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DOSE ESTIMATION IN THIN PLASTIC TUBINGS AND WIRES IRRADIATED BY ELECTRON BEAM

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Abstract

High energy ionising radiation can be used to beneficially change the properties of plastic materials used in the manufacture of coated wires, cables and extruded tubings. For realisation of this process it is preferable to use electron accelerators as radiation sources. In the present study a scanned 2-MeV electron beam was used to irradiate the simulated objects and the real products. The determination of absorbed dose distribution in the irradiated objects was performed by using the thin polyethylene film equivalent to the insulating material. Equations of dose evaluations for "figure eight" irradiation technique for the real products (thin wires and tubes) are given.

1. INTRODUCTION

For irradiation of long products like wires, cables and tubes it is suitable to use an electron accelerator as a radiation source. It allows to organise a continuous irradiation process by way of transportation of long cylindrical products (wires or tubes) through the zone of the scanned electron beam extracted into atmosphere.

During the irradiation process the main objectives are :

- To prevent the waste of electron beam power.
- To provide the distribution of the absorbed dose in the plastic material as uniform as possible.

The realisation of the two above-mentioned objectives mostly depend on the chosen irradiation technique. An efficient way to irradiate a tubular product is a multiple pass system (handling system) using a sets of sheaves or drums. This system allows the product to make a number of passes through the electron beam zone, with a turn (two opposite sides irradiation) to optimise the dose uniformity and the efficiency of electron beam utilisation.

A variant of above - mentioned irradiation technique, which is used in the present work for irradiation of thin wires and tubes, is a "figure eight" technique [1-4].

2. METHODS AND RESULTS

2.1. The distribution of electron beam along the scanning direction

All parts of the product, irradiated using the "figure eight" technique, will pass through the identical irradiation zone of scanned electron beam. It means that the product will absorb the same average dose.

Multiple successive passing of the product under the scanner allows to accumulate the required absorbed dose in separate cycles. It is also known that the dose absorbed (D) is in direct proportion to the electron beam current I and in inverse proportion to the product running speed V (D ~ I/V). As V is constant, for evaluation of the absorbed dose it is necessary to measure the electron beam energy deposited in the product for each of its pass through the irradiation zone. More precisely, it is necessary to know the electron beam distribution along the scanning direction.

Firstly, a qualitative estimation of this distribution was made. An aluminium collector with dimensions 10 × 5 ×250 mm was moved along the scanning direction Z (Fig. 1). The distance between the collector and scanner was 35 mm.

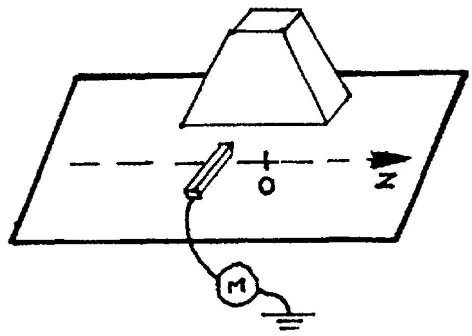

FIG. 1. The position of the collector under the scanner

The electron current I_K in the collector, as it passes along the scanner, was measured by the microamperemeter M. It is observed that the I_K had two maxima, at Z = −135 mm and Z = 145 mm, and a minimum at Z = −3 mm. Outside the zone $-135 \leq Z \leq 145$ mm, the electron beam current I_K decreased very rapidly.

The zone −135 mm ≤ Z ≤ 145 mm was considered as the optimal irradiation field (OIF). For the quantitative estimation of the electron beam along the scanning direction, the electrical scheme given in Fig. 2 was used.

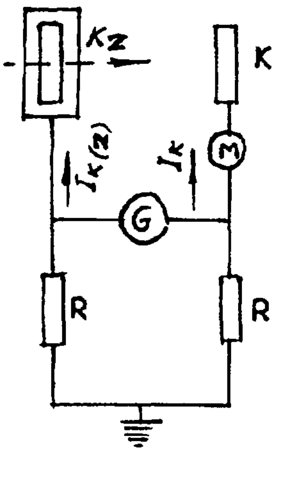

FIG. 2. Electrical scheme for measuring the electron beam distribution along the scanning direction

The aluminium collector K is placed in a fixed position (Z=80 mm) at a distance of 20 mm under the scanner. K and M are respectively the collector and the microampermeter shown in Fig. 1. A hollow collector K_z, placed at a distance 35 mm under the scanner, moves forward and backward (see the arrows in Fig. 2) along the OIF. It is a combination of an aluminium slab (with gap dimensions 10 × 250 mm) with a Faraday cup, isolated from each other. The wall thickness of the Faraday cup and slab are thicker than the maximal range of the electrons with energy 1.81 MeV(electron energy used in this work). G is a galvanometer (5.3 × 10 $^{-3}$ μA/division) with internal resistance 280 Ω. R are ohmic resistances with value of 1500 Ω.

For each pass of the collector K_z along the OIF the indications N (Nmin and Nmax) of the galvanometer G in different zones of OIF were measured. The accelerator parameters were kept constant during these measurements.

The ratio $I_K(z)/I_K$, based on [5], can be calculated by Eq. (1):

$$\frac{I_K(z)}{I_K} = 1 + 0.0116\frac{N}{I_K} \qquad (1)$$

where: $I_K(z)$: is the electron beam current in the collector K_z, and
I_K : is the electron beam current in the collector K.

Taking into account Eq. (1), the OIF was separated in five zones, in such a way that the uniformity of electron beam current $I_K(z)$ in each zone , calculated as the ratio $[I_K(z)]$min / $[I_K(z)]$max to be ≥ 90 %. These zones are:

Zone 1	-50mm ≤ z ≤ 50 mm
Zone 2	50mm ≤ z ≤ 110 mm
Zone 3	110mm ≤ z ≤ 145 mm
Zone 4	-90mm ≤ z ≤ -50 mm
Zone 5	-135mm ≤ z ≤ -90 mm

The data for the nine passes of the collector K_z along the OIF are given in Table I.

TABLE I. THE RATIO $[I_K(z)]$min / Imin and $[I_K(z)]$max / Imin FOR EACH ZONE "i" (i=1-5) [a]

Number	Zone	1	Zone	2	Zone	3	Zone	4	Zone	5
of passes	A/C	B/C	A/C	B/C	A/C	B/C	A/C	B/C	A/C	B/C
1	1.00	1.10	1.01	1.05	1.04	1.09	1.11	1.17	1.17	1.27
2	1.00	1.11	1.01	1.05	1.05	1.11	1.11	1.17	1.17	1.27
3	1.00	1.11	1.01	1.09	1.09	1.13	1.10	1.17	1.17	1.27
4	1.00	1.12	1.00	1.07	1.07	1.10	1.12	1.17	1.17	1.28
5	1.00	1.12	1.01	1.09	1.09	1.14	1.12	1.17	1.18	1.28
6	1.00	1.09	1.03	1.07	1.06	1.13	1.08	1.16	1.17	1.27
7	1.00	1.14	1.03	1.07	1.08	1.13	1.14	1.18	1.18	1.27
8	1.00	1.12	1.02	1.11	1.10	1.15	1.12	1.20	1.21	1.30
9	1.00	1.11	1.02	1.09	1.10	1.15	1.10	1.19	1.19	1.30
Average	1.00	1.11 ±0.02	1.02 ±0.01	1.08 ±0.02	1.08 ±0.02	1.13 ±0.02	1.11 ±0.02	1.18 ±0.01	1.18 ±0.01	1.28 ±0.01

[a] The letters A and B represent respectively: the minimal and the maximal value of electron beam current $I_K(z)$ for each zone "i", while C represents the minimal value of $I_K(z)$ for each pass of the hollow collector along the OIF.

2.2 Dosimetry of irradiation

Before irradiation of the real product (thin wire and tube), the distribution of the absorbed dose in the simulated objects for two-sided irradiation was measured. A thin polyethylene dosimeter film is used for simulation of tube and wire[6]. The dosimeters consist of strips 0.221 mm thick and 25 mm wide.

The irradiation geometry of the simulated objects is given in Fig. 3. The simulated objects (1), are placed under the scanner (3) on the wood holder(4), along the OIF. The collectors (2) are aluminium parallelepipeds with dimensions 5×5×250 mm. They are fixed at the extremities of the OIF. The wood holder and the simulated objects are on the moving table. All they, during the irradiation move with a constant speed, forward and backward, perpendicular to the scanning direction(see the arrows in Fig. 3).

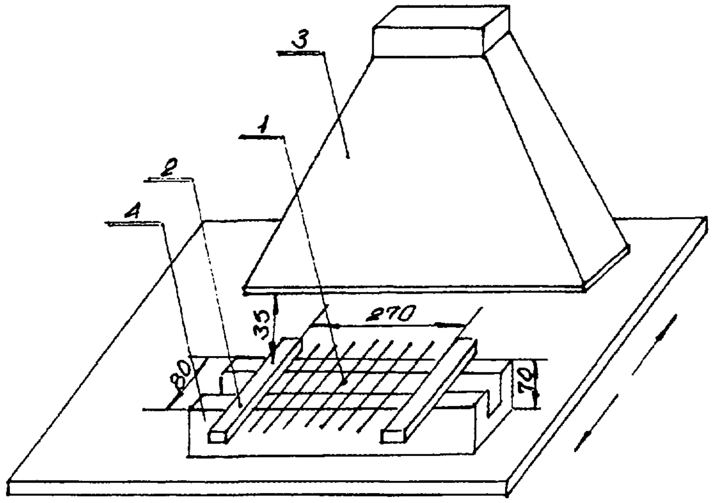

FIG. 3 Irradiation geometry of simulated objects (dimensions in mm)

The irradiation parameters for the simulated objects, tube (insulation wall thickness w =1.5 mm, outer diameter OD = 6mm) and wire (w = 0.9 mm and OD = 4.6 mm) are given in Table II. T, Io, Vo, N given in Table II are : electron energy, electron beam current in collectors, moving speed of the simulated objects, and the number of their passes under the scanner.

TABLE II. IRRADIATION PARAMETERS OF THE SIMULATED OBJECTS

Simulated objects	T (MeV)	Io (μA/cm)	Vo(cm/s)	N
Tube	1.81± 0.02	6.36 ± 0.04	0.721± 0.01	14
Wire	1.81± 0.02	4.35 ± 0.04	0.635 ± 0.01	18

After irradiation the film was unwrapped and the change of the optical density trace ΔOD at 250 nm wavelength was measured along the centre of the film. By using the calibration curve shown in [5] it was possible to calculate the distribution of the absorbed dose. The data for average absorbed dose (minimal and maximal), $D_i$min and $D_i$max in each zone "i", are given in Table III.

TABLE III. THE VALUES (MINIMAL AND MAXIMAL) OF DOSE ABSORBED IN THE SIMULATED OBJECTS FOR EACH ZONE OF THE OIF

Simulated object	Absorbed dose(kGy)	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Tube	Dimin.	185	196	202	213	223
	Dimax.	235	248	256	264	283
Wire	Dimin.	139	143	146	157	169
	Dimax.	252	255	258	281	313

The distributions of absorbed dose in the simulated objects for the zone 1 are given in Fig. 4.

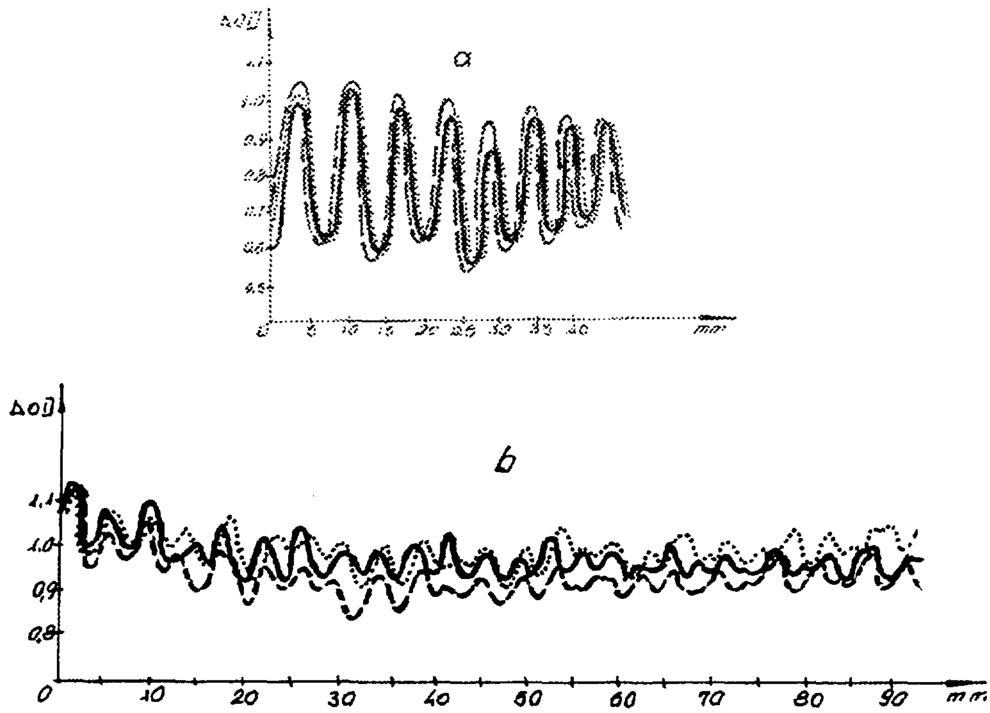

FIG. 4. Dose distributions for the two simulated objects(a-wire, b-tube) in the first zone of OIF.

2.2.1. *Product handling system*

The evaluation of the absorbed dose in the real product is related with the type of the product handling system used. For irradiation of the real products (wire and tube) the "figure eight" irradiation technique was chosen. The design of the product handling system, which can provide the realisation of the above-mentioned technique is given in Fig. 5.

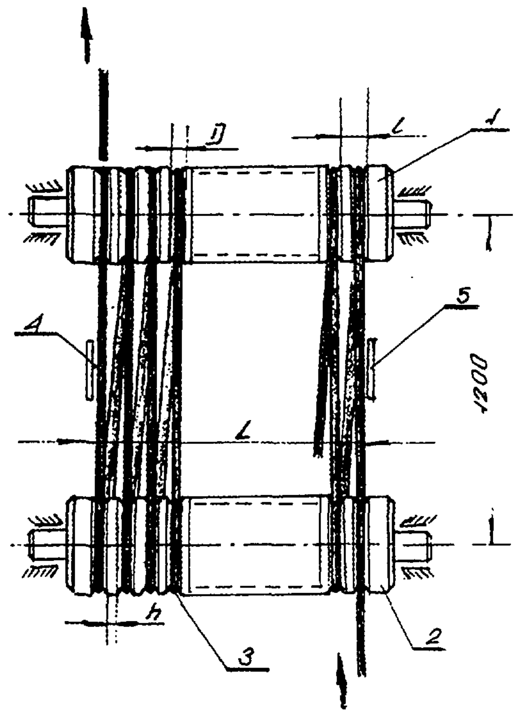

FIG. 5. The design of the product handling system .

If the number of the circular canals (3 in Fig. 5) along the OIF (L) is n_1, then:

$$L= n_1 D +(n_1- 1) h \quad \text{or} \quad n_1= (L+h) / (D+h) \text{, and} \tag{2}$$

$$n = 2 n_1 - 1 \tag{3}$$

where, D : is the diameter of the circular canal on the drum (1and 2 in Fig. 5)
h : is the distance between two successive canals, and
n : is the number of passes, along the OIF, of the real product.

For measuring of the electron beam current, two collectors (5 in Fig.5) (which are the collectors shown in Fig. 3) are put at the extremities of the OIF. This technique has some limitations that were taken into consideration during the irradiation of the real product. The main limitations are :

-the outer diameter of the product may not exceed the half of the centre-line spacing *l* of the circular canals on the drum.

-The accelerator voltage must be equal or higher than the critical value Vc [4].

$$V(kV) = 197p\sqrt{w(OD-w)} + 325 \tag{4}$$

p is the specific gravity of isolated material; w and OD are given in millimetres.

- The relations between duration of the irradiation cycles and interval between them ought to be chosen (by varying the parameters of the handling system) so that the insulation has time to cool.

2.2.2 *Evaluation of dose absorbed from the real product*

The variation of the dose (minimal and maximal) in the first zone (Fig. 4) indicate that the differences between them(for the two simulated objects) are smaller than 10% . The same situation is also valid for the other zones [7-8]. In consequence of that, the data given in Table III where chosen as the representative of the absorbed dose (minimal or maximal) from the simulated products in each zone. Two methods were used for the evaluation of the average dose (minimal or maximal) for the real product.

a) First method

The dose is evaluated as the sum of the average doses (minimal or maximal) absorbed from the real product in each zone "i". If the parameters during the irradiation of the simulated object and the real product are respectively: T, Io, Vo, N (Table II) and T, I, V, n_i then:

$$D\min = \frac{I}{I_o}\frac{V_o}{V}\sum_{i=1}^{5}\frac{D_i \min}{N}n_i \tag{5}$$

$$D\max = \frac{I}{I_o}\frac{V_o}{V}\sum_{i=1}^{5}\frac{D_i \max}{N}n_i \tag{6}$$

where, V, I, n_i and D_i min, D_i max are, respectively, the moving speed of the real product, electron beam current in the collectors, number of passes of the real product in each zone "i" and the average dose (minimal and maximal) absorbed in each zone "i" for the simulated object during N passes under the scanner.

b) Second method

Dose is evaluated based on the average (minimal or maximal) dose absorbed by the simulated object in the first zone and the fact that the dose is in direct proportion to the electron beam current. The distribution of electron beam current along the scanning direction (Table I) indicate that the difference between the extremal values in each zone "i" is smaller than 10%. Therefore, the average values I_i (i=1-5) of this distribution were chosen as the representative values for each zone "i". As the absorbed dose is in direct proportion to the electron beam current, the dose absorbed for the real product is :

$$D\min = \frac{I}{I_0}\frac{V_0}{V}\frac{D_1\min}{N}\sum_{i=1}^{5}\partial_i n_i \tag{7}$$

$$D\max = \frac{I}{I_0}\frac{V_0}{V}\frac{D_1\max}{N}\sum_{i=1}^{5}\partial_i n_i \tag{8}$$

where, parameters I, I_o, V, V_o, n_1, N are those given in Eqs (5) and (6). D_1min and D_1max are minimal and maximal dose absorbed by the simulated object, in the first zone, during N passes under the scanner. The coefficient ∂_i is the ratio I_i / I_1, where I_1 is the average value of the electron beam distribution in the first zone. The values of coefficient ∂_i for each zone "i" are respectively: 1, 1.028, 1.072, 1.106 and 1.193. For irradiation of the real product (wire and tube) the handling system used (Fig. 5) has the dimensions : l=12 mm, D=6 mm and h=6mm.

Using Eqs (2) and (3), the number of passes of the real product in each zone "i", beginning from the first zone, are: 16, 10, 5, 6 and 8.

Eqs (5) and (7) or (6) and (8) can be rewritten as Eqs (9) and (10):

$$\frac{(D\min)_I}{(D\min)_{II}} = \frac{\sum_{i=1}^{5} n_i D_i \min}{D_1 \min \sum_{i=1}^{5} n_i \partial_i} \tag{9}$$

$$\frac{(D\max)_I}{(D\max)_{II}} = \frac{\sum_{i=1}^{5} n_i D_i \max}{D_1 \max \sum_{i=1}^{5} n_i \partial_i} \tag{10}$$

The numbers I and II in Eqs (9) and (10) refer to the first and the second method of dose evaluation. After substitution of the quantities given in Eqs (9) and (10) with their respective values, the ratio of the doses estimated by the two methods was 98%.

Two simulations were made directly on the wire before irradiating it using the polyethylene film dosimeter. The irradiation parameters were: T=1.81 MeV, I=6.66µA/cm and V=1.64cm/s. The minimal (230 kGy and 218 kGy) and the maximal dose value (≈ 390 kGy) were determined by measuring the change of the optical density of the irradiated film dosimeters. The corresponding values estimated from Eqs (5) and (6) or (7) and (8) were Dmin=220 kGy and Dmax= 397 kGy. It means that there is a very good agreement between the dose values estimated by "theoretical" equations and those determined "experimentally". The maximal difference between them was about 5%.

3. CONCLUSIONS

The primary conclusions drawn from this work are:

- Based on the measurements and calculations, the two methods for dose evaluations and their respective equations are given,
- there is a very good agreement between the two methods of dose evaluation. The ratio is 98%, but for practical use the second method is more appropriate. In this case, it is necessary to know the dose distribution only in the first zone,
- the dose values (minimal and maximal) measured directly on the irradiated wire agreed well with those evaluated theoretically. The maximal difference was 5%. It means that the selected method for the dose evaluation is the proper one.

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