Dose Distributions of High-Energy Electrons into Planar and Cylindrical Layers of Low-Density Polyethylene, High-Density Polyethylene, Poly(vinyl chloride), and Copper for Industrial Applications

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ABSTRACT: High-energy electron irradiation of low-density polyethylene, high-density polyethylene, plasticized poly(vinyl chloride) (PPVC), and copper (Cu) of various thicknesses were studied. We measured the dose distributions versus the thicknesses of various layers of these materials. Moreover, we irradiated polyethylene–Cu–polyethylene and PPVC–Cu–PPVC sandwiches and electrical conductors with Cu cores having 1.4–4.8-mm diameters and polymeric (polyethylene and PPVC) insulation 0.6–1.1 mm thick. The irradiation was carried out with 5 and 10 MeV of electrons. The depth–dose distributions for these materials showed that 10 MeV of electrons penetrated polyethylene (up to $R_p \sim 4.5$ cm), PPVC (up to $R_p \sim 3.5$ cm), and Cu (up to $R_p \sim 5$ mm). For the sandwiches (planar geometry), the largest dose levels were at the surfaces of the polymeric insulation materials close to the Cu sheets. For small wires, one-sided irradiation gave a relatively uniform dose distribution, especially with 10 MeV of electrons, and excellent uniform dose distribution was obtained by two-sided irradiation. For wires with comparatively thick insulation, two-sided irradiation with 5 MeV of electrons provided a relatively uniform dose distribution, and a more uniform distribution for this type of wire and cable was achieved by irradiation from four sides and with 10 MeV of electrons. © 2003 Wiley Periodicals, Inc. J Appl Polym Sci 89: 1230–1241, 2003

Key words: polyethylene (PE); poly(vinyl chloride) (PVC)

INTRODUCTION

The crosslinking of polymeric materials by irradiation with an electron beam has been developed for the production of electrical insulation of wires and cables, hot-water piping, heat-shrinkable materials, and so on.[1–8] Irradiation crosslinking can considerably improve the heat resistivity and the resistance to electric discharge, solvents, creep, and environmental and stress cracking. Superior mechanical properties can also be obtained by crosslinking.[3,4,8]

The use of radiation processing in wire and cable manufacturing is regarded as a typical example of its successful industrial application.[5] Electric wires and cables to which radiation processing is applied include wires with thin insulation for electric, electronic, and appliance wiring and power cables with comparatively thick insulation. When an electron beam irradiates polymers, the electron gradually loses its energy by its interaction with the electronic structures of these materials. The distance that the electron traverses depends on the energy of the electron and the density of the irradiated materials.

A serious concern from an engineering point of view is achieving a uniform distribution of the absorbed dose throughout the insulation of wires and cables during irradiation.[9–11] The absorbed dose distribution in small copper (Cu) wire insulation due to multiple-sided irradiation by 0.4 MeV has been reported previously.[11] In this work, we studied the penetration of 5 and 10 MeV of electrons into layers of low-density polyethylene (LDPE), high-density polyethylene (HDPE), plasticized poly(vinyl chloride) (PPVC), and Cu of various thicknesses. Also, we measured the absorbed dose distribution at different position inside the Cu sandwiches with LDPE, HDPE, and PPVC insulating sheets. Moreover, an absorbed dose distribution of 360 around Cu wires and cables irradiated by 5 and 10 MeV of electron beams was measured.

EXPERIMENTAL

Materials

LDPE (LH0030), HDPE (HB0035), and poly(vinyl chloride) (PVC; S6558) were supplied by Iranian Bandar Emam Petrochemical Co. (Khozestan, Iran). Also,

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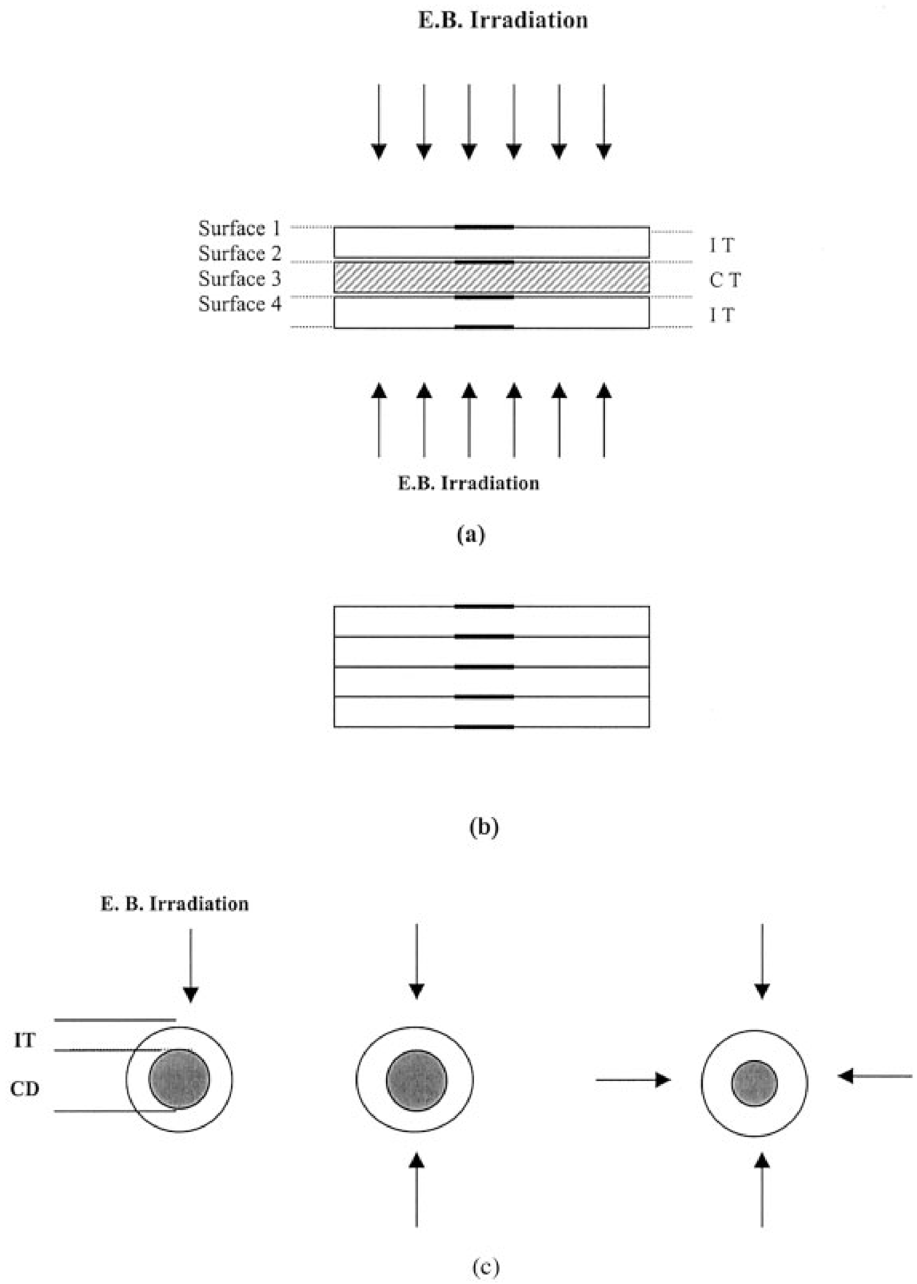


Figure 1 Geometric consideration of sample irradiation: (a) planar, (b) sandwich, and (c) wire. IT = insulation thickness; CT = conductor thickness; CD = conductor diameter.

HDPE (Spanish TR210, Spain) and Cu plates from Iranian Sarcheshmah Copper Co. (Kerman, Iran) were used in this study.

Sample preparation

PVC was mixed with a plasticizer, a stabilizer, and other additives for the preparation of a suitable PPVC compound for wire and cable insulation. The PVC compound and polyethylenes (PEs) were hot-pressed to sheets of 10 × 10 cm^2 and a suitable thickness at 160 and 180°C, respectively. The Cu samples were prepared in sheets of 5 × 10 cm^2 that were 0.1 or 0.2 mm thick. Using these plates, we constructed stacks of plates (Fig. 1) with a suitable thickness of each material interleaved with dosimeter films, as described in ref. 12. In addition, we made from the sheets PE–Cu–PE and PPVC–Cu–PPVC sandwiches. The sandwiches could be planar equivalents of the wires. Also, five types of electrical conductors with PPVC insulation and communication cable with PE insulation were used. The wires were designated $W_{1.4}$, W_2, W_3, and $W_{4.8}$ (Table I), and the cable was denoted C_{200}. The specifications of the cable are explained in Table I.

TABLE I
Specifications of the PPVC-Insulated Cu Wires

Code of wire	$W_{1.4}$	W_2	$W_{2.4}$	W_3	$W_{4.8}$
Conductor diameter (mm)	1.40	2.0	2.40	3.0	4.80
Insulation thickness (mm)	0.6	0.85	0.85	1.0	1.10

Specifications for the cable used in this work is are as follows: A communication cable (200 × 2 × 0.4) designated as C_{200} used in this investigation had 200 pairs of thin wires; each thin wire has a Cu core 0.35 mm diameter and PE insulation 0.25 mm thick. These 400 wires were surrounded by PE insulation 2.3 mm thick, in aluminum cylinder 1.7 mm thick; PE insulation 2.1 mm thick; an aluminum cylinder 0.4 mm thick, and then PE insulation 1.7 mm thick, respectively. The outer diameter of the cable was 36 mm.

Irradiation

The stacks were irradiated from one side, the sandwiches were irradiated from one and two sides, and the wires and cable were irradiated from one, two, and four sides by 5- and 10-MeV electron beams. Irradiation was carried out in air at 25 ± 2°C. A schematic presentation of the irradiation of the samples is shown in Figure 1.

Measurements

A cellulose triacetate (CTA) film (8 mm wide, 0.125 mm thick, absorption band at 280-nm wavelength; FTR125, Fuji Film, Japan) was used as a radiation dosimeter. For planar samples (stack), we measured the dose distribution inside the layers of the different materials to obtain depth–dose distribution curves for each material. For sandwich samples, pieces of the CTA film were inserted between the layers of the insulation material and Cu so that we could measure the doses at surfaces 1–4 (Fig. 1). Figure 1(a) shows surfaces 1–4, on which the CTA films were placed for the absorbed dose measurements. For the wires and cable, the CTA film was wound tightly around the samples. The dose absorbed by CTA films was measured with a Spectronic Genesys Shimadzu spectrometer (Model 8300, Japan). The measurement error was about 5%.

RESULTS

Depth–dose distribution

A general depth–dose distribution curve for the electron irradiation of a homogeneous material is shown in Figure 2. The terms used on the curve have been defined according to ref. 9. Figure 3 presents measured depth–dose distribution curves for LDPE irradiated by 5 and 10 MeV of electrons. Variations of the measured absorbed dose in HDPE as a function of thickness induced by 5 and 10 MeV of electrons are shown in Figure 4. Measured depth–dose distribution curves for PPVC and Cu irradiated by 5 and 10 MeV of electrons are given in Figures 5 and 6, respectively. The electron ranges R_{opt}, R_{50}, R_{50e}, and R_p, deduced from the curves in Figures 2–5, are listed in Tables II and III.

Dose distribution into sandwiches

The absorbed doses inside the Cu sandwiches with sheets of LDPE, HDPE, and PPVC as insulating materials, which were irradiated from two opposite sides by 5 MeV of electrons, were measured (Table IV). Similar absorbed dose measurements for the irradiation of the sandwiches from one side by 10 MeV of electrons are listed in Table V.

Dose distribution into wire and cable insulation

Figure 7(a) illustrates the dose distribution along the CTA dosimeter film, which was wrapped around $W_{1.4}$ wire and irradiated from one side by 5 MeV of electrons. Figure 7(b) shows the polar plot of the dose distribution for regions indicated by letters A–D on curve a. Curves a and b for two-sided irradiation of the same wire by 5 MeV of electrons are presented in Figure 8. The polar plots of the dose distribution for W_2, $W_{2.4}$, W_3, and $W_{4.8}$ wires irradiated from one and

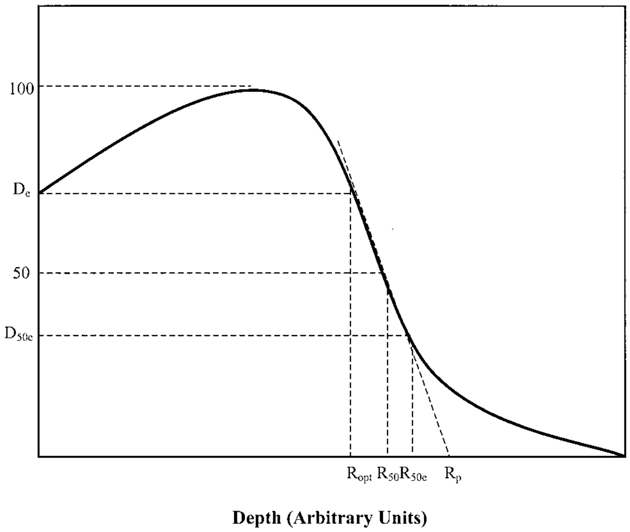


Figure 2 General depth–dose distribution curve for the electron irradiation of a homogeneous material.

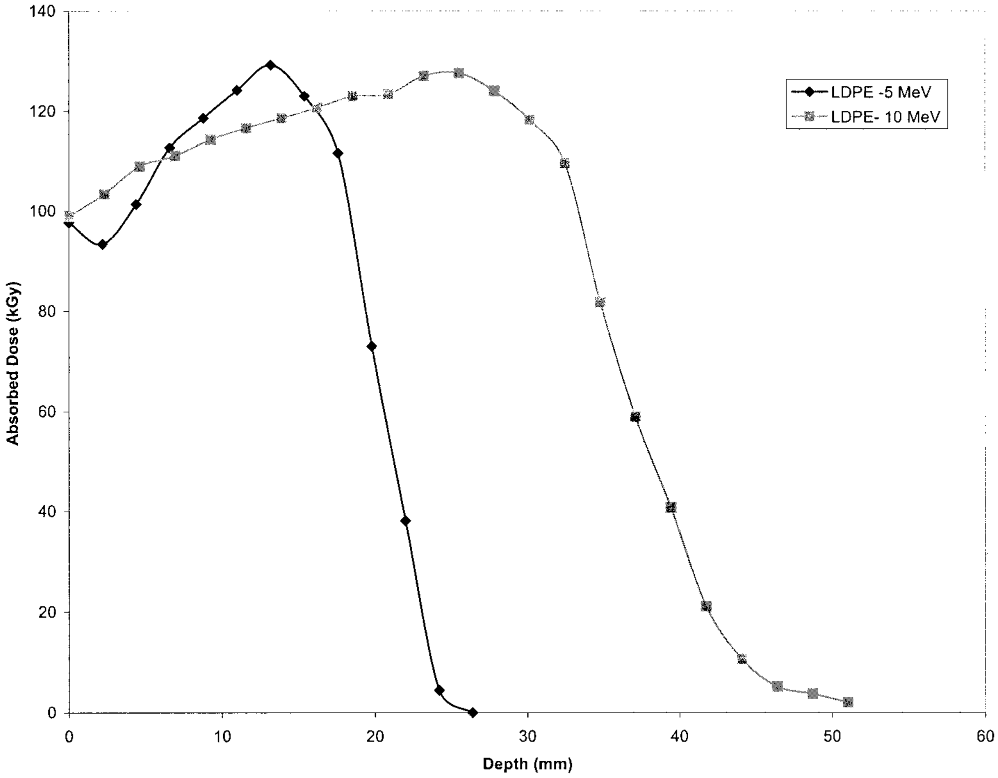


Figure 3 Measured depth–dose distribution curves for LDPE irradiated by 5 and 10 MeV of electrons.

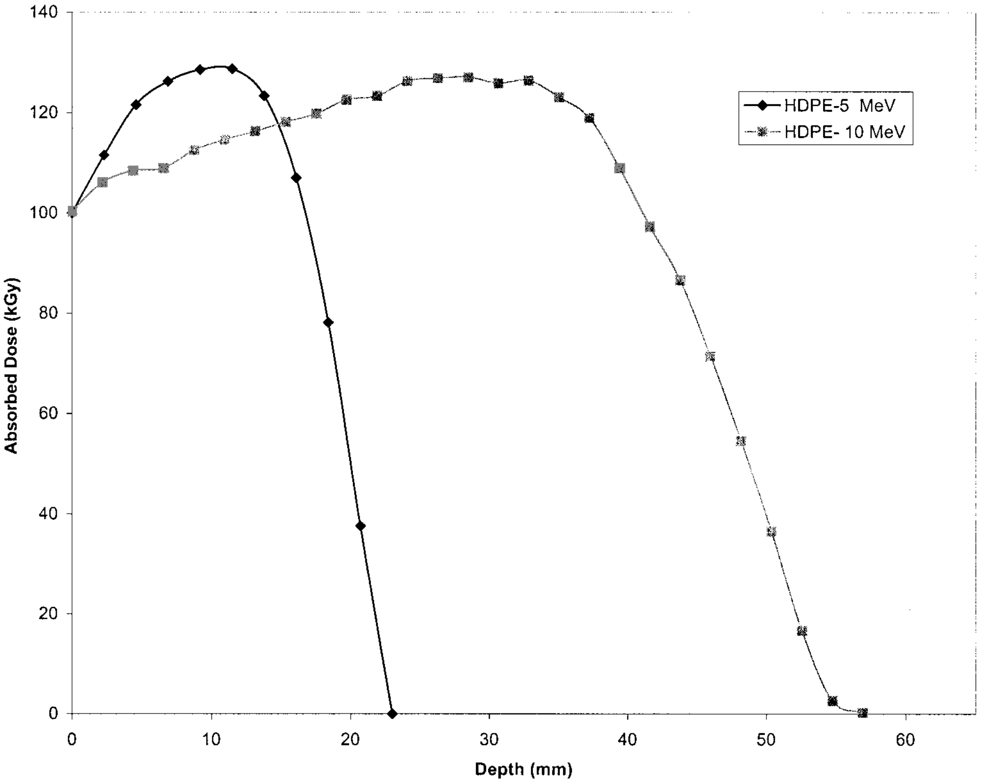


Figure 4 Variations of the measured absorbed dose in HDPE as a function of thickness induced by 5 and 10 MeV of electrons.

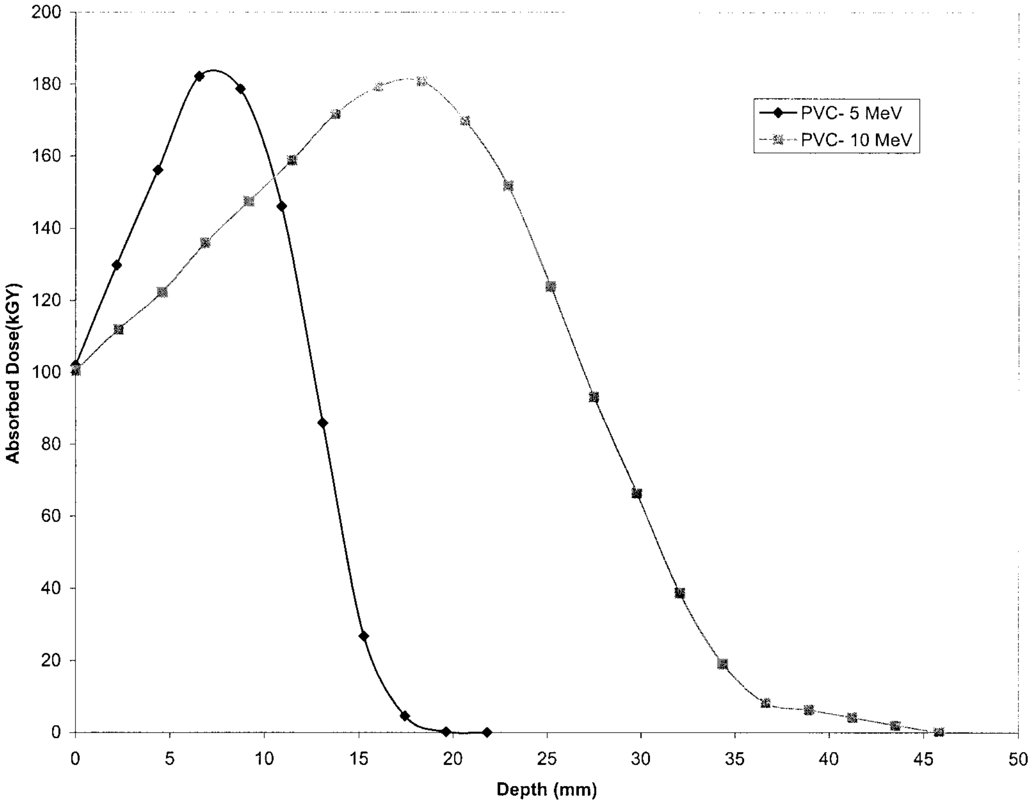


Figure 5 Measured depth–dose distribution curves for PPVC irradiated by 5 and 10 MeV of electrons.

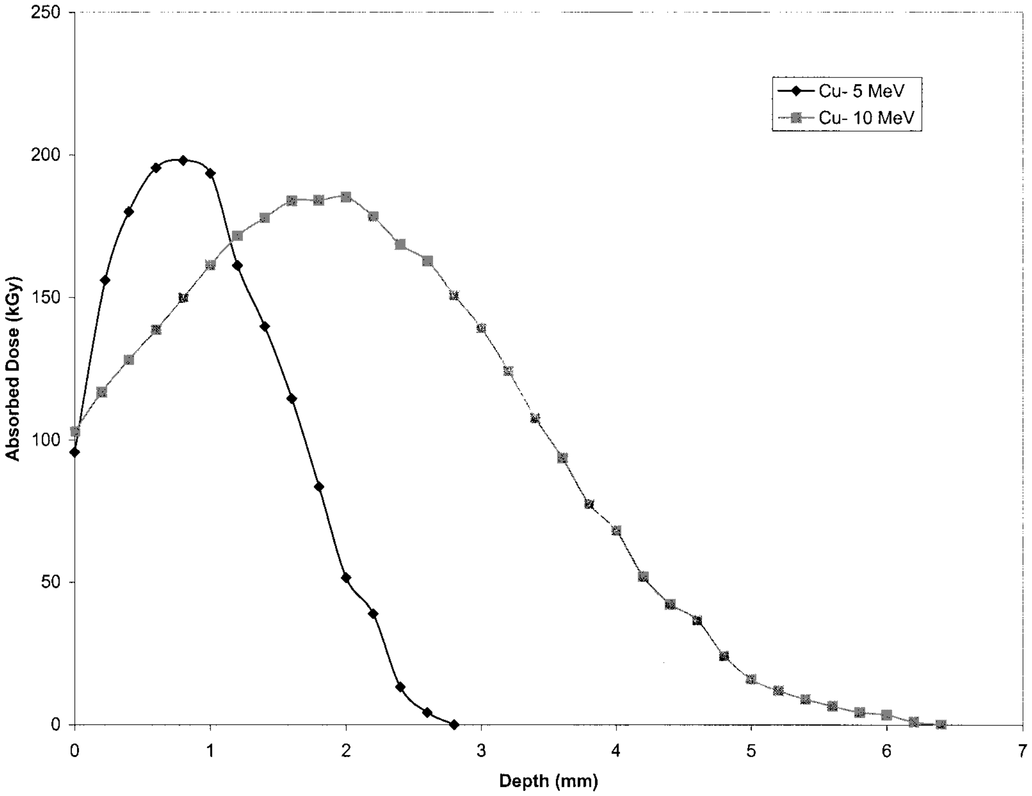


Figure 6 Measured depth–dose distribution curves for Cu irradiated by 5 and 10 MeV of electrons.

TABLE II
Experimental Electron Ranges for Materials Irradiated by 5 MeV of Electrons

Material	$D_{\max}$ (kGy)	D_e (kGy)	R_p (mm)	R_{50e} (mm)	R_{50} (mm)	R_{opt} (mm)
Cu	198.1	95.82	2.38	2.08	1.74	1.7
PVC	146.9	82.18	1.62	1.44	1.29	1.27
HDPE	279.8	217.4	2.26	2	1.92	1.64
LDPE	64.61	48.82	2.42	2.15	2.03	1.83

two sides by 5 MeV of electrons are shown in Figure 9. Polar plots of the dose distribution for PE-insulated communication cable C_{200} irradiated from one and two opposite sides by 10 MeV of electrons are given in Figure 10. The cable was also irradiated from four sides symmetrically by 5 and 10 MeV of electrons. Figure 11 presents polar plots of the absorbed dose distribution around the cable for both cases.

DISCUSSION

Generally, all the experimental depth–dose distribution curves show that the absorbed dose tends to rise with increasing depth within a material to about the midpoint of the electron range, and then it rapidly falls to low values. The shape of the depth–dose distribution curve is determined by the collision of primary and secondary electrons with atomic electrons and nuclei in the absorbing material. Therefore, the shape depends on the atomic composition of the material and on the electron-beam energy. The increase in the dose value at shallow depths can be due to electron scattering. At about the midpoint of the electron range, at which point the electrons slow down, it takes a relatively long time for its energy to be deposited to the material. In this situation, the absorbed dose increases, reaches a maximum value, and then decreases rapidly. The curve for a low atomic material (e.g., PE) has a broad peak, and the electron range is longer. For a higher atomic number material (e.g., Cu), the width of the curve decreases, the height of the peak increases, and the maximum of the curve lies near the surfaces of the materials. When the electron energy changes from 5 to 10 MeV, the depth–dose distribution curves become broader, and the electron ranges (R_{opt}, R_{50}, R_{50e}, and R_p) increase. The depth of penetration is nearly proportional to the electron energy. Therefore, the ranges of 10 MeV of electrons for irradiated samples are considerable (Table II). Similar results for LDPE were obtained previously.[13] Therefore, if high-wall-thickness PE and PVC products are irradiated from both sides,[14] it is possible to irradiate them homogeneously up to about a 10-cm thickness.

For two-sided irradiation of Cu sandwiches by 5 MeV of electrons, the data in Table IV indicate that for thin Cu sheet sandwiches (conductor thickness = 1.4 mm), the average absorbed dose into the insulating material (D = 57 kGy) is higher than twice the irradiation dose at the surface (D_0 = 22 kGy). With increasing Cu sheet thickness (conductor thickness = 4.8 mm), the absorbed dose in the insulating material diminishes to a value slightly higher than the irradiation dose. When the electron-beam energy increases to 10 MeV with an irradiation dose of 60 kGy (D_0 = 60 kGy) in one-sided irradiation of Cu sandwiches (Table III), for thin Cu sheets (conductor thickness = 1.2 mm), the average value of D in front of the Cu sheet is about 69 kGy, slightly higher than D_0 (60 kGy), whereas the absorbed dose in the insulating sheet placed behind the Cu sheet is considerably higher (ca. 87 kGy). For thick Cu sheets (conductor thickness = 4.8), the absorbed dose in an insulating sheet placed behind the Cu sheet diminishes to zero, whereas the absorbed dose in the front sheet is still more than the irradiation dose (Table V).

Seltzer and Berger[15] presented the ratio of D for a thin nylon-base radiochromic dosimeter with a backing of higher atomic number materials to the calculated absorbed dose (D_0) with nylon backing as a function of the atomic number Z of the backing plates for irradiation by a broad beam of 400 keV of electrons with normal incidence. D in the thin dosimeter increased markedly with the atomic number of the backing material, and they obtained D/D_0 = 1.46 for Cu (Z

TABLE III
Experimental Electron Ranges for Materials Irradiated by 10 MeV of Electrons

Material	$D_{\max}$ (kGy)	D_e (kGy)	R_p (mm)	R_{50e} (mm)	R_{50} (mm)	R_{opt} (mm)
Cu	185	103	5.1	4.2	3.6	3.5
PVC	115.5	91.21	3.55	3.1	2.8	2.7
HDPE	127.6	98.9	4.6	4.52	3.85	3.7
LDPE	127.6	98.9	4.45	3.87	3.66	3.33

TABLE IV
Measured Doses at the Surfaces of LDPE-, HDPE-, and PPVC-Insulated Cu Sandwiches Irradiated from Two Sides by 5 MeV of Electrons

Surface	PPPVC (kGy)	LDPE (kGy)	HDPE (kGy)	Thickness of the sheets (mm)	Sandwich code corresponding to wire
1	53.62	55.82	54.98	IT = 0.60	$W_{1.40}$
2	62.22	60.40	60.40	CT = 1.40	
3	61.9	59.21	59.70		
4	53.96	54.64	55.65		
1	37.26	34.86	35.17	IT = 0.85	$W_{2.0}$
2	41.70	43.54	44.50	CT = 2.0	
3	43.19	41.54	47.10		
4	37.26	36.39	37.10		
1	29.69	29.90	31.38	IT = 0.85	$W_{2.40}$
2	38.64	34.47	35.48	CT = 2.4	
3	36.71	33.36	36.59		
4	29.52	29.01	35.25		
1	29.63	28.13	28.13	IT = 1.0	$W_{3.0}$
2	35.55	32.71	33.77	CT = 3.0	
3	35.13	31.94	33.06		
4	28.6	28.39	28.13		
1	27.14	28.13	28.8	IT = 1.10	$W_{4.80}$
2	32.92	32.12	33.54	CT = 4.8	
3	31.78	31.90	33.08		
4	28.05	27.17	27.88		

IT = insulation thickness, CT = conductor thickness. The irradiation dose in a CTA film at the surface 1 (in the absence of a sandwich) was 22 kGy.

TABLE V
Measured Doses at the Surface of LDPE-, HDPE-, and PPVC-Insulated Cu-Sandwiches Irradiated from One Side by 10 MeV of Electrons

Surface	PPPVC (kGy)	LDPE (kGy)	HDPE (kGy)	Thickness of the sheets (mm)	Sandwich code corresponding to wire
1	67.07	64.12	65.98	IT = 0.60	$W_{1.20}$
2	71.12	69.1	70.77	CT = 1.20	
3	93.77	70.88	68.24		
4	80.54	69.8	63.12		
1	68.80	64.91	66.60	IT = 0.60	$W_{1.4}$
2	85.20	80.77	83.12	CT = 1.40	
3	47.77	77.16	70.13		
4	40.20	60.54	61.45		
1	69.90	61.90	64.12	IT = 0.85	$W_{2.0}$
2	90.30	80.60	81.13	CT = 2.0	
3	10.20	30.12	30.29		
4	5.12	14.10	13.17		
1	68.18	61.30	61.50	IT = 0.85	$W_{2.4}$
2	96.12	90.65	88.80	CT = 2.40	
3	4.20	8.30	11.30		
4	2.20	7.21	8.20		
1	66.20	62.60	65.30	IT = 1.0	$W_{3.0}$
2	86.50	86.50	80.20	CT = 3.0	
3	0.80	1.60	1.80		
4	~0	~0	~0		
1	63.90	61.50	63.07	IT = 1.10	$W_{4.80}$
2	70.20	65.77	68.11	CT = 4.8	
3	~0	~0	~0		
4	0	0	0		

IT = insulation thickness, CT = conductor thickness. The irradiation dose measured by a CTA film at the surface 1 (in the absence of samples) was 60 kGy.

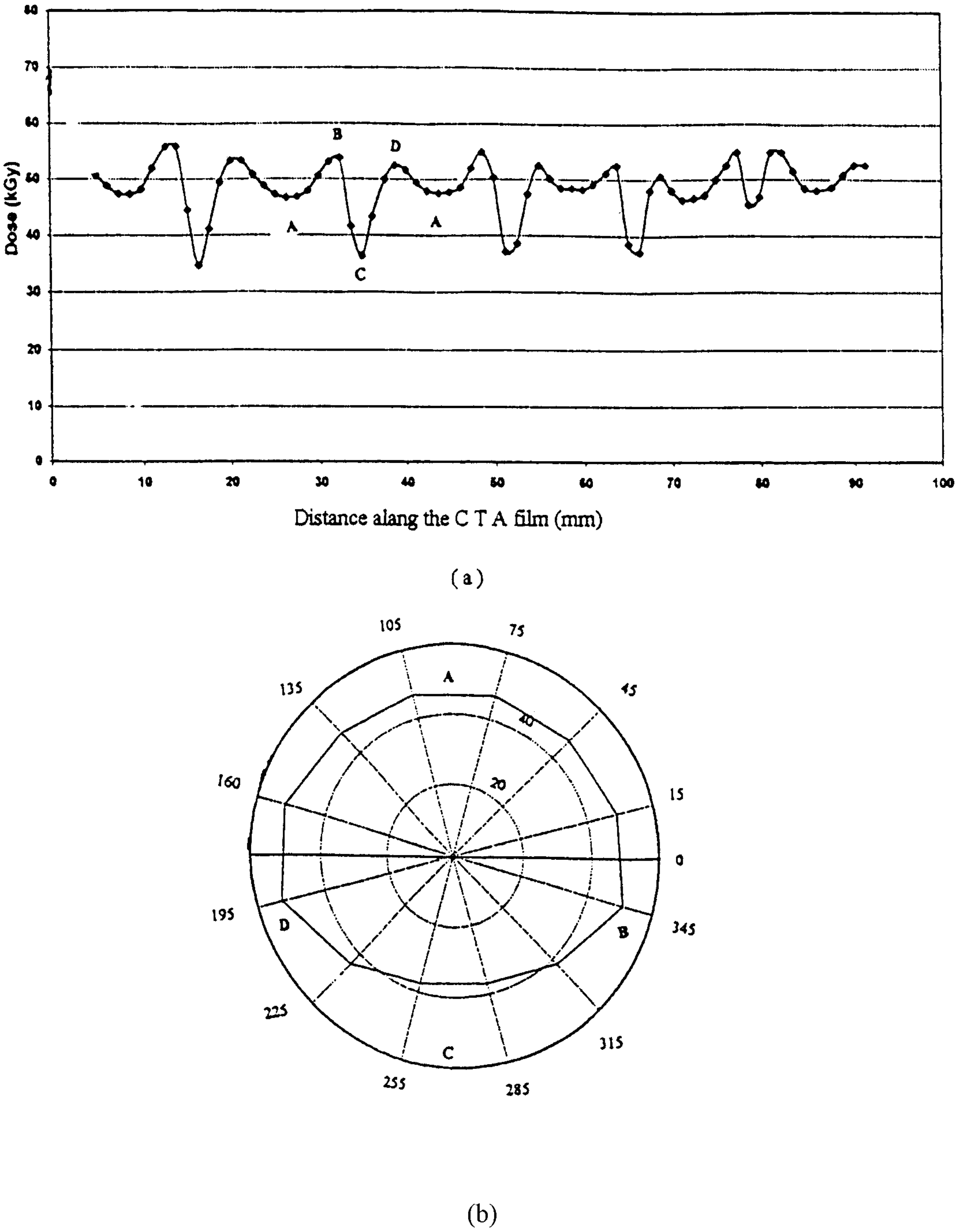


Figure 7 (a) Dose distribution for a CTA dosimeter film wrapped around $W_{1.4}$ wire and irradiated from one side by 5 MeV of electrons and (b) polar plot of the dose distributions for regions indicated by letters A–D on curve a.

= 29) backing. Our results for 10 MeV of electron-beam irradiation (Table V) shows D/D_0 equal to about 1.2–1.6 for Cu sheets with different thicknesses. A Cu sheet 2.4 mm thick has a maximum value ($D/D_0 = 1.6$). This thickness is nearly equal to the electron range at the maximum absorbed dose in Cu. The increase of the absorbed dose level in the insulating materials when they are placed close to the Cu sheet can be explained by depth–dose distribution curves of Cu and insulating materials. When the thickness of the Cu sheet is less than the electron range at the maximum absorbed dose in Cu, there is considerable electron backscattering. The transmission of electrons decreases with increasing Cu sheet thickness, and for a Cu sheet about 4.8 mm thick, the transmission is stopped (Table III). When the sandwich is irradiated from two sides, the dose uniformity in the insulating materials increases in comparison with one-sided irradiation.

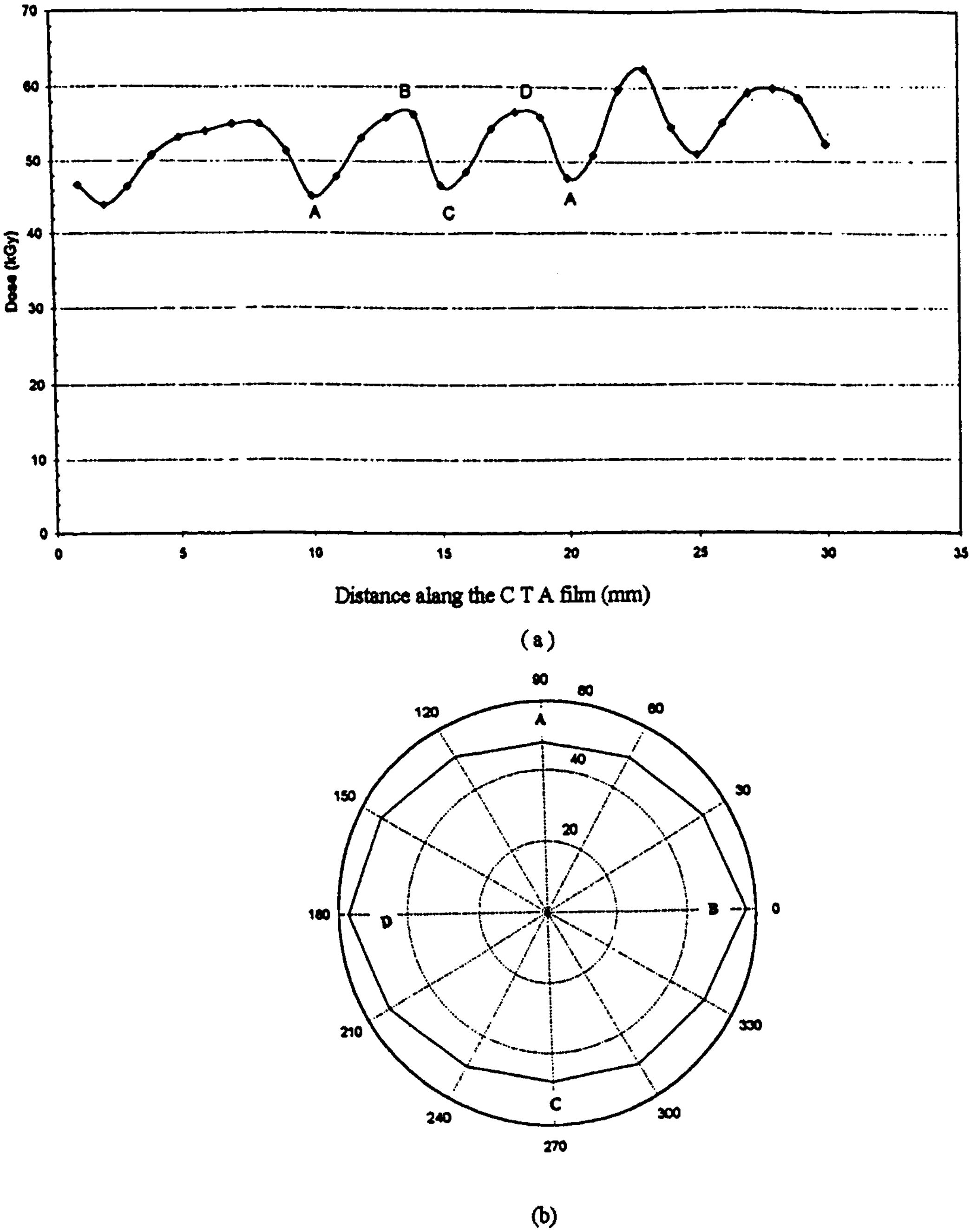


Figure 8 (a) Dose distribution for a CTA dosimeter film and (b) polar plot of the dose distribution for two-sided irradiation of $W_{1.4}$ wire by 5 MeV of electrons.

For wire and cable, for the one-sided irradiation of small Cu wires ($W_{1.4}$ and W_2), the absorbed dose around the wire is approximately uniform with a slight decrease behind the wire and a slight increase at lateral sides (Figs. 7 and 9). However, with the conductor diameter increasing to 4.8 mm, there is a markedly nonuniform dose distribution because of attenuation by the Cu core and a buildup in the dose in the lateral sides of the insulation (Fig. 9). When the wires are irradiated from two opposite sides, there is a considerable improvement in the dose uniformity, and especially for small Cu wires, the dose uniformity is excellent. The uniformity decreases gradually with increasing Cu wire diameter, and the dose level in the lateral sides is higher than the dose level in the front and back of the wire (Figs. 8 and 9). It can be observed from Figure 10 that one-sided irradiation of the C_{200} cable induces a practically nonuniform dose distribution around the cable, with the highest dose levels in the lateral sides (~100 kGy) and a zero dose level in the back of the cable. Double-sided irradiation presents relatively better dose distribution uniformity,

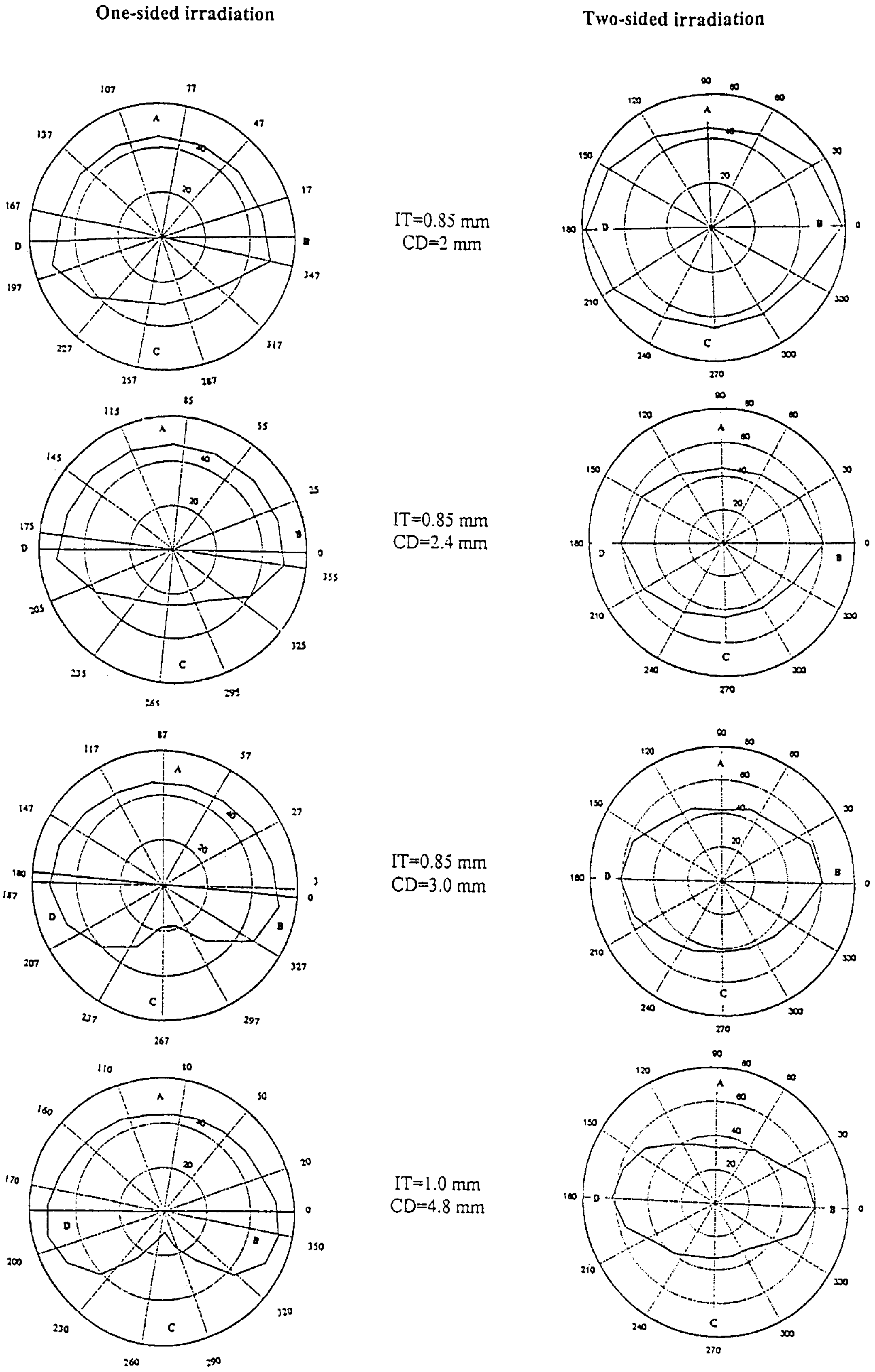
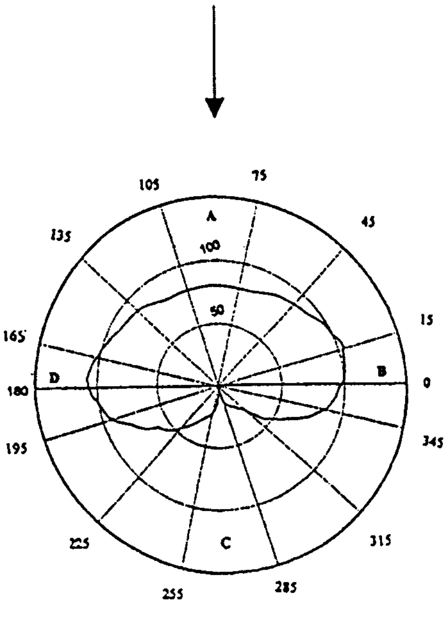
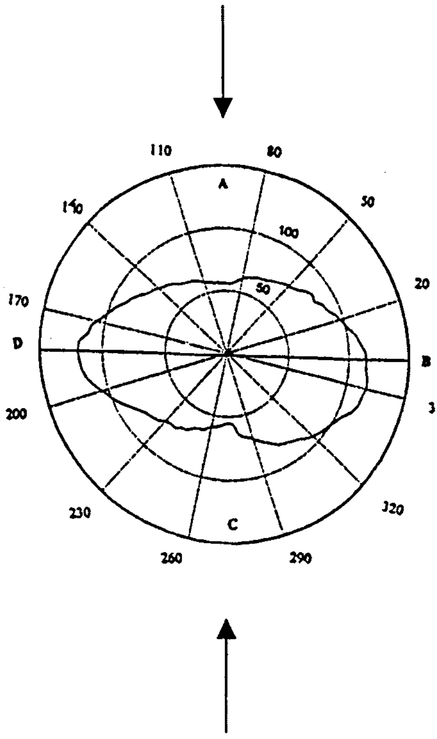


Figure 9 Polar plots of dose distributions for W_2, $W_{2.4}$, W_3, and $W_{4.8}$ wires irradiated from one side and two sides by 5 MeV of electrons.

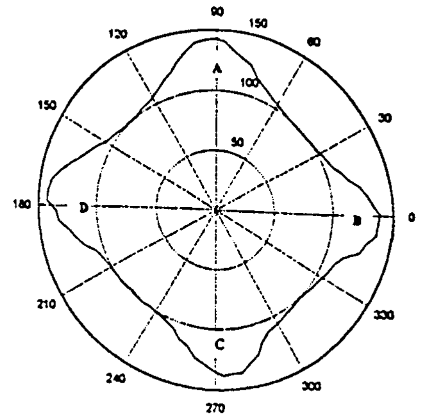


One-sided irradiation

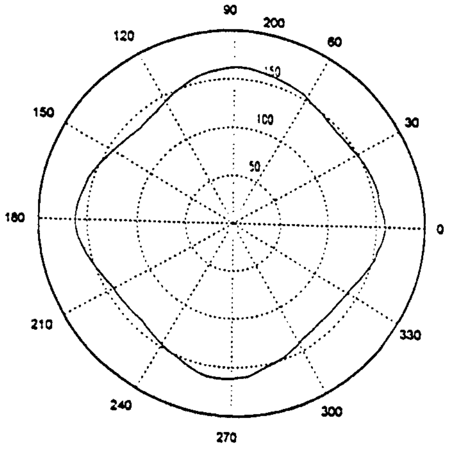


Two-sided irradiation

Figure 10 Polar plots of the dose distribution for PE-insulated C_{200} communication cable irradiated from one side and two sides by 10 MeV of electrons.



Four-sided irradiation (5MeV)



Four-sided irradiation (10 MeV)

Figure 11 Polar plots of absorbed dose distributions around C_{200} cable irradiated from four sides symmetrically by 5 and 10 MeV of electrons.

although the variation of the dose level around the cable is still about 60 kGy. A more uniform dose distribution is afforded by equivalent irradiation from four sides by 5 MeV of electrons (Fig. 11) with a variation dose level of about 40 kGy.

As a result, the dose level at the lateral sides is somewhat higher because of attenuation by the Cu core, electron backscattering, and the relatively long range of electrons that enter directly into the insulation at the lateral sides. The nonuniformity of the dose distribution in one-sided irradiation can be removed by multiple-sided irradiation of thick wire and cable with high-energy electrons. It is obvious from Figure 11 that the dose distribution around the C_{200} cable irradiated from four sides by 10 MeV of electrons is relatively uniform and that the variation of the dose level is about 15 kGy.

High-energy electron-beam irradiation of LDPE, HDPE, and PVC results in crosslinking. The crosslinking of these materials, which are used widely as insulation and jackets of cables and wires, improves their mechanical and thermal properties. The optimum absorbed dose that induces the maximum crosslinking of these materials has been investigated in our previous works.[3,4] Therefore, we have investigated here the conditions for obtaining homogeneous absorbed dose distributions in these materials to provide homogeneous crosslinking.

CONCLUSIONS

1. The depth of the penetration depends on the electron-beam energy, and a 10-MeV electron beam has a longer range (ca. twofold) in LDPE, HDPE, PPVC, and Cu in comparison with a 5-MeV electron beam.
2. The dose level at the surfaces of these materials is lower than immediately below the surface, and the maximum absorbed dose below the surface is very pronounced for Cu.
3. Because of one-sided irradiation by 10 MeV of electrons and the influence of the electron backscattering of the Cu sheet being placed behind the insulation layer (LDPE, HDPE, or PPVC), the absorbed dose in the insulation increases up to about 30 kGy higher than the irradiation dose ($D/D_0 = 1.2$–1.6). These values increase with increasing Cu sheet thickness.
4. For two-sided irradiation of Cu sandwiches by 5 MeV of electrons, the augmentations of D due to the presence of thin Cu sheets are more than twice D_0 at each surface. However, with increasing Cu sheet thickness, the absorbed dose diminishes to a value slightly higher than the irradiation dose.
5. The double-sided irradiation of small wires with 5 MeV of electrons induces an excellent uniform absorbed dose distribution into the insulation of these wires. For thicker wires (i.e., $D = 4.8$ mm), four-sided irradiation by 5 MeV of electrons is recommended. However, for the cable (i.e., C_{200}), more dose distribution uniformity can be achieved by four-sided irradiation and by 10 MeV of electrons.

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