CONTRIBUTION TO THE ISSUES CONNECTED WITH THE INTERACTION BETWEEN γ-PHOTONS AND SHIELDING MATERIALS

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Received 30 April 2017; accepted 15 May 2017

1. Introduction

The optimisation of radiation protection is a crucial task in the applications of ionising radiation as well as within the decommissioning of nuclear installations. To carry out the analysis of radiation situation and/or to propose the appropriate shielding, the data regarding the source term, shielding geometry and material composition are inevitable.

Based on the aforementioned data it is possible to calculate the dose rate at a point by several analytical expressions (e.g. Sievert integral function [1]) and their (often numerical) solution. However, these expressions take into account uncollided (unscattered) photons only. In the real case, the scattering of the photons occurs (by Compton scattering, Bremsstrahlung and annihilation radiation [1]). This phenomenon leads to increase of the photon fluency rate (and thus the dose rate) at the point of interest and has to be corrected.

The calculation of effective doses can be carried out in two ways in general – either by using **stochastic** or **deterministic** methods [2] , [3] . The **stochastic methods** applying Monte Carlo method (e.g. MCNP code) investigate the transport of each photon in the defined system by solving the transport equation (the Boltzmann transport equation) [2] , [4] . The main advantage of this method is the high accuracy of the calculations, however, the calculation time is usually very large and the user interface is not very comfortable to carry out the complex analyses of radiation situation. On the other hand, there are **deterministic methods** like point kernel method. This method assumes that a volume source consists of finite number of point sources and thus the photon fluency rates as well as the dose rates are calculated as a sum of the contributions from each point source. This point kernel method is implemented in codes such as VISIPLAN 3D ALARA, MicroShield or MERCURAD. These codes are more user-friendly than MCNP code and the calculation times are shorter. On the other hand, the calculations are less precise and the **results have to be corrected by** so-called **buildup factors (BUF)** [2] , [3] .

From the aforementioned facts it is obvious that the **stochastic methods** can be considered as **reference** and can be also **applied for the calculation of buildup factors**.

2. Basic characterisation of buildup factor

The simple and very general definition of BUF can be found in [5] :

$$BUF = \frac{\begin{array}{c} some\ desired\ property \\ (particle\ flux, energy\ flux, dose, etc.) \\ of\ the\ total\ \gamma\ ray\ flux\ at\ R \end{array}}{same\ property\ due\ to\ the\ uncollied\ flux\ at\ R} \tag{1}$$

The more detailed definition of BUF is according to [4] :

$$BUF = \frac{R}{R^0} = \frac{\int_0^{E_0} dE\mathcal{R}(E)\phi(r,E)}{\mathcal{R}(E)\phi^0(r)}, \quad (2)$$

where:
- R is the detector response,
- R^0 corresponds to the response to uncollided photons,
- $\mathcal{R}(E)$ represents the detector response function,
- $\Phi(r, E)$ is the flux density of photons of energy E at a distance of r from a point source,
- $\Phi^0(r)$ represents the flux to uncollided photons at a distance r.

The other similar definitions of BUFs can be found for example in [2] and [6] . From the Eq. (2) it is obvious that the BUFs are not constants but depend on many parameters.

2.1 Methods for buildup factor calculations

The buildup factors obtained from the calculations by stochastic methods are for the specific cases, i.e. almost exclusively for point-isotropic and monoenergetic sources in infinite media [6] . In addition, the values are given for specific photon energies and specific thickness of shielding. From these reasons the different approximation methods were developed to calculate the buildup factor for a specific energy [1] , [4] , [5] , [6] , [7] :

- **Linear form** – probably the oldest formula,
- **Taylor form** – a frequently used form (e.g. in VISIPLAN 3D ALARA, MicroShield). This can be expressed by the following equation [1] , [5] :

$$BUF(E, \mu R) = Ae^{-\alpha_1(E)\mu R} + (1 - A)e^{-\alpha_2(E)\mu R} = \sum A_n e^{-\alpha_n \mu R}, \quad (3)$$

where:
- E represents the source energy,
- μ is the linear attenuation coefficient, evaluated at the source energy E,
- R is the distance from the source,
- A, α_1, α_2 parameters obtained from the respective tables.

- **Polynomial form**,
- **Empirical Linear and Quadratic forms**,
- **Berger form,**
- **Semi-logarithmic interpolation** – used in MERCURAD code,
- **Geometric Progression Approximation (GPA)** – more modern, more accurate form developed by Harima et al. [6] :

$$BUF(E_0, \mu r) \cong 1 + \frac{(b-1)(K^{\mu r}-1)}{K-1}, K \neq 1 \quad (4)$$

$$BUF(E_0, \mu r) \cong 1 + (b-1)\mu r, K = 1, \quad (4)$$

where $$K(\mu R) = c(\mu R)^a + d\frac{\tanh\left(\frac{\mu r}{\xi}-2\right)-\tanh(-2)}{1-\tanh(-2)}, \quad (5)$$

in which a, b, c, d and ξ are parameters dependent on the gamma-ray energy, the attenuating medium and the nature of the response. The selection of these data is for example in [6] . It has to be emphasised that r in Eq. (4) and (5) is in the number of mean free paths (MFP), i.e. the thickness of a shielding medium must be divided by the average mean-free path of the photons of definite energy in the respective medium.

The above mentioned formulas were for buildup factors of single shield. However, in the real situations there are very often so-called **multi-layered shields** or **laminated materials**, i.e. a shielding consists of more materials with different thickness. If the outer layer of a laminated shield is 2 or 3 mean free paths thick, the buildup factor for this outer shield can be applied [5] . However, in the cases when the thickness of outer layer is less than about 2 mean free paths, the aforementioned consideration may be inadvisable [5] . For such cases several formulas were developed [5] :

- Bowman-Trubey formula,
- Kalos formulas,
- Broder formula,
- Kitazume formula,
- Harima-Nishiwaki formula.

It is necessary to emphasize that the **overall BUF depends also on the order of shielding materials**. When 2-layer shields are considered of optical thicknesses (mean free paths) l_1 and l_2 and effective atomic number Z_1 and Z_2 numbered in the direction from source to detector [6] , among the above mentioned formulas the following rule can be commonly applied [6] :

- **If $Z_1 < Z_2$** then the overall buildup factor is approximately equal to the buildup factor B_2 for material 2 evaluated at the total optical thickness $l_1 + l_2$.
- **If $Z_1 > Z_2$** then the overall buildup factor is the product $B_1(l_1)* B_2(l_2)$.

3. Basic description of used calculation tools

In this chapter a brief overview of the calculation tools applied in the field of planning of radiation protection is given.

3.1 MicroShield

The code was developed by the company Grove Software, Inc. The modelling of the radiation situation is possible by selection of pre-defined volumes and shielding geometries. The code uses either Grove or ICRP-38 library for the data regarding the emission of photons (energy, probability). The buildup factors are related to pre-defined materials stated in ANSI/ANS-6.4.3-1991 standard, the dose conversion coefficients are from ICRP 51 [8] .

3.2 VISIPLAN 3D ALARA

The code was developed in Belgian company SCK-CEN and is a more suitable to be applied within different tasks than MicroShield since it offers more combination of source/shielding geometries. The attenuation coefficients as well as the parameters of Taylor form for buildup factors assessment are taken from ANSI/ANS-6.4.3-1991 standard. Similarly as in the case of MicroShield, the dose conversion factors for different irradiation geometries are taken from ICRP 51 [9] .

Both of the codes require the selection of BUFs manually by the user. In the case of multi-layered shield there is a question that buildup factor of which shield should be considered. Both codes offer the result without and with buildup factor. This can be useful for assessment of the influence of the buildup factors on the results within the studied case. Should be there a big difference between the dose rates without and with buildup factor, the further investigation is necessary.

The general rule is to use either the last shield between the source and the dose point or the most dominant shield (that is, the one with the most mean free paths) [8] .

The different approach is applied in MERCURAD code which automatically chooses the appropriate buildup factor. For a multi-layered shield the code uses an iterative process together with neural networks [7] .

4. The characterisation of the studied case

In this analysis, the influence of the relative position of the shielding on the dose rate was studied. The dimensions of the source (cylinder with approx. 1 cm height and 0.5 cm of diameter) can be neglected (the distance from the detector is at the order of tens of cm) and thus it is considered as a **point source**. The **source term** is ^{137}Cs with the activity of 3.09×10^{7} Bq. The effective **distance** between the source and the detector is 32.96 cm. The **shielding** consists of iron plate with the thickness of 2.15 cm. The **detector** is type RT-30 (RS 220) Super-Ident from the Czech company GEORADIS and within the measurements the NaI(Tl) scintillation crystal was used (cylindrical volume with diameter and height of 51 mm) [10] . In each measurement 190 values (1value per second) were evaluated. The considered uncertainty of the measurement is 20%.

The **measurement** of the dose rates consists of the following steps:

- Measurement of the background – the average value is substracted from the average values of other measurements.
- Measurement with the source only.
- Measurement with the shielding in front of the source.
- Measurement with the shielding in front of the detector.

Subsequently, the calculations of the dose rates were performed using VISIPLAN 3D ALARA and MicroShield codes considering the conditions of the measurement. During the calculations, the influence of 4 values of buildup factors was investigated: BUF of air, BUF of iron (shielding) and 2 BUFs obtained from Eq. (4) and (5) and from the assumptions depicted at the end of Chapter 2.1. The values of parameters *a, b, c, d* and ξ were taken from [6] for photons energy of 0.600 MeV.

5. Results and Discussion

The results of the measurement and the calculations are depicted in Tab. 1 and Tab. 2. From the depicted data the following can be stated:

- In the case of iron shielding in front of the source the measured dose rate is bigger than in the case of iron shielding in front of the detector. This can be expected because the layer of iron following the air rapidly absorbs the scattered photons produced in the air [5] .
- **The importance of the sequence of the materials** (air and iron) **is not reflected in the calculations**. This presents one of the disadvantages of VISIPLAN 3D ALARA and MicroShield codes.
- In the case when no shielding is present, there is a negligible difference between the calculated results with and without BUF. However, the values obtained from the codes are higher than the measured ones. This is due to the fact that the codes are aimed on the estimation of radiation situation for radiation protection purposes and thus are quite conservative.
- In both cases when iron shielding is present it can be seen that the results without any BUFs are underestimated. On the other hand, when BUF for air is applied, the calculated dose rates are much overestimated. The main reason is that the MFP of 0.600 MeV photons in the air is about 102 m which is much more than the distance in the experiment (about 30 cm). The similar can be said in the case of BUF of iron (MFP 1.67 cm), however, the difference is lower.
- Appling the BUFs obtained from GPA, the results are within the confidence interval of the measurement.

Tab. 1. *Measured and calculated dose rates. Legend: SH – shielding, BCG – background*

Geometry	**Measured dose rates [mSv/h]**		**Calculated dose rates [mSv/h]**							
			MicroShield				**VISIPLAN 3D ALARA**			
	With BCG	**Without BCG**	**Without BUF**	**BUF air**	**BUF iron**	**BUF GPA**	**Without BUF**	**BUF air**	**BUF iron**	**BUF GPA**
Without SH	1.80E-02	1.78E-02	2.08E-02	2.09E-02	-	-	2.20E-02	2.20E-02	-	-
SH in front of the source	1.01E-02	9.89E-03	5.70E-03	1.64E-02	1.30E-02	9.76E-03	6.10E-03	2.80E-02	1.60E-02	1.04E-02
SH in front of detector	9.27E-03	9.11E-03	5.70E-03	1.64E-02	1.30E-02	9.75E-03	6.10E-03	2.80E-02	1.60E-02	1.04E-02

Tab. 2. *Comparison of the measured and calculated dose rates.*

Geometry	**Relative deviation** [(calculated-measured)/measured*100]							
	MicroShield				**VISIPLAN 3D ALARA**			
	Without BUF	**BUF air**	**BUF iron**	**BUF GPA**	**Without BUF**	**BUF air**	**BUF iron**	**BUF GPA**
Without SH	16.93%	17.27%	-	-	23.50%	23.50%	-	-
SH in front of the source	-42.35%	65.56%	30.97%	-1.33%	-38.31%	183.19%	61.82%	5.60%
SH in front to of the detector	-37.43%	79.71%	42.16%	7.07%	-33.04%	207.38%	75.65%	14.58%

6. Conclusion

The use of the deterministic methods of dose rate calculations is often practical in the radiation protection assessments. However, in this case the application of BUFs is inevitable. Based on the review as well as from the presented results it can be useful to present the calculated results for the smallest and largest BUFs of the individual shielding materials [5] . Moreover, the formulas for BUFs calculation are based on the so-called ray theory, i.e. that the photon beam is perpendicularly incident on the detector [6] . However, in the real situations, studied in detail e.g. in [11] , the obliquely incident beams are present. This requires the application of the modified BUFs depending also on the angle of incidence [6] .

In conclusion it can be stated that the results of deterministic calculations methods are quite conservative. However, when the measured dose rates are available, the sufficient methods could be applied to decrease the overestimation of the calculation results.

Acknowledgement

The authors would like to thank Mr. Andrej Slimák from the company VUJE, a.s. for many useful comments. This project has been partially supported by the Slovak Grant Agency for Science through grant VEGA 1/0863/17, by the Slovak Research and

Development Agency through grant APVV-15/0558 and by the Ministry of Education by decree CD-2009-36909/39460-1:11 within the bounds of project CONRELMAT.

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