Monte Carlo Simulation of Scattering Phenomenon Effects on Industrial Radiography

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Abstract: As x or gamma rays pass through different materials, some of the photons interact with the matter and their energy can be absorbed or scattered. Scattering is the main factor of reducing the sensitivity of radiographs in industrial and also medical radiography. One way to determine the accuracy of the experiments and the sensitivity of those experimental determinations of μ to scatter and collimation, and other geometrical effects, is to simulate the scattering and absorption processes as the beam passes through a material. In an effort the linear and effective attenuation coefficients and Build Up factor, as important radiography factors affected by scattering phenomenon were calculated for different type of specimens such as pipe and plates by simulation through Monte Carlo method. Simulation results clearly show thickness dependence of the above factors. A comparison between achieved results gives a view of different scattering situations of the above mentioned specimens in general. A comparison between the Monte Carlo simulation results and experimental results which were obtained by radiography of those specimens according to the standard procedures are also indicated in this paper.

1. Introduction

As x or gamma rays pass through different materials, some of the photons interact with the particles of the matter and their energy can be absorbed or scattered. This absorption and scattering is called attenuation. The main photon attenuating processes are photoelectric effect, scattering and pair production [1]. The total attenuation is the sum of the attenuation due to different types of interaction. The linear attenuation coefficient (μ) describes the fraction of a beam of x-rays or gamma rays that is absorbed or scattered per unit thickness of the material. It basically accounts for the probability of a photon being scattered or absorbed when they pass through a material. For a narrow beam of mono-energy photons of gamma and x-ray, the fraction of beam which passes through a material without any collision can be expressed in the form of an equation as [2]:

$$I = I_0 . e^{-\mu . t} \qquad (1)$$

Where:

- I = intensity of photons transmitted across distance t
- I_0 = initial photons intensity
- μ = linear attenuation coefficient
- t = penetrated thickness

Linear attenuation coefficients may be used to make a number of calculations such as finding the intensity of transmitted radiation through a medium when the incident intensity, the material and the medium thickness are known, also determining the thickness of the medium when the incident and transmitted intensity, and the material are known,…[2], [3].

The above simple absorption equation is based upon the assumption that all scattered radiation are completely removed from the beam. However, in reality it is not the case especially in thick material which a number of scattered photons will reach to the observation point (detector such as film). Actually, the measured intensity of radiation after passing a material is higher than that calculated using the simple absorption equation. The above phenomenon is well known as buildup radiation due to scattering. Thus in practice, the absorption equation is modified by introducing another quantity known as buildup factor which are defined in the next section.

The linear attenuation coefficients for a variety of single energy photon beams are available in various references for different materials [4], [5], but references do not contain such a data for multi-energy sources which are commonly used in industrial and medical radiography.

In the present work μ as a function of thickness was calculated for iridium-192 source mathematically using data extracted from NIST (National Institute of Standards and Technology) [4] data bank and also it is calculated through Monte Carlo simulation [6], [7]. Also Buildup factor and effective attenuation coefficient for two types of specimens (plate and pipe with a variety of thicknesses) were calculated through Monte Carlo method and finally experimental results on calculation of effective attenuation coefficient on a pipe specimen is presented and compared to the simulation results.

2. Theory

The linear attenuation coefficient is strongly energy dependent. In general, lower energetic gamma and X-ray photons have a higher interaction probability. Since radioisotopes and X-ray devices produce photons in a wide energy range, the transmission should actually be considered for the whole energy range.

For the intensity calculation of the x-ray beam and radio isotopes such as Ir-192 which emits multi-energy photons the energy dependence of the attenuation coefficient should be taken into account, the intensity equation for these cases is:

$$I = \int I_0(E).e^{-\mu(E).t}dE \qquad (2)$$

The linear attenuation coefficient for mono-energy beams is a constant value over the material thickness, but for multi-energy sources such as x-ray tubes and radioisotopes which are commonly used in radiography it is vary by the thickness and should be determined for each source as a function of thickness.

The above absorption equation is (similar to Eq. 1) based upon the assumption that scattered radiation is completely removed from the beam. Actually due to a number of scattered photons that reach to the observation point the measured intensity of radiation after passing a material is higher than that calculated using the simple absorption equation.

The above phenomenon is well known as buildup radiation due to scattering. Thus in practice, the absorption equation is modified by introducing another quantity known as buildup factor. The absorption equation now becomes:

$$I = B.I_0 e^{-\mu.t} \qquad (3)$$

Where B is the buildup factor and can be defined as the ratio of total intensity of collided and un-collided photons received by the detector to the intensity of un-collided photons reach to the detector [8]. Buildup factors are not constant, but rather vary with a number of parameter such as medium thickness and material, geometry, source type, detector position … [1], [3].

3. Material and Methods

3.1 Mathematical Calculation of μ for Ir-192 Source

Ir-192 as a radio isotope source emits photons with the energy and probability according to table-1(Ir-192 emits photons by about 26 different energies but here only the most probable photons are indicated and used in calculations).

Table-1: Photon Emission Products of Ir-192[9]

Fraction	Energy(MeV)
I1=0.04573	E1=0.58858
I2=0.05336	E2=0.61246
I3=0.08202	E3=0.60441
I4=0.29015	E4=0.29596
I5=0.29678	E5=0.30846
I6=0.48055	E6=0.46807
I7=0.82853	E7=0.31651

According to Eq. 1, μ (linear attenuation coefficient) for an Ir-192 source is calculated as follows:

$$I_j = I_{j0}.e^{-\mu_j.t} \quad \text{, j=0, 1, …, n (n=the number of different energies, here n=7)} \qquad (4)$$

$$I_{total} = \sum_{j=1}^{n} I_{j0}.e^{-\mu_j.} = I_{10}.e^{-\mu_1.t} + I_{20}.e^{-\mu_2.t} + ... + I_{70}.e^{-\mu_7.t} \qquad (5)$$

Where: Ij = intensity of photons with the energy of Ej transmitted across distance x

Ij_0 = initial intensity of photons with the energy of Ej

μj = the linear attenuation coefficient regarding the energy of Ej

t = penetrated thickness

If it is purposed to have an equivalent linear attenuation coefficient for this cases, μ, is defined as:

$$I_{total} = (I_{10} + I_{20} + ... + I_{70}).e^{-\mu.x} \qquad (6)$$

And thereby:

$$(I_{10} + I_{20} + ... + I_{70}).e^{-\mu.x} = I_{10}.e^{-\mu_1.x} + I_{20}.e^{-\mu_2.x} + ... + I_{70}.e^{-\mu_7.x} \qquad (7)$$

Finally: $$\mu = -\frac{1}{x}\ln\left(\frac{I_{10}.e^{-\mu_1.x} + I_{20}.e^{-\mu_2.x} + ... + I_{70}.e^{-\mu_7.x}}{I_{10} + I_{20} + ... + I_{70}}\right) \qquad (8)$$

As it is clear from the Eq. 8, μ is dependant to the medium thickness. In order to calculate μ according to the Eq. 8, Ij0 are known from table1, and μj is extracted from a data bank. μj for Ir-192 photon energies from NIST data bank are indicated in table2 (these data were extracted by a curve digitizer software).

Table-2: Linear attenuation coefficient for Ir-192 photons

Fraction	Energy(MeV)	Lin. Att. Coe.(cm)
I1=0.04573	E1=0.58858	μ1=0.613
I2=0.05336	E2=0.61246	μ2=0.602
I3=0.08202	E3=0.60441	μ3=0.605
I4=0.29015	E4=0.29596	μ4=0.87
I5=0.29678	E5=0.30846	μ5=0.858
I6=0.48055	E6=0.46807	μ6=0.687
I7=0.82853	E7=0.31651	μ7=0.847

Linear attenuation coefficients calculated from this method for an iron plat with a range of thicknesses are indicated on Fig.1.

3.2 Monte Carlo Simulation

The general purpose Monte Carlo N-particle radiation transport computer code (MCNP4C) is used for simulation of Ir-192 radiation source and radiography setups [3], [10] as follows:

A1. An iron plate with 10 cm × 10 cm area, thicknesses from 6mm to 90mm (acceptable thickness range of iron for radiography by Ir-192 source, according to BS standard [11]). In this setup, source to detector distance is 100 cm and the distance between specimen and detector is 1mm (similar to radiography situation that film is placed just behind the specimen).

A2. An iron plate with size and setup similar to A1 configuration, except that for the distance between specimen and detector which is 50 cm (similar to situation such as shielding calculations that detector is often assumed far from the specimen).

A3. A 6” iron pipe with 35 cm high and different thicknesses according to table 3. In this setup, source to detector distance is 120 cm and the distance between specimen and detector is 1 mm (similar to radiography situation that film is placed just behind the specimen).

The density of iron is supposed to be 7.9 g/cm^3. Photon energies and fractions are taken according to table 1. A point (circle) detector with 1 mm radius is defined as tally of the MCNP4C code to record the transmitted photons and 50 million photons is traced for each simulation run.

In each case the total number of photons reached to the detector (I_{total}) and the number of un-collided photons reached to the detector ($I_{uncollided}$) are recorded. The number of initial photons reached to the detector (I_0) is recorded while the specimen has been removed from configuration (empty media between source and detector).

Linear attenuation coefficient (μ), effective attenuation coefficient (μ_{eff}) and Buildup factor (B) have been calculated for each case as follows:

$$\mu = -\frac{1}{x}\ln(\frac{I_{uncollided}}{I_0}) \quad (9)$$

$$\mu_{eff} = -\frac{1}{x}\ln(\frac{I_{total}}{I_0}) \quad (10)$$

$$B = \frac{I_{total}}{I_{uncollided}} \quad (11)$$

Results of Monte Carlo simulation are shown on Figs. 1 - 7.

3.3 Experiments

An experimental work has previously been performed in a cooperated research project (CRP) conducted by International Atomic Energy Agency (IAEA). In a part of this work, effective attenuation coefficient of pipes with a range of thicknesses similar to A3 configuration (described above) has been investigated. In this work, which has been carried out in NDT department of INRA, a unique effective attenuation coefficient was accepted equal to 0.46 cm^{-1} (to review details of this experiment see [12-13]). Experimental value accepted for μ_{eff} in that project is approximately equal to the obtained simulation results when media thickness to be between 2.5-3 cm (see Fig. 6). According to the discussed mathematical and simulation results, attenuation coefficient (both linear and effective) is thickness dependant especially for effective μ which deeply affected by Buildup factor.

4. Results and Discussion

Reference data libraries such as NIST provide linear attenuation coefficient, μ, for a variety of materials as a function of the energy of photon beams. If radiation source emits photons of different energies, μ will not to be a constant value. In this case, it is thickness dependant and should be calculated according to Eq. 8. Mathematically calculated μ for an Ir-192 source by using NIST data are indicated on Fig. 1. Medium in this case was an iron plat (A1). Monte Carlo simulation results for the same situation also are indicated on Fig. 1. It is clear that the mathematically obtained results and Monte Carlo simulation results are in a very good agreement.

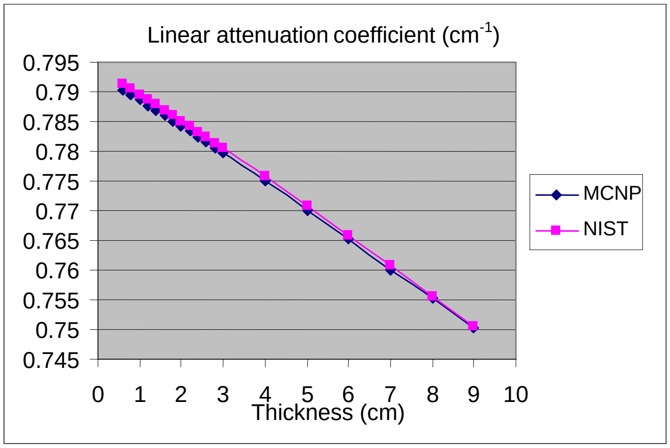

Fig 1- Linear attenuation coefficient (cm^{-1})-mathematically calculated Based on NIST data and calculated through simulation-configuration A1.

Effective attenuation coefficient (μ_{eff}) and buildup factor (B) are calculated by Monte Carlo simulation for A1 configuration. The results are illustrated in Figs. 2 and 3, respectively. The results of the same parameters are indicated on Figs. 4 and 5 for configuration A2.

A comparison between Figs. 3 and 5 shows that lower amount of scattered photons reach to the detector when detector is placed far from the specimen.

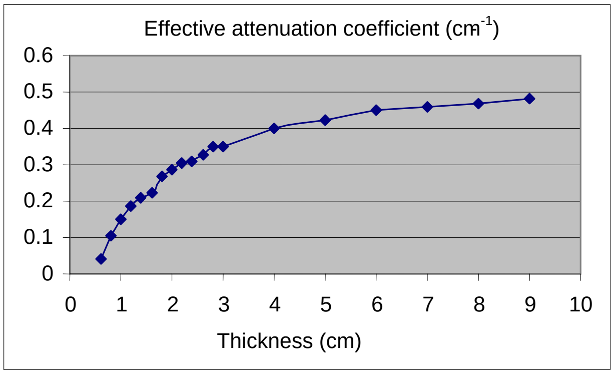

Fig. 2 Effective attenuation coefficient (cm^{-1}) calculated through simulation- configuration A1.

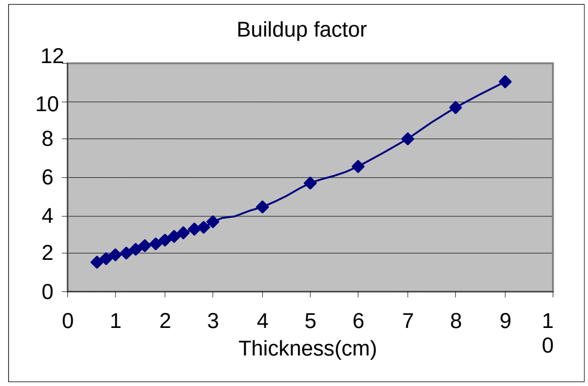

Fig. 3 Buildup factor calculated through simulation-configuration A1.

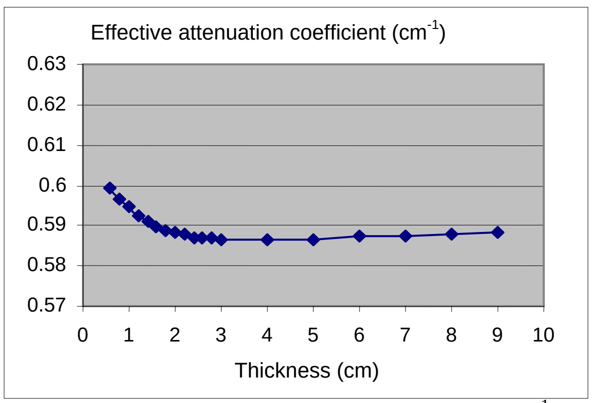

Fig. 4 Effective attenuation coefficient (cm^{-1}) calculated through simulation- configuration A2.

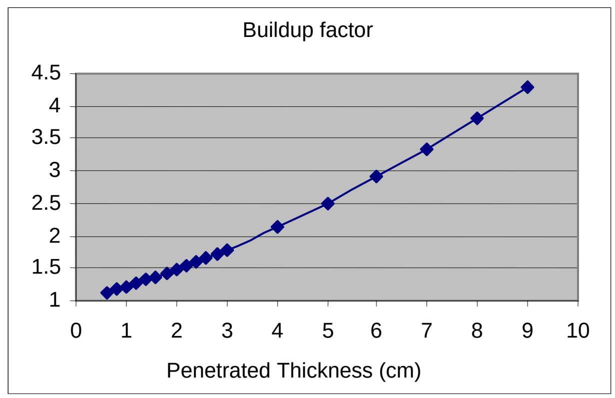

Fig. 5 Buildup factor calculated through simulation-configuration A2.

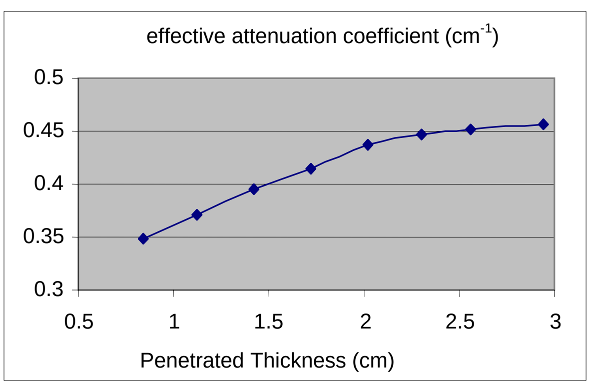

Fig. 6 Effective attenuation coefficient (cm^{-1}) calculated through simulation- configuration A3.

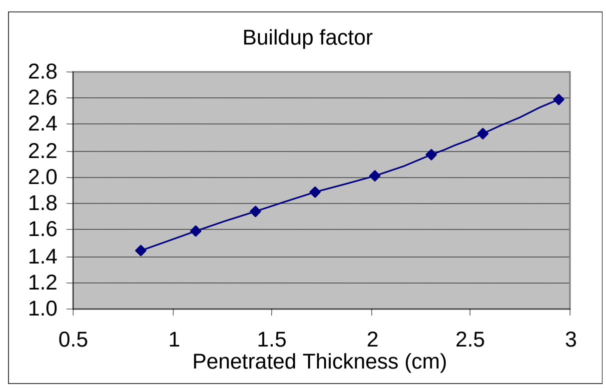

Fig. 7 Buildup factor calculated through simulation-configuration A3.

Figs. 3 and 5 show that buildup factor rapidly growth by increasing thickness. In case that the detector is just behind the specimen the growth speed is higher in comparison to the situation that detector is far from specimen, due to a huge number of scattered photons which reach to the detector.

Buildup factor and effective attenuation coefficient resulted by Monte Carlo simulations for configurations A3 are shown on Figs. 6 and 7, respectively.

5. Conclusion

In order to calculate the linear attenuation coefficient (μ) for multi-energy sources such as Ir-192, which is one of the main sources in radiography, two methods were introduced and applied in this paper: I- A mathematical method; in which attenuation coefficient for each energy of photons of the beam should be extracted from a valid data bank and put them into the Eq. 8, II- A simulation method, by Monte Carlo method as explained through the test. Results show good agreement between two introduced methods.

Also, in order to calculate the effective attenuation coefficient (μ_{eff}) and the buildup factor (B) Monte Carlo simulation method is used. It is shown that μ, μ_{eff} and B are functions of the material thickness by theoretical method and also through the simulation results.

6. References

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