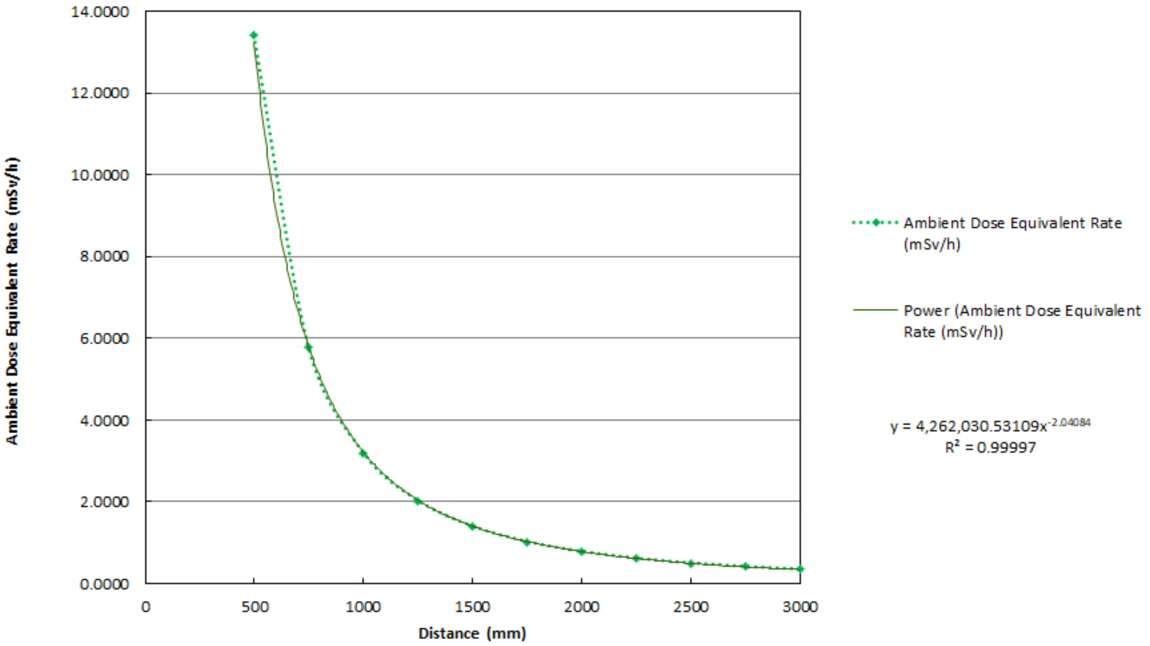

Figure 3: *Curve of experimental ambient dose equivalent rates for cesium-137 exposures without attenuation by distance variation and its power function.*

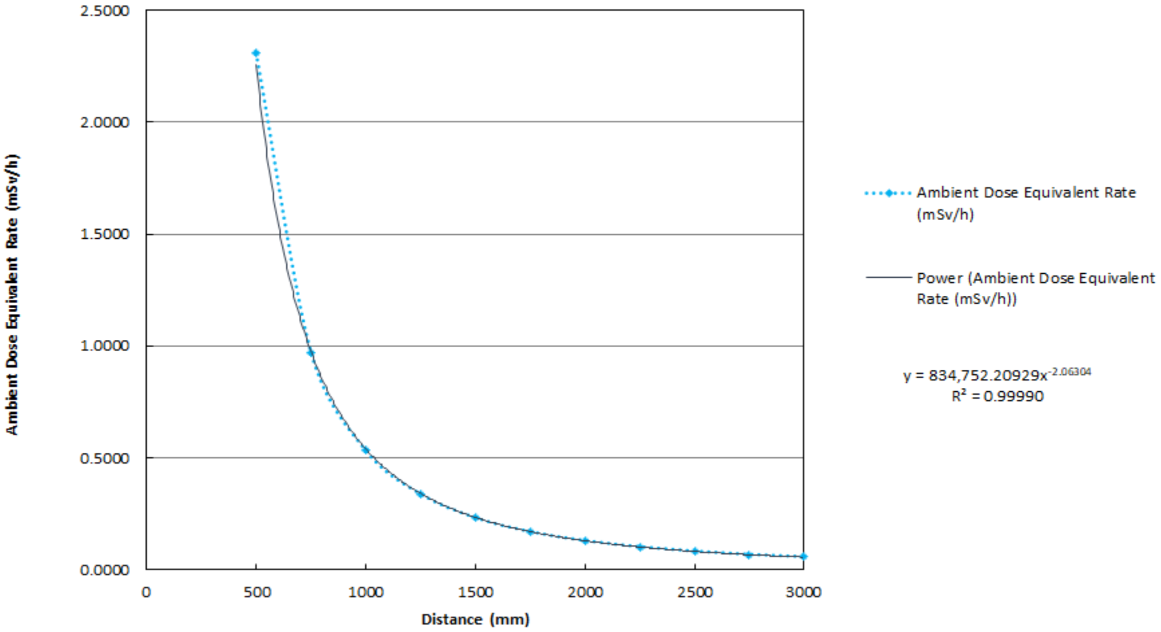

Figure 4: *Curve of experimental ambient dose equivalent rates for cesium -137 exposures with A15 attenuator by distance variation and its power function.*

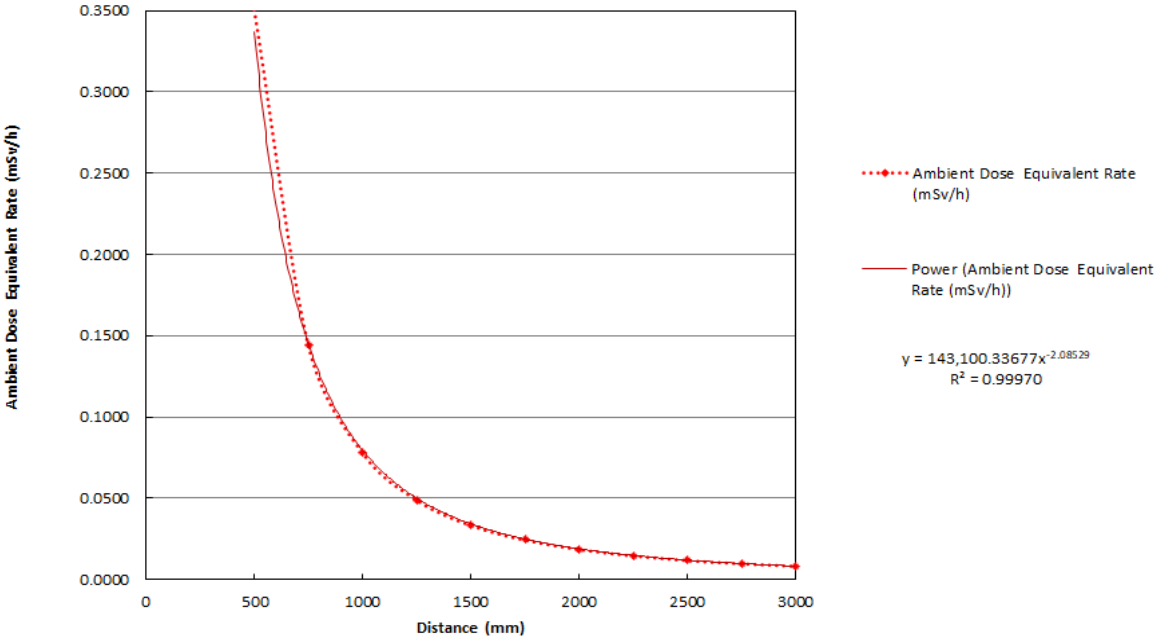

Figure 5: *Curve of experimental ambient dose equivalent rates for cesium -137 exposures with A32 attenuator by distance variation and its power function.*

By analyzing the graphs presented in Figures 3, 4 and 5, it is identified that the mathematical model that best fits the set of experimental data have characteristic of power function as represented in Equation 9.

$$Y(X) = B \times (X^A) \quad (9)$$

The coefficient of determination (R^2), which represents the measure of fit of a generalized linear statistical model, such as simple or multiple linear regression to the observed values, is also explained next to each graph mentioned above. Indeed , the mathematical models proved to be adequate to the experimental data, to the extent that the higher the R^2, the more explanatory the model adopted. The coefficients of determination of the three cases (A0, A15 and A32) are equal to 0.99997; 0.99990 and 0.99970, that is, close to 1, indicating that there is a polynomial relationship between the data obtained in this research - behavior acceptable from the theoretical point of view, since it is investigated an environmental dose equivalent rate varying with the distance according to the ISL. Therefore, the proposed mathematical model explains more than 99.97% of the total variation of the dependent variable from the independent variable of the model. In addition, the potential function model proved to be efficient to describe the behavior of the actual physical phenomenon under analysis.

It is also emphasized that, in all cases, the coefficients A obtained for the power functions (Equation 9) are approximately equal to -2, It is reiterated that the experiments performed are appropriate to the Law of the Square of the Inverse of distance; since the power functions significantly represent reality and have exponents close to -2, similar to Equation 3 for point sources [5]. That is, it is evident that the dimensions of the source geometry are despicable compared to the dimensions of the radiation field.

3.3. Irradiator system conformity check

Taking as reference the positioning at 2000 mm between the Source of cesium-137 and the ionization chamber, the LabCal conformity in this commissioning was investigated. To this goal, the calculated theoretical values and their respective values measured experimentally of the magnitude of the ambient dose equivalent rate were compared.

According to ISO 4037-1 [4], standard on radiological protection for dosimeter calibration and dose rate meters in gamma radiation, the measurements of the air kerma rate and, consequently, the ambient dose equivalent rate should be proportional within 5% of the respective theoretical values predicted through the ISL for various test points along the main axial axis. The distances of 1000 and 3000 mm on the reference date (04/06/2021) were chosen for this analysis.

Table 5: Calculation of relative deviations for the quantity ambient dose equivalent rate for A0, A15 and A32 tested at 1000 and 3000 mm.

Attenuator	Test	Distance (mm)	Ambient dose equivalent rate measured (mSv/h)	Ambient dose equivalent rate theoretical (mSv/h)	Relative deviation (%)
A0	Reference	2000	0.779	0.779	0.00
A0	1º Test	1000	3.193	3.117	2.43
A0	2º Test	3000	0.344	0.346	0.58
A15	Reference	2000	0.129	0.129	0.00
A15	1º Test	1000	0.533	0.515	3.37
A15	2º Test	3000	0.057	0.057	0.67
A32	Reference	2000	0.019	0.019	0.00
A32	1º Test	1000	0.078	0.074	4.85
A32	2º Test	3000	0.008	0.008	0.02

With the data collected from Tables 2, 3 and 4, Table 5 shows the relative deviation, in percentage, between the rate of ambient dose equivalent measured experimentally and the theoretical ambient dose equivalent rate, calculated by ISL (Equation 2), which represents the conventional true value.

It is emphasized that the relative deviations are less than 5% for all combinations of attenuators and selected distances. Thus, the conformity conference of LabCal's cesium-137 irradiator system was demonstrated in the light of ISO 4037-1 [4]

4. CONCLUSIONS

The research objective was achieved by checking between experimental values, mathematical models and theoretical foundation.

The results of this research showed that, for exposure without attenuator, the range of ambient dose equivalent rate found was 0.344 mSv/h to 13.401 mSv/h at the reference date. However, the use of lead attenuators with 15 and 32 mm allowed the extension of this range of magnitude to 0.008 mSv/h at 13.401 mSv/h, maintaining its continuity.

Another relevant finding is the indication of the power function to represent the behavior of the experimental data, due to the fact that the coefficient of determination of the three cases addressed in this research is approximately equal to the unit. In detail, the mathematical model proposed by the software (power function) proved to be adequate to describe the behavior of the actual physical phenomenon under analysis because it offers better fit. In the cases under study, the exponents obtained are approximately equal to -2. Thus, the results suggest that the experiments performed are in conformity with the Law of the Square of the Inverse of distance and that the geometric dimensions of the radiative source are despicable compared to the dimensions of the studied radiation field, in accordance with the expected theoretical behavior.

The work also allowed contributing in future time to the determination, through mathematical devices, of the necessary laboratory parameters (distance and attenuator) to exposure at a certain rate of normative environment ambient dose equivalent. This can be seen in Tables 2, 3 and 4 and in the graphs of Figures 3, 4 and 5 of this study. Therefore, it is perceived that this methodology (configuration determination) is essential to structure the calibration tests for gamma radiation monitors.

As a result of the results described in Table 5, it is possible to positively assess the conformity of LabCal's cesium-137 irradiator system, since the relative deviations obtained were within the normative limit of 5% in all cases evaluated.

Finally, in the continuation of the qualification of the Laboratory of Calibration of Gamma Radiation Monitors, the main objective of this work, the aim is to carry out other tests to compose the commissioning of the LabCal irradiator system, such as: influence of scattered radiation, uniformity radiation beam, field size, and head radiation leakage. In addition, concepts, studies and evaluations of uncertainties associated with the commissioning process and, consequently, with the calibration process will be inserted in the future.

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