Radioprotection 2022, 57(1), 71–77

https://doi.org/10.1051/radiopro/2021038

Available online at:
www.radioprotection.org

ARTICLE

Gamma-ray shielding calculations using empirical formulas for build-up factor: application to a practical case
To Professor J.J. Fletcher

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Received: 7 December 2021 / Accepted: 31 December 2021

Abstract – Exposure of people to external ionizing radiation is controlled by time, distance and shielding. In the latter case, the radiation dose is reduced if shielding attenuates the radiation. The present study was aimed at comparing gamma-ray shielding calculation methods, the well-known trial-and-error method and a direct calculation method that make use of build-up factor's empirical fitting formulas. The latter method was then applied to a practical case in gamma industrial radiography. The results showed that both methods provide comparable results. For high energies and high-density materials, it has been observed that all the build-up factor forms studied provide similar values. Contrariwise, it has also been observed that the linear form of the build-up factor seemed to underestimate shielding thickness for low gamma energies (lower than ≈ 1 MeV). Furthermore, the application of the method using empirical build-up factor functions to a practical case in gamma industrial radiography showed that the calculations are in agreement with the measurements carried out on the field. This demonstrates that this method is efficient and can still be used even though more sophisticated and accurate methods are now available.

Keywords: shielding / gamma-ray / build-up factor / air kerma / ambient dose equivalent

1 Introduction

Exposure of people to external ionizing radiation is controlled by three parameters: time, distance and shielding. The radiation dose received by individuals is proportional to the time they spent in the radiation field. The radiation dose is as well reduced substantially by increasing the distance from the source of radiation since it generally follows an inverse square law. Finally, the radiation dose is reduced if shielding attenuates the radiation (Podgorsk, 2005). Shielding design consists of three steps: (1) selecting a upper limit value for the effective dose in the occupied area (in general 0.5 μSv/h for a public area and 7.5 μSv/h for a supervised area); (2) estimating the radiation field in the occupied area considering only the unshielded radiation source; (3) obtaining the attenuation factor that is necessary to reduce the dose value from effective dose in (2) to the effective dose in (1). In a broad beam geometry, the measured dose rate will be greater than that described in a narrow beam geometry because scattered photons will also be detected. Such conditions usually apply to the shields required for protection from gamma-ray sources (Turner, 2012). Consideration of the build-up factor of gamma-rays is therefore essential for shielding calculations. The commonly used methods for computing accurate gamma-ray build-up factors are the iterative method, the invariant embedding method, the Monte Carlo method and the geometric progression (GP) method (Sharaf, 2015). Most of these methods are not only complicated but also time consuming. The GP fitting method is as good as the other method mentioned above and is relatively simple to apply. The only problem the persons interested in applying this method is that the fitting parameters, provided by the American Nuclear Society and the American National Standards Institutes, are not access free. Another alternative is the use of the trial-and-error method, which has been widely used so far and proven

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Fig. 1. The gamma radioactive source used during the evaluation. Here the source is either within a fixed box on the transport vehicle (a) or within a simple transportation box (b). Are also shown the survey meters used to measure ambient dose equivalent rates (c) and the accessories (d) – remote control, ejection cable and guide tube – for exposing the sealed gamma source.

Table 1. Gamma radioactive source used during the evaluation of the shielded enclosure.

Manufacturer	Model	Activity on 07/07/2021	Radionuclide
QSA Global Inc.	Sentinel	37 Ci	Ir-192

Table 2. Survey meters used during the evaluation of the shielded enclosure.

Type	Brand	Model	Date of last calibration	Dose rate range	Energy range
Portable spectrometer	ATOMTEX	AT6102A	15/06/2021	0.01 μSv/h–100 mSv/h	50–3000 keV
Personal radiation detector	RadEye	PRD	15/06/2021	≤ 250 μSv/h	60 keV–1.3 MeV

efficient in practice (Cember, 2009; Turner, 2012). The issue with this method is that it is difficult to apply for radiation sources emitting more than two gamma-ray energies.

This work, in its first part, compares the results obtained by the trial-and-error methods and those obtained by the use of empirical formulas to fit gamma-ray build-up factors. In the second part of the study, the latter method is applied to a practical case in gamma industrial radiography.

2 Materials and methods

2.1 Material

The features of the gamma radioactive source (Fig. 1) used during the evaluation of the shielded enclosure where radiography work is to be performed are presented in Table 1. The features of the survey meters used during this evaluation are given in Table 2.

3 Methods

Gamma-ray shielding calculations using empirical formulas for build-up factor are carried out. Depending on the case, either of the formulas below were used:

$$\dot{K}_a = \sum_i \frac{Af_iE_i}{4\pi d^2} B_i e^{-\mu_i x} \left(\frac{\mu_{en}}{\rho}\right)^i_{air}, \quad (1)$$

$$\dot{H}^*(10) = \sum_i \frac{(H^*(10)/K_a)_i Af_iE_i}{4\pi d^2} B_i e^{-\mu_i x} \left(\frac{\mu_{en}}{\rho}\right)^i_{air}, \quad (2)$$

where $\dot{K}_a$ and $\dot{H}^*(10)$ are, respectively, the air kerma rate and the ambient dose equivalent rate calculated at distance d from the gamma radioactive source considered as punctual (the dimensions of the source are negligible compared to the distance d), $(H^*(10)/K_a)_i$ is the air kerma, K_a, to ambient dose equivalent, $H^*(10)$, conversion coefficient. The conversion coefficient corresponding to gamma energy E_i were determined from the values given in ISO 4037-3 (ISO, 1999) standard for monoenergetic photon radiation using linear interpolation where needed; f_i is the gamma emission probability for energy E_i. Values of f_i and E_i for the radionuclides used in this work were taken from reference (IAEA, 2007). Particularly, those for Ir-192 are given in Table 3. A is the activity of the gamma source, B_i is the build-up

Table 3. Gamma energies and the corresponding emission probabilities used in the present study for Ir-192 (IAEA, 2007).

Energie (keV)	f (%)
205.79	3.34
295.96	28.72
308.46	29.68
316.51	82.75
468.07	47.81
484.58	3.19
588.58	4.52
604.41	8.20
612.46	5.34

factor for energy E_i, μ_i is the linear attenuation coefficient for energy E_i and the relevant material, $\left(\frac{\mu_{en}}{\rho}\right)^i_{air}$ is the mass-energy absorption coefficient in air for energy E_i, x is the shielding material thickness; μ_i and $\left(\frac{\mu_{en}}{\rho}\right)^i_{air}$ were determined from values provided by the National Institute of Standards and Technologies (NIST). The forms of build-up factor used in the study are as follows:

– Linear

$$B(E, \mu x, m) = 1 + k_0(E)\mu x, \tag{3}$$

– Quadratic

$$B(E, \mu x, m) = 1 + k_1(E)\mu x + k_2(E)(\mu x)^2, \tag{4}$$

– Berger

$$B(E, \mu x, m) = 1 + k_3(E)\mu x e^{-\lambda_0 \mu x}, \tag{5}$$

– Taylor

$$B(E, \mu x, m) = k_4(E)e^{-\lambda_1 \mu x} + (1 - k_4)e^{-\lambda_2 \mu x}, \tag{6}$$

where $B\ (E,\mu x,m)$, which is a function of the energy E of the gamma-ray incident on the shielding, the shielding material m and the shielding thickness x (or the mean free path μx), is the build-up factor, k_r, $r = \{0, 1, 2, 3, 4\}$, et λ_j, $j = \{0, 1, 2, 3\}$ are constants, given in reference (Trubey, 1966), that are function of energy E and shielding material.

In general, the goal is to determine the shielding thickness x given a known dose rate $\dot{H}^*(10)$ at a known distance d from the gamma la source. Equation (1) can be solved either by writing a computer program or by using an Excel sheet in which x is gradually increased, from the initial value $x = 0$ cm (unshielded source), until the desired dose rate value is reached. In the present work, the use of the second option (Excel sheet) was preferred.

Sometimes, one's maybe interested in finding the distance d associated with either a controlled, a supervised or a public area whose corresponding dose rate values are set by the regulatory body.

The first part of the work consisted of calculating shielding thickness from some selected situations that has been dealt with in the literature (Cember, 2009; Turner, 2012) and then comparing the results obtained. These situations are listed below:

– Situation 1

Determining the lead thickness needed if the air kerma rate at a distance of 1 m from a 1-Ci ^{137}Cs point source is not to exceed 25 µGy/h.

– Situation 2

Calculating the thickness of a lead shield needed to reduce the air kerma rate 1 m from a 10-Ci point source of ^{42}K to 21.9 µGy/h (2.5 mR/h).

– Situation 3

Determining the water depth needed if the air kerma rate at a point 6 m directly above a 10-Ci point source of ^{24}Na is not to exceed 175.2 µGy/h (20 mR/h).

– Situation 4

Finding the lead thickness needed to attenuate the air kerma rate from a 1-Ci point source of ^{24}Na to 87.6 µGy/h (10 mR/h).

In the second part of the work, field measurements were carried out on the site where the shielded enclosure is located (Fig. 2).

The shielded enclosure has a length of 10.60 m, a width of 4.60 m and a height of 3 m. It is made of demountable ordinary concrete walls of 30 cm thick (Fig. 3). Ambient dose equivalent rates measurements were taken as illustrated in Figure 3. A 37-Ci ^{192}Ir source and a collimator of attenuation 1/250th were used during the evaluation. The beam was directed towards the floor since the operator made the choice to carry out radiography work only in this configuration.

4 Results and discussion

4.1 First part

The results obtained for the four situations mentioned previously are presented in Tables 4–7. The first observation is that values provided in this study, for all the build-up factor forms, are consistent with those provided in references (Cember, 2009; Turner, 2012) which were determined by the use of the trial-and-error method. It is also observed, as shown in the results for situation 1, that the linear form of the build-up factor seems to underestimate shielding thickness for low gamma energies (lower than ≈ 1 MeV). This form of the build-up factor seems to provide the larger shielding thickness for high energies (greater that ≈ 1 MeV) and low-density materials (*e.g.*, results for situation 3). For high energies and high density materials, all the build-up factor forms studied in the present work provide similar values (*e.g.*, results for situations 2 and 4).

Fig. 2. Image of the shielded enclosure subject to testing.

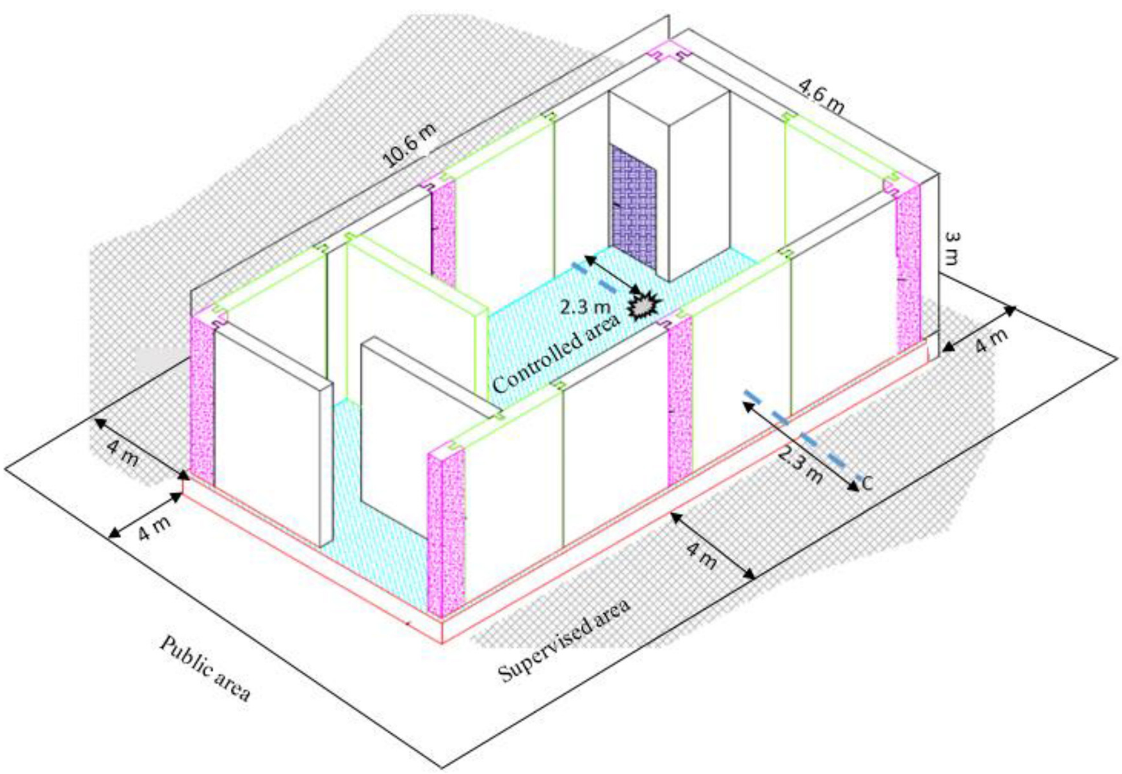

Fig. 3. Configuration of the shielded enclosure. Dose equivalent rates were measured at point C, about 4.6 m from a 37-Ci ^{192}Ir source.

Table 4. Comparison of the results for situation 1.

Situation 1; target dose rate: 25 μSv/h				
	Calculated dose rate (μGy/h)	Build-up	*mfp***	Calculated thickness (cm)
(Cember, 2009)*	26	2.12	5.50	4.40
		This study		
Linear	24.95	1.81	5.32	4.12
Quadratic	24.89	2.09	5.46	4.23
Berger	24.91	2.17	5.50	4.26
Taylor	24.73	2.24	5.53	4.29

* The problem is solved in (Cember, 2009) using the trial-and-error (add-one-*HVL*) method; *HVL* stands for half-value layer.
** $mfp = \mu x$, stands for mean free path.

Table 5. Comparison of the results for situation 2.

Situation 2; target dose rate: 21.9 μGy/h (2.5 mR/h)				
	Calculated dose rate (μGy/h)	Build-up	*mfp***	Calculated thickness (cm)
(Turner, 2012)*	21.62	3.6	7.60	13
		This study		
Linear	21.80	3.47	7.54	12.79
Quadratic	21.81	3.54	7.55	12.82
Berger	21.89	3.59	7.57	12.84
Taylor	21.85	3.80	7.62	12.94

* The problem is solved in (Turner, 2012) using the trial-and-error method (different from the add-one-*HVL* method).
** $mfp = \mu x$, stands for mean free path.

Table 6. Comparison of the results for situation 3.

Situation 3; target dose rate: 175.2 μGy/h (20 mR/h)					
	Gamma energy (keV)	Calculated dose rate (μGy/h)	Build-up	*mfp***	Calculated thickness (cm)
(Turner, 2012)*	2750	146.29	4.80	4.70	109
	1370	30.66	15	6.70	
		This study			
Linear	2754.01	137.47	5.30	4.77	113.40
	1368.63	37.68	19.25	6.86	
Quadratic	2754.01	144.54	4.72	4.61	109.44
	1368.63	30.63	12.31	6.62	
Berger	2754.01	146.10	4.55	4.56	108.33
	1368.63	29.08	10.93	6.56	
Taylor	2754.01	145.82	4.59	4.57	108.57
	1368.63	29.36	11.20	6.57	

* The problem is solved in (Turner, 2012) using the trial-and-error method (different from the add-one-*HVL* method).
** $mfp = \mu x$, stands for mean free path.

Table 7. Comparison of the results for situation 4.

Situation 4; target dose rate: 87.6 μGy/h (10 mR/h)					
	Gamma energy (keV)	Calculated dose rate (μGy/h)	Build-up	*mfp***	Calculated thickness (cm)
(Cember, 2009)*	2750	74.46	3.4	6.3	13
	1370	6.13	3.6	8.2	
This study					
Linear	2754.01	80.08	4.00	6.21	12.64
	1368.63	7.15	3.45	7.98	
Quadratic	2754.01	78.50	3.29	6.03	12.28
	1368.63	9.08	3.49	7.75	
Berger	2754.01	78.31	3.33	6.05	12.31
	1368.63	9.10	3.56	7.77	
Taylor	2754.01	77.80	3.34	6.06	12.33
	1368.63	9.56	3.79	7.78	

* The problem is solved in (Cember, 2009) using the trial-and-error (add-one-*HVL*) method; *HVL* stands for half-value layer.
** $mfp = \mu x$, stands for mean free path.

Table 8. Comparison of measurements results with those computed from the various forms of build-up factor.

37-Ci Ir-192 source					
	Measurements	Linear	Quadratic	Berger	Taylor
$\dot{H}^*(10)$ (μSv/h)	0.64 ± 0.12	0.54	0.56	0.66	0.78

4.2 Second part

In this section, the results for the calculations are compared with measurements carried out in the field at a distance of about 4.6 m from the source, outside the shielded enclosure whose walls have a thickness $x = 30$ cm. The source was exposed with the use of a collimator of attenuation 1/250th, the beam being directed towards the floor. Results are given for the various forms of build-up factor used (Tab. 8).

These results show that the calculations are in agreement with the measurements carried out around the shielded enclosure. Indeed, the calculated ambient dose equivalent rates are in the range [0.53 μSv/h, 0.76 μSv/h] of the measurements performed, apart from the value calculated using the Taylor form of the build-up factor. This value is just above the measurement interval and, as such, may constitute the most conservative case from which radiation protection measures should be taken (*e.g.*, delineation of areas).

Based on calculations for the different forms of build-up factor used in the present work, delineation of areas was carried out (Tab. 9) for the case of a 40-Ci ^{192}Ir source as the shielded enclosure was approved by the regulatory body for a maximum activity not greater than this value. As expected, Taylor's form of build-up factor provided the largest restricted areas. Based on Taylor's formula of build-up factor, zoning should be carried out using values given in Table 9. For radiation protection reasons, these values were rounded up as shown in Figure 3. For these same reasons, the inside of the shielded enclosure is considered a controlled area.

The delineation of area was undertaken taking into account the use of a collimator of attenuation 1/250th and the fact that the beam was directed towards the floor. This configuration, as shown in the present study, reduces the zoning distance around the radiation source and may limit the skyshine effect. If, for any reason, the beam is directed to any wall, the zoning provided in this study will no longer be valid. Values in Table 9 for exposure of the source without collimator shall be used. However, the environment around the shielded enclosure does not allow this (Fig. 2). This means that additional shielding will be needed. Adding lead shielding on the interior surface of the shielded enclosure may be an appropriate solution.

5 Conclusion

This work was aimed at comparing gamma-ray shielding calculation methods, the well-known trial-and-error method and a direct calculation method that make use of build-up factor's empirical fitting formulas. The latter method was then applied to a practical case in gamma industrial radiography. It has been shown that both methods provide comparable results. Furthermore, the application of the method using empirical build-up factor functions to a practical case in gamma industrial radiography showed that the calculations are in agreement with the measurements carried out in the shielded enclosure. This demonstrates that this method is efficient and can still be used even though more sophisticated and accurate methods are now available.

Table 9. Delineation of areas around the shielded enclosure for a ^{192}Ir source of 40 Ci maximum activity.

	Distance (m)		
	Public area	Supervised area	"Green" controlled area
Linear			
With collimator	4.98	1.29	0.35
Without collimator	78.79	20.34	11.14
Quadratic			
With collimator	5.08	1.31	0.36
Without collimator	80.38	20.75	11.37
Berger			
With collimator	5.48	1.41	0.39
Without collimator	86.64	22.37	12.25
Taylor			
With collimator	5.96	1.54	0.42
Without collimator	94.16	24.31	13.32

Based on the field measurement configuration, a delineation of areas was carried out which would no longer be valid if, for any reason, the configuration is to be changed.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This work has received operational support from the General Directorate of Radiation Protection and Nuclear Safety, Ministry of Energy and Hydraulic Resources, Gabon.

Ethical approval

Ethical approval was not required.

Informed consent

Informed consent was not required.

Authors contributions

P. Ondo Meye: Conceptualization, methodology, data acquisition and analysis, manuscript drafting. C. Chaley: Data acquisition and analysis, reviewing. S. Y. Loemba Mouandza: Methodology, data analysis, reviewing. B. C. Mabika Ndjembidouma: Data analysis, reviewing. G. H. Ben-Bolie: Supervision, reviewing.

Acknowledgements

The authors are grateful to the anonymous reviewers for helping improve the work through their invaluable suggestions.

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Cite this article as: Ondo Meye P, Chaley C, Loemba Mouandza SY, Mabika Ndjembidouma BC, Ben-Bolie GH. 2022. Gamma-ray shielding calculations using empirical formulas for build-up factor: application to a practical case To Professor J.J. Fletcher. *Radioprotection* 57(1): 71–77