

ELECTRON ENERGY, BEAM CURRENT AND BEAM POWER  
REQUIREMENTS FOR ELECTRON BEAM PROCESSING

M.R. Cleland and R.A. Galloway  
IBA E-Beam X-Ray Solutions  
Edgewood, NY 11717, USA

**Introduction**

Equations and data for calculating the electron energy, beam current and beam power requirements for typical electron beam (EB) processing applications are presented in the paper listed below, which has been published in the proceedings of the 12th International Meeting on Radiation Processing, held in Avignon, France, 25-30 March, 2001.

M. Cleland, R. Galloway, G. Genin, M. Lindholm, The use of dose and charge distributions in electron beam processing, Radiation Physics and Chemistry, Vol. 63, Nos. 3-6 (2002) pp. 729-733.

The supporting data for that paper are given in the IBA-RDI Technical Information Series Report, TIS 01666, Monte Carlo Calculations of High-Energy Electron Depth-Dose Distributions in Polyethylene, R.A. Galloway and M.R. Cleland. Depth-dose distributions have been obtained for a wide range of electron energies, from 0.3 MeV to 12 MeV. The results of these calculations are summarized below.

**Material Thickness vs Electron Energy**

When materials are irradiated with high-energy electrons, the absorbed dose increases with greater depth to about the midpoint of the electron range and then decreases to low values near the end of the range. Several useful parameters can be obtained from the shapes of such curves.  $R(\text{opt})$  is the depth where the exit dose equals the entrance dose.  $R(50)$  is the depth where the exit dose equals 50% of the maximum dose.  $R(50e)$  is the depth where the exit dose equals 50% of the entrance dose.  $R(p)$  is the depth where a line tangent to the decreasing curve at its steepest slope (the inflection point) crosses the zero-dose axis. Values of these parameters for flat sheets of polyethylene are given in Table 1.

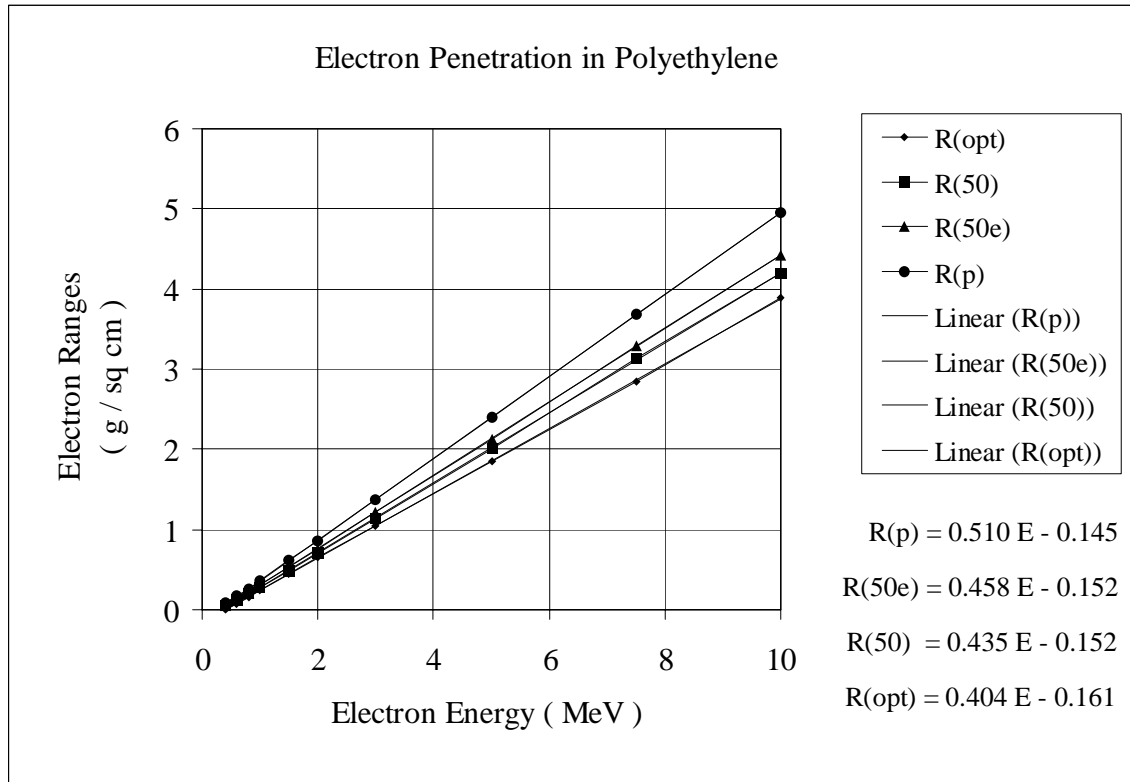
The depth is given in grams per square centimeter, which equals the depth in centimeters multiplied by the volume density in grams per cubic centimeter. The combined unit is the weight per unit area, which is called the area density or the areal density. This is the usual method to accommodate changes in volume density, such as plastic foam, without having to change the data in the table.

For example: with a volume density of 0.94 grams per cubic centimeter for polyethylene, the  $R(\text{opt})$  thickness at 1.0 MeV would be  $0.243/0.94 = 0.259$  cm, at 3.0 MeV it would be  $1.054/0.94 = 1.12$  cm, and at 10 MeV it would be  $3.884/0.94 = 4.13$  cm.

Table 1. Depth Parameters for Flat Sheets of Polyethylene

Energy (MeV)	R(opt) (g/sq cm)	R(50) (g/sq cm)	R(50e) (g/sq cm)	R(p) (g/sq cm)
0.40	0.000	0.054	0.054	0.083
0.60	0.075	0.126	0.129	0.169
0.80	0.161	0.202	0.214	0.262
1.00	0.243	0.282	0.302	0.358
1.50	0.449	0.486	0.529	0.610
2.00	0.652	0.699	0.754	0.861
3.00	1.054	1.128	1.209	1.373
5.00	1.859	2.000	2.131	2.405
7.50	2.854	3.134	3.284	3.682
10.00	3.884	4.204	4.429	4.955

These depth values increase linearly with the incident electron energy above 0.4 MeV. For flat sheets, they can be calculated with sufficient accuracy by using the equations shown in the following figure.



## Area Throughput vs Beam Current

The area throughput rate  $A/T$  in square meters per minute is proportional to the electron beam current  $I$  in milliamperes and inversely proportional to the entrance surface dose  $D(o)$  in kilograys, according to the following equation:

$$A/T = K(o) F(i) I / D(o) \quad (1)$$

The factor  $K(o)$  is the entrance surface value of the area processing coefficient. This is 6 times the surface value of the energy deposition per electron  $D(e, o)$  in MeV sq cm/g. The energy deposition is a quantity that can be obtained by Monte Carlo calculation of the depth-dose distribution. Values of these parameters for flat sheets of polyethylene are given in Table 2, following the section on mass throughput vs beam power.

$F(i)$  is the fraction of electron beam current that is intercepted by the processed material. It can be as high as 0.9 for wide, flat sheets of material, but much lower for products such as small-diameter plastic tubing or low-voltage, low-current insulated wire, where less than half of the beam might be intercepted with a multiple-pass product handling fixture.

If this area throughput equation is used to calculate the throughput rate of the product conveyor, then any object on the conveyor will receive the specified dose on the surface facing the electron beam window. With spherical or cylindrical shapes, the dose on the surface facing the beam window will be lower than the dose on other areas where the incident beam is not normal to the surface. The electron energy must be high enough so that the interior parts of the product will receive higher doses than the surface value.

Example 1: With a beam current  $I$  of 1.0 milliampere, an entrance surface dose  $D(o)$  of 10 kilograys, a beam current fraction  $F(i)$  of 0.9 for a wide, flat sheet of material, and a minimum surface value for the area processing coefficient  $K(o)$  of 11.16 with 5 MeV electrons, the area throughput rate would then be:

$$A/T = 11.16 \times 0.9 \times 1.0 / 10$$

$$A/T = 1.00 \text{ square meters per minute}$$

This relationship is called the unity rule, because a beam current of 1 milliampere gives a surface dose of 10 kilograys (1 megarad) to material moving through the beam with an area throughput rate of 1 square meter per minute. With lower electron energies, the area throughput rate per milliampere would be higher, according to the  $K(o)$  values in Table 2.

Example 2: With a beam current of 30 mA, a surface dose of 50 kGy, a beam current fraction of 0.9 for a wide flat sheet of material, and a minimum value for the area processing coefficient of 11.16 with 5 MeV electrons, the area throughput rate would be:

$$A/T = 11.16 \times 0.9 \times 30 / 50$$

$$A/T = 6.03 \text{ sq m/min}$$

or  $A/T = 6.03 \times 60$

$$A/T = 362 \text{ sq m/hour}$$

With the optimum area density  $R(\text{opt})$  of 1.859 g/sq cm or 18.59 kilograms per square meter for 5 MeV electrons in polyethylene, the mass throughput rate would be:

$$M/T = R(\text{opt}) \times (A/T) \quad (2)$$

$$M/T = 18.59 \times 362$$

$$M/T = 6,722 \text{ kilograms per hour}$$

or  $M/T = 6.72 \text{ metric tonnes per hour}$

### **Mass Throughput vs Beam Power**

The mass throughput rate  $M/T$  in kilograms per second is proportional to the electron beam power  $P$  in kilowatts and inversely proportional to the average absorbed dose  $D(\text{ave})$  in kilograys within the material according to the following equation:

$$M/T = F(p) P / D(\text{ave}) \quad (3)$$

$F(p)$  is the fraction of emitted beam power that is absorbed by the processed material.  $F(p)$  consists of two factors, the fraction  $F(i)$  of beam current that is intercepted by the material and the fraction  $F(e)$  of intercepted beam power that is absorbed by the material. Therefore:

$$F(p) = F(i) F(e) \quad (4)$$

Example 3: With an absorbed beam power  $F(p) P$  of 1.0 kilowatt and an average dose  $D(\text{ave})$  of 1.0 kilogray, the mass throughput rate would then be 1.0 kilogram per second. This is another version of a unity rule for radiation processing.

If the entrance surface (minimum) dose  $D(o)$  is a more important processing parameter than the average dose  $D(\text{ave})$  within the material, then a reduced value  $f(e)$  for the fraction of intercepted beam power can be used. This is based on the simplifying assumption that all of the interior dose values are the same as the surface dose. Then:

$$f(p) = F(i) f(e) \quad (5)$$

and

$$M/T = f(p) P / D(o) \quad (6)$$

Example 4: With an emitted beam current of 30 mA, an emitted beam power of  $30 \times 5 = 150$  kilowatts, an entrance surface dose of 50 kilograys, a beam current interception fraction of 0.9 for wide, flat sheets, and a reduced value of the beam power absorption fraction of 0.692 (from Table 2) with the optimum thickness  $R(\text{opt})$  for a 5 MeV electron beam (from Table 1), the mass throughput rate would be:

$$M/T = 0.692 \times 0.9 \times 150 / 50$$

$$M/T = 1.87 \text{ kilograms per second}$$

or  $M/T = 1.87 \times 60 \times 60$

$$M/T = 6,730 \text{ kilograms per hour}$$

or  $M/T = 6.73 \text{ metric tonnes per hour}$

This is essentially the same mass throughput rate as the value of 6.72 tonnes per hour obtained above in the area throughput section. So, the area throughput vs beam current and the mass throughput vs beam power relations, Equations (1) and (3), are compatible for flat sheets of material.

With complex product shapes, it is more difficult to calculate the electron energy absorption fraction  $f(e)$  than the beam current interception fraction  $F(i)$ , which is just the area of the products divided by the area of the conveyor. Then for such applications, Equation (1) is easier to use than Equation (3).

Table 2. Entrance surface values of the electron energy deposition  $D(e, o)$ , the area processing coefficient  $K(o)$ , the reduced energy absorption fraction  $f(e)$  and the full energy absorption fraction  $F(e)$  for flat sheets of polyethylene.

Energy (MeV)	$D(e, o)$	$K(o)$	$f(e)$	$F(e)$
0.4	4.96	29.78	0.000	0.000
0.6	3.80	22.77	0.474	0.496
0.8	2.98	17.89	0.599	0.695
1.0	2.55	15.30	0.619	0.777
1.5	2.12	12.71	0.634	0.850
2.0	1.97	11.80	0.641	0.862
3.0	1.89	11.32	0.663	0.867
5.0	1.86	11.16	0.692	0.875
7.5	1.86	11.16	0.708	0.873
10.0	1.88	11.27	0.730	0.867

## **Conclusion**

The equations and data presented above can be used to calculate the electron energy, beam current and beam power requirements for a variety of EB applications.

The area throughput relation, Equation (1), and the area processing coefficients,  $K(o)$  in Table 2, show that the electron beam processing rates  $A/T$  and  $M/T$  can be increased or the beam current  $I$  and beam power  $P$  can be decreased by using the lowest electron energy which would be sufficient to penetrate the thickest part of the products.

Selecting the electron energy and beam power requirements in this manner can increase the productivity or decrease the capital and operating costs of an industrial electron beam processing facility.