Indian Journal of Pure & Applied Physics
Vol. 56, January 2018, pp. 48-52

Comparison of measured and Monte Carlo-calculated electron depth dose distributions in aluminium

S Vandana[a]*, P G Benny[b] & T Palani Selvam[a]

[a]Radiological Physics & Advisory Division, Bhabha Atomic Research Centre,
Mumbai 400 085, India

[b]Isotope and Radiation Application Division, Bhabha Atomic Research Centre,
Mumbai 400 085, India

Received 21 February 2017; accepted 22 August 2017

Depth dose profiles in aluminium have been measured using the cellulose triacetate dosimeter against different electron energies (4, 4.5 and 5 MeV) at a recently upgraded 15 kW industrial electron beam accelerator facility. The study also includes comparison of these profiles against Monte Carlo calculations. The measured and simulated depth dose profiles are similar in shape. For all electron energies, at initial depths, the measured doses are higher than the simulated ones. The simulated and measured normalized surface dose values are 0.58 and 0.66, respectively, independent of electron energy. The difference in the surface dose between Monte Carlo and experiment could be attributed to possible presence of low energy electrons in the measurements whereas the Monte Carlo calculations are based on monoenergetic electrons. Between the region of dose maximum and the tail portion of the depth dose curve, the measured dose is smaller than the simulated values (about 17% to 40% at 5 MeV). Using the depth dose profiles, electron beam parameters such as depth at which maximum dose occurs, $d_{\max}$, practical range, R_p and half-value depth, R_{50} have been determined. Using the measured parameters R_p and R_{50}, the incident kinetic energy of the electron beam has been determined. The estimated electron energies while using R_p are 4.02, 4.41 and 4.75 MeV. When using R_{50}, the corresponding values are 3.83, 4.21 and 4.64 MeV. The measured R_P/R_{50} ratios are slightly larger than the Monte Carlo-calculated values, which suggest that the electron beam may not be monoenergetic.

Keywords: Electron parameters, Aluminium, Electron beam accelerator, Dosimetry

1 Introduction

Industrial electron beam accelerators are used worldwide for irradiation of various products to improve and enhance the quality of the products. High energy electron beam accelerators are being beneficially utilized for application in the field of polymer modifications, sterilization of health care products, hygienization and preservation of food and environmental remediation[1-3]. In India, Isotope and Radiation Applications Division of Bhabha Atomic Research Centre (BARC) is using an industrial electron beam accelerator as demonstration and research facility for radiation processing applications[4-7]. Recently, initial kinetic energy of the electron beam of the accelerator has been upgraded from 2 MeV to a maximum electron kinetic energy of 5 MeV, to process thick polymers and packaged products. This accelerator (ILU type from Budker Institute of Nuclear Physics, Novosibirsk, Russia) is capable of delivering powered electron beams up to 15 kW average beam power in the energy range 3 to 5 MeV.

As the electron has limited penetration depth on the entry of the beam, the measurements of depth dose in a reference material is essential. The depth dose depends on type of material and energy of the beam. The dose delivered to the material/product should be high enough to ensure the intended radiation effect but must not exceed the level necessary for reasons of time, efficiency and, uniformity in the performance of the processed product[8-12]. Therefore, depth dose profile in a reference medium is one of the important dosimetry parameters to be measured and used for optimum irradiation condition for the product. The dosimetric parameters such as practical range (R_p) and half-value depth (R_{50}) can be obtained from the depth dose profile[13]. R_p is the distance from the incident surface to the point where linear extrapolation of points on the almost straight descending portion of depth dose curve meets the depth axis. R_{50} is the depth in homogeneous material at which the absorbed dose decreases to 50% of its maximum value. R_p and R_{50} can be correlated with the incident electron energy using appropriate equations as given in ICRU report[13] 35 and ISO/ASTM[14] 51649.

---

*Corresponding author (E-mail: bikaiv_barc@rediffmail.com)

In our earlier work, we have carried out absorbed dose measurements as a function of graphite thickness against 1.6 MeV electron beam from the ILU-6 accelerator[15]. Dose measurements as a function of depth in a 1.2 cm thick graphite calorimeter were also carried out. The measured dose values were compared to the Monte Carlo calculated values. The objective of the present work is to measure depth doses in the reference medium of aluminium for the incident electron beam energies of 4, 4.5 and 5 MeV and compare the same against Monte Carlo calculated values. The Monte Carlo calculations are based on the DOSRZnrc-based user-code[16] of the EGSnrc Monte Carlo code system[17].

2 Experimental Details

2.1 Method

Irradiations were carried out with scanned electron beam from an industrial type 15 kW ILU pulsed linear electron beam accelerator (Fig. 1) with the beam parameters as shown in Table 1. The accelerator is equipped by a scanning horn with a scan width of 90 cm. Scan horn is mounted vertically at 90° to the product path way. Pulse current and pulse frequency can be varied from 80 to 250 mA and 2 to 50 Hz, respectively. The accelerator is provided with a conveyor and its speed can be varied in the range of 1.5 to 10 cm per second. The distance between the accelerator extraction window and the conveyor can be varied by adjusting the height of conveyor platform. During the irradiation, product passes under the beam to deliver the uniform dose to the product.

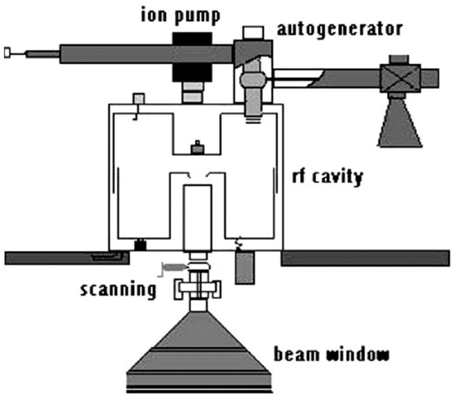

Fig. 1 — Schematic sketch of an industrial electron beam accelerator (ILU-6 type) at Bhabha Atomic Research Centre, India used for radiation processing.

Table 1 — Accelerator parameters during the experiment

Beam Parameter	Values
Energy	4, 4.5 and 5 MeV
Average beam current	1 mA
Pulse repetition frequency	25 Hz
Scan width	810 mm
Mode of operation	Conveyor mode
Conveyor speed	1.5 cm/s
Pulse current	100 mA
Pulse duration	500 µs

Due to the higher gradients of dose distributions in the material, the dosimeters used are thin in their size for electron beam process. Film dosimeters are convenient means of obtaining beam profile information. The cellulose triacetate (CTA) dosimeter has a linear response in the dose range[15] of 10 to 160 kGy. These films have thickness of 0.125 mm and have a dose-rate dependent response. The CTA film is available in the form of long tape of 100 m. With automated strip feeder measurement system, this film is convenient for the measurement of depth doses. In the present work, calibrated CTA film strip dosimeters were used for the measurement of depth dose profile.

For depth dose measurements, wedge pair of aluminium with 15° angle was fabricated. The density of aluminium is 2.7 g/cm^3. The CTA strip was held tightly between the wedge pairs. The experimental-set up for the depth dose measurement is shown in Fig. 2. The calibration of CTA film strip dosimeters was carried out by irradiating the dosimeters together with transfer-standard dosimeters (Alanine dosimeters) directly under the electron beam at the facility. Calibrations used in this study are directly traceable to the calibration facility at the Radiation Safety Systems Division of BARC, which maintains Indian National Radiation Standards for high doses. The aluminium block was irradiated by passing through the electron irradiation zone using a conveyor. The irradiated strips were read at 280 nm using Aerode dosimetry system (Spectronic Genesis 5 spectrophotometer) with an automated strip feeder mechanism from aerial operating at measurement resolution of 10 points/cm. Practical range (R_p) and half-value depth (R_{50}) were then determined from these depth dose curves. The electron beam energy was determined from the measured depth dose profile in aluminium.

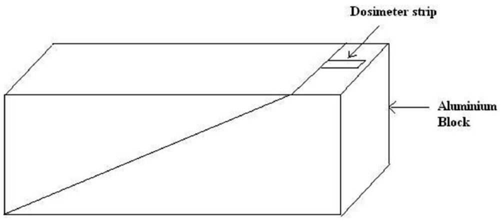

Fig. 2 — Schematic sketch of an aluminium block.

2.2 Monte Carlo simulation

Monte Carlo simulations were performed to obtain absorbed dose in aluminium as a function of depth[16] using the DOSRZnrc user-code of the EGSnrc code system[17]. The simulations were carried out separately for three different mono-energetic electron energies of 4, 4.5 and 5 MeV. In the Monte Carlo calculations, parallel mono-energetic electron beam of radius 15 cm passing through a 35 cm thick air column is made to incident on the aluminium block of radius 16 cm, height of 7.5 cm. Central axis depth doses were scored in 1.5 cm radius×0.02 cm thick slabs. The density of aluminium is 2.7 g/cm^3. The 521icru.pegs4dat distributed along with the EGSnrc code system[17] was used for the Monte Carlo simulation. The low-energy threshold for the production of knock-on electrons (AE) was set to 521 keV for an electron with 10 keV kinetic energy, and the threshold for secondary bremsstrahlung photons (AP) was set to 10 keV. The transport cut-off energies for photons and electrons were set at 10 keV. All Monte Carlo simulations utilized the PRESTA-II electron-step-length and EXACT boundary-crossing algorithms. The electron step size parameter was ESTEP set to 0.25. We have used electron range rejection technique by setting ESAVE 2 MeV. The 1 σ statistical uncertainties on the simulated depth dose values were between 0.03 and 1%, depending upon the depth.

3 Results and Discussion

An analysis of simulated and measured depth doses in aluminium suggests that there is a gradual increase in dose with depth till depth of maximum dose ($d_{\max}$) and thereafter it decreases with depth. In both Monte Carlo calculations and measurements, there is a flat region over which the dose is maximum. Table 2 compares the simulated and measured values of $d_{\max}$ at electron energies 4, 4.5 and 5 MeV.

Figures 3 to 5 present the variation of normalised depth dose values in aluminium for electron beam energies of 4, 4.5 and 5 MeV, respectively. The measured and simulated depth dose profiles are similar in shape. At initial depths, the measured doses are higher than the simulated ones. For a given electron energy, between the region of dose maximum and the tail portion of the depth dose curve, the measured dose is smaller than the simulated values. The difference between the simulated and measured normalized depth dose values is obtained using the following Eq. (1):

$$\%\,difference = \frac{(Simulated\ value - Measured\ value)}{Measured\ value} \times 100 \quad \ldots (1)$$

This difference is more pronounced for high energy electrons. For example, depending upon the depth, the difference is about 17% to 40% at 5 MeV. The reason for

Table 2 — Comparison of simulated and measured values of range of depths in aluminium at which dose is flat and maximum for 4, 4.5 and 5 MeV electron beams

Energies (MeV)	Range of depths at which dose maximum occurs (cm)	
	Monte Carlo	Experiment
4.0	0.25 – 0.31	0.24 – 0.28
4.5	0.29 – 0.37	0.27 – 0.31
5.0	0.35 – 0.43	0.31 – 0.39

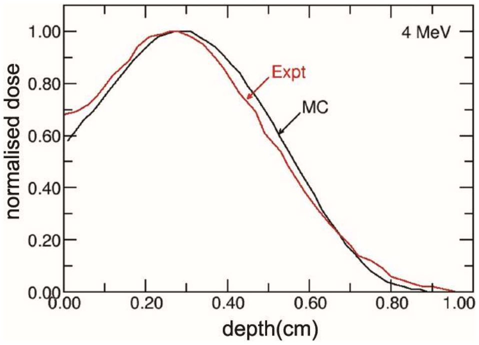

Fig. 3 — Plot of normalised dose values as a function of depth (cm) in aluminium for 4 MeV electron beam.

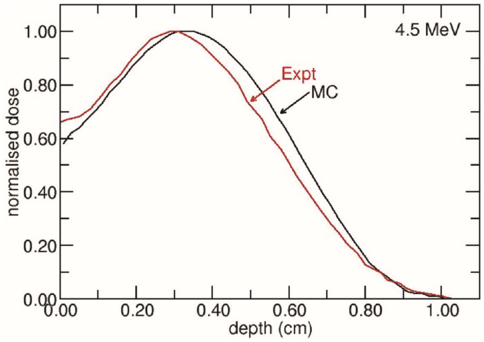

Fig. 4 — Plot of normalised dose values as a function of depth (cm) in aluminium for 4.5 MeV electron beam.

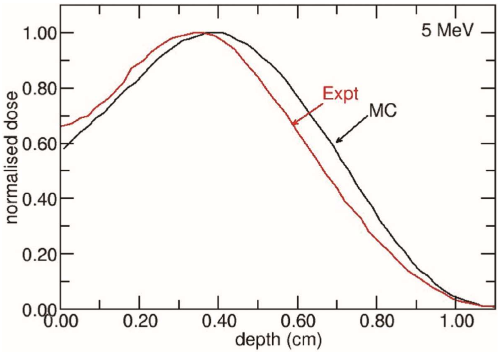

Fig. 5 — Plot of normalised dose values as a function of depth (cm) in aluminium for 5 MeV electron beam.

this difference could be due to the monoenergetic electron beam considered in the Monte Carlo calculations which will have forward scattering and higher penetration. However, such differences in the depth dose values between simulations and measurements have not affected the value of R_p significantly.

The simulated and measured normalized surface dose values are about 0.58 and 0.66, respectively, independent of beam energy. The difference in the surface dose between Monte Carlo and experiment could be attributed to possible presence of low energy electrons in the measurements whereas in the Monte Carlo calculations, we have considered single electron energy. A similar observation was made in a previously published study[15] at 1.6 MeV wherein measured normalized surface dose was higher than the simulated value. It may be noted that angular distribution of electrons also has strong influence on the depth dose distribution in the medium[13]. The influence of angular spread of mono-energetic electron beam on the shape of depth dose curve is reported[13] in ICRU report No. 35.

ICRU report[13] 35 provide the following expression correlating the most probable energy E_p (in MeV) defined by the peak of the energy distribution and the R_p (in cm) in aluminium:

$$E_p = 0.20 + 5.09 \times R_p \qquad \text{... (2)}$$

Equation (2) is applicable in the recommended energy range of 5 MeV to 25 MeV.

The ISO/ASTM 51649 Report[14] provides the following expressions to determine E_p involving R_p and R_{50} in aluminium:

$$E = 0.256 + 4.91 \times R_p - 0.0248 \times R_p^2 \qquad \text{... (3)}$$

$$E = 0.297 + 6.61 \times R_{50} - 0.325 \times R_{50}^2 \qquad \text{... (4)}$$

Equations (3) and (4) are applicable in the energy range of 1 MeV to 10 MeV. The values of R_p and R_{50} are obtained from the depth dose profiles for individual electron energies. Table 3 presents the values of R_P, R_{50} and the ratio (R_P/R_{50}) obtained through measurements and Monte Carlo calculations for 4, 4.5 and 5 MeV electron beams. Note that R_p and R_{50} values obtained from both calculations and measurements are comparable. R_P/R_{50} ratios given in Table 3 are in the range of 1.40 to 1.35 (measured) and 1.35 to 1.32 (Monte Carlo). The ISO/ASTM 51649 values[14] of R_p and R_{50} and ratio (R_P/R_{50}) for 5 MeV electron beam (shown in Table 3) are in good agreement with the Monte Carlo-based values. The measured ratio (R_P/R_{50}) for 5 MeV electron beam is 1.35 which is about 3% higher than the ISO/ASTM quoted value of 1.31 which is an indication that the electron beam is not a monoenergetic beam. According to ISO/ASTM[14] 51649 the ratio of R_p and R_{50} are nearly independent of electron energy and the lowest values lie in the range from 5 to 20 MeV. In a practical situation, if the measured value of R_P/R_{50} ratio is found to be greater than the ratios quoted in the ISO/ASTM[14] 51649, the beam may not be monoenergetic. A broad beam spectrum reduces R_{50} more than R_p, so R_P/R_{50} ratio is the indication of energy spread in the beam.

Table 4 presents the values of energy of the electron beams estimated using Eqs (2) to (4). Equation (3) involving R_p predicts the electron energy more accurately than Eq. (4) involving R_{50}. Depending upon

Table 3 — Values of practical range (R_p) and half-value depth R_{50} for 4, 4.5 and 5 MeV electron beams determined using Monte Carlo method and experimental

Set energies (MeV)	R_p (cm)		R_{50} (cm)		Ratio (R_p/R_{50})	
	Measured	Monte Carlo	Measured	Monte Carlo	Measured	Monte Carlo
4.0	0.77	0.77	0.55	0.57	1.40	1.35
4.5	0.85	0.86	0.61	0.64	1.39	1.34
5.0	0.92	0.96	0.68	0.73	1.35	1.32
	0.97*		0.74*		1.31*	

*ISO/ASTM 51649 quoted values

Table 4 — Values of estimated electron energy for 4, 4.5 and 5 MeV electron beams determined experimentally using Eqs (2-4)

Set energies (MeV)	Estimated electron energy (MeV)		
	Using R_P in Eq. (2)	Using R_{50} in Eq. (3)	Using R_P in Eq. (1)
4.0	4.02	3.83	-
4.5	4.41	4.21	-
5.0	4.75	4.64	4.89

the electron energy, Eq. (3) results in agreement in the range 0.05 - 5% whereas in the case of Eq. (4), the agreement is in the range of 4.4 - 7.8%. At 5 MeV, Eq. (2) which is applicable in the energy range 5 - 25 MeV, predicted the energy of electron energy as 4.89 MeV, which is more accurate than using Eqs (3) and (4).

4 Conclusions

Depth dose profiles for electron energies (4, 4.5 and 5 MeV) of 15 kW industrial electron beam accelerator facility were measured in aluminium using the CTA dosimeter. The depth dose profiles at these energies were also simulated using the Monte Carlo methods. A comparison of simulated and measured dose profiles indicates that the incident electron beam may not be monoenergetic. Using the measured parameters R_p and R_{50}, the incident kinetic energy of the electron beam was determined. The estimated electron energies while using the ISO/ASTM 51649 formalism involving R_p are 4.02, 4.41 and 4.75 MeV. The same formalism while using R_{50}, results in electron energy values as 3.83, 4.21 and 4.64 MeV. Formalism given by ICRU report 35 for 5 MeV electron beam, predicts energy of the electron more accurately (predicted energy is 4.89 MeV). The measured R_P/R_{50} ratios are slightly larger than the Monte Carlo-calculated ones, which suggest that the electron beam may not be monoenergetic.

Acknowledgement

The authors would like to thank K S S Sarma, Head, Isotope and Radiation Application Division, Bhabha Atomic Research Centre, Mumbai for his support and encouragement.

References

1 Chmielewski A G, Iller E, Zimek Z, Romanowski M & Koperski K, *Radiat Phys Chem*, 46 (1995) 1063.
2 Cleland M R & Parks L A, *Nucl Instrum Methods Phys Res Sec B*, 208 (2003) 74.
3 Zimek Z, Walis L & Chmielewski A G, *Radiat Phys Chem*, 42 (1993) 571.
4 Sarma K S S, *IANCAS Bulletin,* 2nd Edn, (2005) 128.
5 Sarma K S S, Sabharwal S & Kalurkar A R, *J Radiat Nucl Chem*, 206 (1996) 341.
6 Sarma K S S, Benny P G, Khader S A & Patkari R K, *Indian J Pure Appl Phys*, 50 (2012) 805.
7 Sarma K S S, Rawat K P, Benny P G & Kader S A, *BARC News Lett*, 323 (2011) 38.
8 Benny P G, Khader S A & Sarma K S S, *Nucl Instrum Methods Phys Res A*, 680 (2012) 108.
9 Benny P G, Khader S A & Sarma K S S, *Radiat Eff Def Solids*, 168 (2013) 358.
10 Benny P G, Khader S A & Sarma K S S, *Nucl Instrum Methods Phys Res A,* 739 (2014) 48.
11 Benny P G, Khader S A & Sarma K S S, *Nucl Instrum Methods Phys Res A,* 751 (2014) 88.
12 Benny P G, Khader S A & Sarma K S S, *Nucl Instrum Methods Phys Res A,* 774 (2015) 25.
13 *ICRU report 35*, Radiation dosimetry; electron beams with energies between 1 and 50 MeV (1984).
14 ISO/ASTM 51649, Standard practices for dosimetry in an electron beam facility for radiation processing at energies between 300 keV and 25 MeV.
15 Benny P G, Palani Selvam T & Sarma K S S, *Nucl Instrum Methods Phys Res A,* 703 (2013) 98.
16 Rogers D W O, Kawrakow I, Seuntjens J P & Walters B R B, *NRC User Codes for EGSnrc: Technical Report No. PIRS-702* (2006). (see/http://www.irs.inms.nrc.ca/inms/irs/EGSnrc/EGSnrc.html).
17 Kawrakow I & Rogers D W O, *The EGSnrc Code System: Monte Carlo Simulation of Electron and Photon Transport, Technical Report No. PIRS-701* (2006).