Annals of Nuclear Energy 57 (2013) 246–255

Contents lists available at SciVerse ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

An inverse calculation technique for optimization of gamma ray shielding designs

K.V. Subbaiah [a], L. Thilagam [b,*], R. Sarangapani [c], D.K. Mohapatra [b]

[a] Manipal Centre for Natural Sciences, Manipal University, Manipal 576 104, India
[b] AERB-Safety Research Institute, Kalpakkam 603 102, India
[c] Radiological Safety Division, IGCAR, Kalpakkam 603 102, India

A R T I C L E I N F O

Article history:
Received 4 September 2012
Received in revised form 28 January 2013
Available online 8 March 2013

Keywords:
Gamma ray shielding
SHIELD DESIGN code
Inverse calculation technique
Iterative procedures

A B S T R A C T

A new computer code named as SHIELD DESIGN has been developed in Visual Basic Version 6.0 for precise estimation of shielding thickness in gamma ray shielding designs. In the conventional forward calculations using point kernel method, the sources and geometry are specified along with the shield thickness to obtain dose rates at desired locations. But in this code, a new computational technique based on inverse calculation and iterative procedures have been employed to estimate the shield thickness using the dose rate criteria as input information. This new technique enables quicker and easier way of shield design optimization by computing shield thickness required in a single run whereas in the forward shield design optimization method, dose rate computations need to be carried out for various shield thicknesses. The shielding thickness arrived with this code provides a first hand information to the designer to carry out forward calculations for accurate optimization. Also, the code is very useful to regulators for quicker verification of shield calculations submitted by the designers for approval. Further, various options available in this code extend its flexibility and user friendliness. This paper briefly presents the development and validation of the code, SHIELD DESIGN. The validation has been carried out by performing analyses of the gamma shielding design for some standard problems. The results were compared with those of renowned forward calculations, experimental measurements, NCRP-51 benchmarks and other gamma radiation shielding utilities like RAD-PRO and satisfactory agreement was observed. These validation tests demonstrate the precise estimation of shield thickness.

1. Introduction

Radiation shielding computer codes need to be developed with the newer algorithms for the quicker optimization of shield design with the choice for materials of efficient shield characteristics. This study introduces a new computer code, SHIELD DESIGN based on inverse calculation technique for precise estimation of shielding thickness in gamma ray shielding designs.

In the usual forward shielding calculations (Penner et al., 1994; QADCGGP, 1980; Subbaiah and Sarangapani, 2006, 2008), generally the source specifications for geometry, strength, energies and emission probabilities, source to detector distance, shielding material and thickness are given. By using the above information in the standard point kernel method, the dose rates are estimated. However, often the shield designer is not provided with the type of shielding material and the thickness required. Instead, only the dose rate criteria and source strength are provided to arrive at the suitable material and the thickness required. Shield thickness is arrived at by computing the dose rates for various shield thicknesses. This kind of shield design optimization in practice usually involves many trial runs and is time consuming. Hence, a need was felt to develop a new code with an innovative computational technique for quicker and easier way of optimization of shielding thickness.

Towards this objective, a new algorithm based on inverse calculation technique has been made and implemented in the code, SHIELD DESIGN. Though the radiation utility tool like RAD-PRO (RAD PRO, 2009) employs similar approach, it is with several limitations viz. It can handle only a point source, slab shield geometry and standard sources with built-in energy information whereas volume sources with multiple energies are frequently encountered in practice. On the other hand, SHIELD DESIGN code can handle multiple sources of different shapes and sizes, various shield geometries and user defined energy information of sources in addition to built-in energy information of standard sources. Also, the code has several user friendly input options regarding source

* Corresponding author.
E-mail addresses: kvs2552@gmail.com (K.V. Subbaiah), thilagam@igcar.gov.in (L. Thilagam).

0306-4549/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.anucene.2013.01.053

description, source to detector distance, target dose rates, selection of shield materials and their properties and choice of shield calculations say either shield design optimization for the prescribed dose criteria or dose rate calculations for the given shield thickness, etc. These options extend the flexibility and usefulness of the code in various radiation shield design applications.

The following sections explain in sequel about the mathematical formulations employed in SHIELD DESIGN, various OPTIONS available in it, its validation and conclusions.

2. Mathematical formulations

SHIELD DESIGN code has been developed based on inverse calculation technique, i.e., the shield thickness required is calculated for the prescribed dose from the target dose rate at the desired location. In shield design computations, three types of sources are generally expected. They are (1) a point source emitting single gamma energy, (2) a point source emitting multiple gamma energies, (3) Multiple point sources emitting single/multiple gamma energies and (4) Multiple volume sources emitting single/multiple gamma energies. Simplified flow diagram of SHIELD DESIGN code is given in Fig. 1. The mathematical formulations for the above source descriptions are given below.

2.1. A point source emitting single gamma energy

The dose rate $D(E, d)$ at any point at a distance 'd' from the source after transmitting through shield slab of thickness 'x' cm is given by

$$D(E,d) = D_o(E,d)B(E,\mu x)e^{-\mu x} \tag{1}$$

where $D(E, d)$ is the dose rate at distance 'd' due to gamma ray of energy 'E', $D_o(E, d)$ is the dose rate at distance 'd' due to gamma ray of energy 'E' by considering only the geometric attenuation, $B(E, \mu x)$ is the buildup factor of the medium (ANSI/ANS-6.4.3, 1991) based on energy 'E' and mean free path 'μx', μ is the linear attenuation coefficient of the shield material at the energy 'E' MeV (cm^{-1}), x is the thickness of the shield material (cm).

$D_o(E, d)$, which is valid in the energy range of 0.1–3.0 MeV, is given by

$$D_o(E,d) = \frac{0.54CE}{d^2}\left(\frac{R}{\mathrm{h}}\right)$$

,where C is in 'Curies (Ci)', E is in 'MeV' and d is in 'm' (Cember and Johnson, 2009).

$$D_o(E,d) = \frac{0.54CE x 10^{-6}}{d^2}\left(\frac{\mathrm{Sv}}{\mathrm{h}}\right), \tag{2}$$

where d is in 'cm'. More precisely, $D_o(E, d)$ can also be obtained by multiplying photon flux at that point with the flux-to-dose rate conversion factors for entire gamma energy range of 10 keV–30 MeV ANSI/ANS-6.4.3, 1991). In the forward calculations, generally the source strength, energies, emission probabilities, shielding material and thickness are given. By substituting the given information in Eqs. (1) and (2) the dose rate can be estimated. However, often the designer is not provided with the type of shielding material and the thickness required. Instead, only the dose rate criteria $D(E, d)$ and source strength are provided. The shield designer is expected to arrive at suitable material and thickness required. The shield thickness can be obtained straight away by rearranging the Eq. (1).

Rearranging Eq. (1) as

$$e^{\mu x} = \frac{D_o(E,d) * B(E,\mu x)}{D(E,d)} \tag{3}$$

where $\left(\frac{D_o}{D}\right)$ is obtained based on the calculated dose rate D_o and the dose rate criterion D. In Eq. (3), μ can be calculated knowing shield material and density and taken it to be known in subsequent in discussions. The other parameters 'x' and 'B' are unknown and moreover 'x' is an implicit function of 'B'. To solve for two variables, we need two equations. To circumvent this difficulty, we assume $B(E, \mu x) = 1$, which gives minimum thickness, thus eliminating one variable. Initial minimum thickness $\mu x'$ is computed as given in step 0 below, where all other quantities are known. The algorithm adopted in the computation is explained in steps below.

Step 0: Initial thickness is obtained from $\mu x' = \mathrm{Ln}\{D_o/D\}$.

Step 1: Compute the ratio $\left(\frac{D_o}{D}\right)$ based on dose rate in air (D_o) and dose rate criterion (D). 'D_O' can be estimated through Eq. (2) once source strength is known.

Step 2: Compute $B(E, \mu x)$ using the following equation

$$B(E,\mu x) = 1 + \frac{(b-1)(K^x-1)}{(K-1)} for\, K \neq 1$$
$$B(E,\mu x) = 1 + (b-1) * x \quad \text{for } K = 1$$

where

$$K(E,x) = c * x^a + d\frac{\tan\ h(x/X_k - 2) - \tan\ h(-2)}{1 - \tan\ h(-2)}$$

where E is the incident photon energy, x is the penetration depth in mean free path, a, b, c, d and X_k are the G–P fitting parameters and b is the value of buildup factor at 1 mfp. The parameter $K(E, x)$ is the photon dose multiplication factor and change in the shape of the spectrum.

Step 3: Compute $\mu x' = \ln\left[\frac{D_o(E,d) * B(E,\mu x)}{D(E,d)}\right]$

Step 4: Check for convergence $\left|\frac{\mu x'}{\mu x} - 1\right| \leqslant 0.001$

If it is satisfied, exit.

Else, Goto Step 2 and repeat the other steps.

These iterations will go on till final convergence has been achieved. As the function 'B' is a smooth and monotonically increases with thickness 'x' and hence convergence is very fast and it is observed that within four iterations the expected convergence of 0.1% in 'x' is obtained.

On Exit: Compute

$$x = \frac{\mu x}{\mu}$$

Then, STOP. Thus by few iterations, the algorithm given converges and gives out precise estimate of thickness required.

2.2. A point source emitting multiple gamma energies

In the case of problems involving source with the multiple energies, the algorithm is complex. If the gamma source is of multiple energies of 'N' components, then the dose rate in air due to each energy component is computed with the following expression

$$D_o(E,d) = \frac{0.54C \times 10^{-6}}{d^2} E_i P_i \left(\frac{\mathrm{Sv}}{\mathrm{h}}\right) \tag{4}$$

where P_i is the probability of emission of ith component E_i.

The shield thicknesses $[x_1, x_2, x_3, \ldots, x_i]$ required to reduce the above dose rate in air to target dose rate is calculated first for each energy component by using the technique as explained