Electron Beam Crosslinking of Wire and Cable Insulation

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Crosslinking provides significant commercial benefits to wire and cable insulation. Ionizing energy, as provided by an accelerated electron beam (EB), is an efficient means of crosslinking the polymers that are used for wire and cable jacketing. In this process, chemical bonds are formed between polymer molecules to produce a three-dimensional insoluble network. This can be done without heat. In most instances, ionization causes the abstraction of hydrogen from a polymer to produce active sites along a polymer chain that can bond to similar sites on adjacent chains without the use of crosslinking agents. In some instances, specific activators may also be used to enhance the crosslinking process. EB processing is faster, more controllable and more economical than thermal and/or chemical crosslinking when used in the production of insulated wires and cables.

EB crosslinked wire and cable insulation exhibits several desirable properties. It will not melt and flow at elevated ambient temperatures, nor melt and flow should the conductor become heated due to a shorted electrical circuit. EB crosslinking protects wire and cable insulation during a soldering operation, when a short circuit condition occurs or at high-temperatures, as near the engine or exhaust pipe of an automobile. EB crosslinking reduces the risk of flame propagation should a fire occur in electrical equipment. Tensile strength, especially at elevated temperatures, is increased, as are abrasion resistance, stress crack resistance and solvent resistance [1-9].

Applications

The use of crosslinked polyvinyl chloride (PVC) and polyethylene (PE) insulation for thin wall, low voltage wires that are found in motors, automobiles, household appliances, computers and other electronic equipment was introduced and gained commercial acceptance more than thirty years ago. The EB crosslinking process has been proven to be less expensive, requiring less factory floor space, allowing a greater selection of insulating materials, permitting production over a wider range of wire gauges and giving faster processing rates than continuous vulcanization (CV), which requires heat and time. The CV process is impractical for small diameter wires because of their limited tensile strength. The use of moisture to cure silane crosslinked PE is an even slower process than CV with heat. The nearly instantaneous EB crosslinking process facilitates shorter runs with various product specifications and just-in-time production schedules.

The first company to produce EB crosslinked wire and other crosslinked plastic products was the Raychem Corporation, which was founded by Paul Cook in 1957. Its main offices are in Menlo Park, California, but it has operations in 40 countries and sales in 85 countries. It produces about 50,000 different products, and its annual sales are well over 1.0 billion dollars. This pioneering company is now an important part of Tyco Electronics Corporation [10].

One of the largest commercial applications of electron beam crosslinked wire was the production of distributing frame wire for the central exchanges of the Bell Telephone system. Crosslinked PVC was adopted in the early 1970s to replace a more complex and costly wire consisting of uncrosslinked PVC which was covered with a cotton braid that had to be coated with a special lacquer to promote fire retardance. Tetra-ethyleneglycol dimethacrylate (TEGDM) was

added to the PVC to aid in EB crosslinking. A stabilizer, a processing lubricant and a polymeric plasticizer were also included [11]. This successful application motivated other organizations to develop wire and cable products using crosslinked PVC insulation [12-16]. Crosslinked PE and other ethylene copolymers were also being developed at that time for high-performance wires and cables [17, 18].

The Union Carbide Corporation (now part of Dow Chemical) developed an EB crosslinkable low smoke, low toxicity, flame retardant, non-halogen containing, cable jacketing compound that consists mainly of ethylene vinylacetate (EVA) and aluminum trihydrate (ATH). Similar EB crosslinked cables were specified by the New York City Transit Authority for their buses and subway trains during the 1980s [9].

Following a tragic fire aboard the aircraft carrier USS Forrestall in 1967, the United States Navy realized that toxic fumes and dense smoke from burning PVC jacketed cables created a dangerous firefighting environment within the confines of a ship [19]. In response to this, the US Navy developed a new specification for a family of low smoke, low toxicity shipboard cables. The conductors were insulated with polyolefins and jacketed with polyvinylidene fluoride (PVDF-Kynar™) [9]. Both of these materials were crosslinked with EB processing.

EB crosslinked ethylene tetrafluoroethylene (ETFE-Tefzel™) wire is also used in aircraft airframes. This insulation is thinner and lighter than the materials used for comparable wires. It can be used at temperatures up to 200 degrees Celcius and will perform temperatures as low as -65 °C [9]. In general, fluoropolymers are superior to the polyolefins, such as polyethylene, for very high temperature applications [20-24].

Another application of EB crosslinking is the production of anti-lock brake cables for automobiles. These cables must be flexible and resistant to abrasion from sand and gravel that are thrown up from the road. Resistance to salt, oil and gasoline is also important. EB crosslinking is also used in the production of welding cables wherein EB crosslinks a rubber jacketing. In many areas, EB processing is THE alternative to CV curing, as in this case. The advantage of EB curing is a higher production through-put rate and lower energy consumption than alternative curing systems [9].

Crosslinkable Formulations

Polyethylene (PE) is the most common polymer used for EB crosslinkable insulation. PE has low cost, has a favorable response to EB processing and minimal toxicity when exposed to a fire. Blends of PE and ethylene-propylene copolymers (EPM) or ethylene-propylene-diene (EPDM) elastomers are used if greater flexibility is needed. Flame retardant compositions of PE/EPM or PE/EPDM are replacing polyvinyl chloride (PVC) because of concerns over the release of toxic chlorinated byproducts when PVC compounds are exposed to a fire. PE, EPM and EPDM can be made flame retardant by adding aluminum hydrates or other compounds to the formulation. Hydrates absorb energy and release water vapor when decomposed in a flame and thereby retard its propagation.

A typical flame retardant EB crosslinkable formulation is given below in Table 1. PE/EPM or PE/EPDM are used as the polymer base. This combination provides flexibility while not lowering dielectric properties and not increasing moisture permeability as would ethylene copolymers, such as ethylene vinyl acetate (EVA) and ethylene acrylate copolymers, such as ethylene ethylacrylate (EEA). In this illustrative formulation, Hydral 710 is aluminum trihydrate (Al(OH)3), a compound that releases water when exposed to combustion conditions. Zinc oxide (ZnO) is commonly used to enhance the aging properties of the material. A process aid, such as mineral oil, facilitates compound extrusion around the conductor. Silane A-172 is a wetting agent used to enhance the interaction between the polymer and the Hydral 710. The antioxidant also reduces aging effects. Trimethylol propane triacrylate (TMPTA) and tri-allyl cyanurate (TAC) are multi-functional monomers that enhance the crosslinking response and thus reduce the amount of dose needed to crosslink the wire or cable jacketing. This effect increases the processing speed. One or the other of these agents can be used. This type of insulation can tolerate temperatures as high as 150 °C [7,25-30]. The weight fraction of Hydral 710 is 250/373 = 0.67 and the calculated density of the insulation is 1.61 g/cu cm. The density and atomic composition of this type of flame retardant insulation should be taken into account when determining the maximum EB penetration. (See the section below on Physical Aspects, etc.)

Table 1.
Typical Flame Retardant Wire and Cable Formulation

Component	Parts by Weight
PE-EPDM	100
Hydral 710	250
Zinc Oxide	5
Process Aid	10
Silane A-172	2
Antioxidant	1
TMPTA or TAC	5

Processing Methods

Small diameter wires or cables are usually EB crosslinked by passing them many times through a wide, scanning beam. This method has several benefits. (1) A narrow, high-current electron beam must be scanned to increase its width and reduce the average current density to avoid overheating the thin metallic beam window of the accelerator; (2) The scanning beam will be much wider than the wire or cable diameter, so that such products can pass through the beam many times to intercept most of the beam current; (3) Multiple passes also avoid the possibility of overheating the insulated wire or cable by allowing some of the heat from EB processing to dissipate between passes.

Small wires can be EB processed while passing back and forth through the beam by using a wire handling fixture that consists of two rows of sheaves or two solid drums displaced on opposite sides of the scanning beam, as shown in Figure 1.

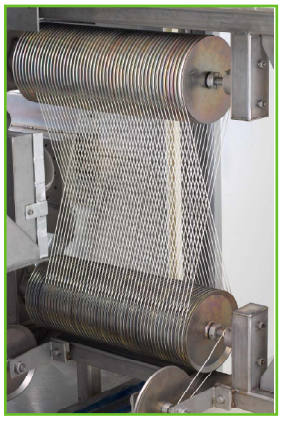


Figure 1.
A figure-eight multiple sheave fixture for electron beam processing of small size insulated wire and plastic tubing.

This arrangement is usually called the figure-eight method of under beam exposure. Larger wires and cables require a larger bending radius and can be processed with a four-drum fixture, as shown in Figure 2.

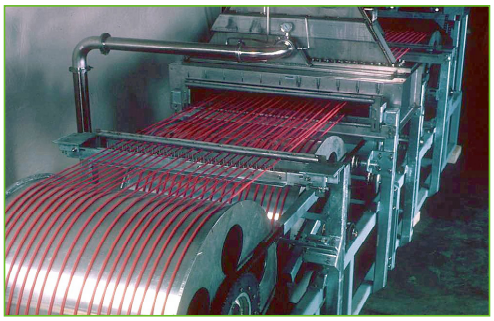


Figure 2.
A four-drum fixture for electron beam processing of medium size insulated wire, cable and plastic tubing.

This is a modification of the simpler two-drum race track method, which has the disadvantage when processing thicker wires and cables with larger drums in that the forward pass is closer to the beam window and receives a higher dose than the more distant reverse pass. In addition to using larger outer drums for thicker wires and cables, the two inner drums of the four-drum fixture bring the reverse pass closer to the forward pass so that the doses on opposite sides of the products are nearly the same. This method also keeps the forward and reverse passes perpendicular to the plane of the scanning electron beam so that the beam strikes the wires and cables at right angles to their direction of motion, thereby providing the greatest penetration into the insulating material [30-32].

The EB energy and consequently the electron range should be at least sufficient to penetrate the radial thickness of the insulation and preferably more than this. Some of the beam will strike near the sides of the wire or cable where the chordal thickness is greater than the radial thickness. The electrons need not penetrate the full chordal thickness since the wires will be treated from opposite sides and small wires will twist slightly between successive passes on the under-beam handling system when passing through the beam. Also, the divergence of the scanning beam causes the sides of the wire or cable to be treated as the wire progresses from one end to the other of the multiple pass under-beam fixture [32].

The outer sheaths on very large cables can be treated by rotating the cables as they pass through the electron beam along the scanning direction. With this method, both the pay-off and take-up reels are rotated outside of the shielded treatment room. The electron energy needs to be just enough to penetrate the radial thickness of the sheath. In this way, a nearly uniform dose distribution around the cable will result. Large cables may have to be cooled inside and outside of the treatment room when a relatively high dose is delivered in a single pass through the beam [33]. However, proper formulation of the cable jacketing can reduce the dose needed to impart crosslinking and thereby reduce the temperature rise.

Physical Aspects of Electron Beam Processing

Electron Energy Requirement

The amount of crosslinking increases with the dose, which is defined as the absorption of energy per unit mass. The common unit of dose for electron beam processing is the kilogray (kGy) or the absorption of one joule (watt-second) per gram of material. Polymer crosslinking usually requires doses in the range of 50 to 150 kGy, depending on the chemical composition of the material.

The dose within the material is usually not uniform. With electron energies above 500 kiloelectron volts (keV), the dose tends to increase with depth in the material to about half of the maximum electron range and then decrease to nearly zero at a greater depth where the electrons have dissipated most of their kinetic energy. A useful quantity is the depth where the exit dose has diminished to 50 percent of the entrance dose. The electron energy should be enough to make this quantity, usually named R(50e), equal to or greater than the thickness of the insulation. Values of R(opt), the depth where the exit dose equals the entrance dose, R(50), the depth where the exit dose equals 50 percent of the maximum dose, and R(50e) are given in Tables 2A and 2B for a wide range of electron energies in flat materials, assuming the material composition listed in Table 1 above [34-36].

Table 2A.
Electron Ranges in Flame Retardant Polyethylene Insulation

Electron Energy keV	400	600	800	1000	1500	2000	2500	3000
R(opt) cm	0.0000	0.0419	0.0924	0.143	0.273	0.400	0.527	0.653
R(50) cm	0.0339	0.0765	0.122	0.170	0.300	0.428	0.560	0.694
R(50e) cm	0.0339	0.0789	0.131	0.187	0.334	0.478	0.624	0.770

The normalized ranges (thickness x density in g/sq cm) can be obtained by multiplying the ranges in cm, as given above, by the volume density of the flame retardant insulation, which has been calculated to be 1.614 g/cu cm. Materials with different volume densities tend to have similar normalized ranges, which can also be called areal or area densities. The areal density of a flat sheet can be measured by dividing its weight by its area. (Thickness x density = weight / area in g/sq cm). The areal density is a useful quantity for comparing electron ranges in materials with different compositions and volume densities [34-36].

Table 2B.
Electron Ranges in Flame Retardant Polyethylene Insulation

Electron Energy keV	400	600	800	1000	1500	2000	2500	3000
R(opt) g/sq cm	0	0.0677	0.149	0.230	0.440	0.645	0.850	1.053
R(50) g/sq cm	0.0548	0.124	0.197	0.274	0.484	0.690	0.903	1.120
R(50e) g/sq cm	0.0548	0.127	0.212	0.301	0.538	0.772	1.006	1.242

In addition to specifying the average dose needed to crosslink the insulation, knowing the absorbed dose distribution within the wire or cable insulation can provide more assurance that the electron energy is sufficient. The absorbed dose distribution depends on the thickness, density and atomic composition of the insulation as well as the diameter and composition of the metallic conductor. Because of the cylindrical geometry and the shielding and backscattering effects of the conductor, accurate calculations of the dose distribution are not simple, but they can be done with suitable Monte Carlo probability codes. Several codes are available, but most of them are not very user-friendly [37, 38]. IBA Industrial, Inc. can provide advice regarding these types of calculations [35].

Temperature Rise

The thermal capacity of polymeric insulating material is typically about half that of water, e.g. about 2 joules per gram per degree Celcius. With this value, a dose of 100 kGy absorbed quickly in a single pass of the wire through the electron beam would cause the temperature of the insulation to rise about 50 degrees Celcius. However, with a multiple-pass underbeam fixture which could have more than 100 passes, the dose per pass would be less than 1 kGy and the temperature rise per pass would be less than half a degree Celcius. The multiple-pass method allows much of this heat to dissipate between passes.

Processing Rate

The results of Monte Carlo calculations of electron energy depositions can also be used to estimate the line speed of an electron beam treatment process. The absorbed dose is proportional to the number of energetic electrons injected per unit area of the processed material, while the beam current is a measure of the number of electrons emitted per unit time. Therefore, the processing rate or line speed of the wire or cable within the electron beam increases with the beam current and the number of passes and decreases with increasing beam width and dose according to the following equation:

$$S = 6.0\ D(e)\ I\ N\ /\ (W\ D)$$

where S is the line speed in meters per minute and D(e) is the energy deposition per electron in MeV per unit areal density (thickness times volume density). This quantity can be calculated with a suitable Monte Carlo code. I is the electron beam current in milliamperes, N is the number of passes through the beam, W is the width of the scanning beam in meters and D is the total dose in kGy [34-36].

Values of the energy deposition per electron D(e) for a wide range of incident electron energies at the entrance of flat materials are given in Table 3, assuming the material composition listed in Table 1 above.

Table 3.
Electron Energy Deposition in Flame Retardant PE Insulation

Electron Energy - keV	400	600	800	1000	1500	2000	2500	3000
D(e) - MeV sq cm/g	4,75	3,74	2,95	2,51	2,07	1,88	1,80	1,76

For example, in flame retardant polyethylene, the value of D(e) is about 3.0 MeV per unit areal density (in grams per square centimeter) for an electron energy of 800 keV. Assuming that the beam current is 65 mA, the number of passes is 140, the scan width is 0.91 meters (36 inches) and the total dose is 150 kGy on the side of the wire facing the beam, then the line speed will be about 1200 meters per minute.

Electron Accelerators

Electron beam crosslinking of wire insulation and cable jackets is usually done with electron energies in the range from 500 keV to 1.5 MeV, although some facilities use higher energies up to 3 MeV. The energy is determined by the thickness, density and atomic composition of the insulation and the diameter of the conductor. The electron beam current is usually in the range of 25 to 100 mA. The beam current requirement is determined by the absorbed dose and the line speed. These relationships have been described briefly in the previous sections.

Facilities with electron energies less than 1.0 MeV can be shielded with steel panels or a combination of steel and lead panels to protect operating personnel from the X-rays generated by the electron beam. Facilities with energies greater than 1.0 MeV are usually shielded with thick concrete walls, which are less expensive than equivalent steel and lead panels for the higher energies.

Photographs of a Minitron™ 500 keV self-shielded system are shown in Figures 3 and 4. Drawings of an Easy-e-Beam™ 800 keV self-shielded system are shown in Figures 5 and 6. Drawings of Dynamitron® 1.5 MeV and 3.0 MeV concrete shielded systems are shown in Figures 7 and 8. All of these systems are suitable for electron beam crosslinking of wires and cables.

Figure 3.
A Minitron™ 500 keV self-shielded system for electron beam processing of small size insulated wire and plastic tubing.

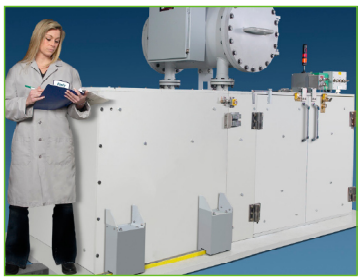


Figure 4.
The interior of a Minitron™ steel and lead shielded enclosure showing the vacuum pumps, beam scanning magnet, scan horn, figure-eight multiple pass fixture for small wire and tubing, and the water-cooled beam stop.

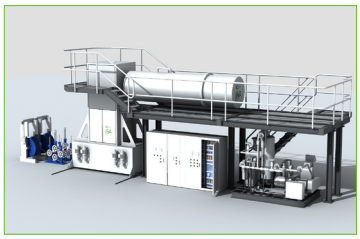
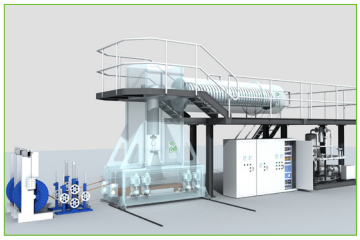


Figure 5 & 6.
An Easy-e-Beam™ 800 keV self-shielded system for electron beam processing of medium size insulated wire, cable and plastic tubing.



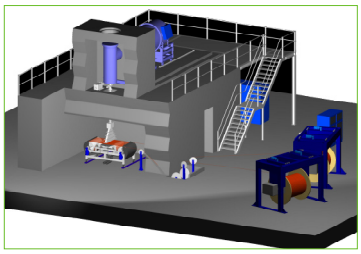


Figure 7. A Dynamitron® 1.5 MeV concrete shielded system for electron beam processing of medium and large size insulated wire, cable and plastic tubing.

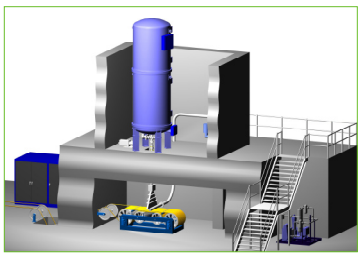


Figure 8. A Dynamitron® 3.0 MeV concrete shielded system for electron beam processing of medium and large size insulated wire, cable and plastic tubing.

Summation

IBA Industrial, Inc. (formerly known as Radiation Dynamics, Inc.) has made many industrial electron accelerators, called Dynamitrons®, which are used to crosslink wire and cable insulation and for other applications as well. This equipment has been proven to be reliable and long lasting. Some Dynamitrons® have been in use for more than 40 years. New models with the latest automatic control systems are now being produced to meet the present requirements for these applications

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References

[1] A. Charlesby, Atomic Radiation and Polymers, Pergamon Press, London, UK (1960).
[2] A. Chapiro, Radiation Chemistry of Polymeric Systems, Interscience Publishers, John Wiley & Sons, Inc., London, UK (1962).
[3] J. W. T. Spinks and R. J. Woods, An Introduction to Radiation Chemistry, John Wiley & Sons, Inc., New York, USA (1964).
[4] J. W. T. Spinks and R. J. Woods, An Introduction to Radiation Chemistry, Third Edition, Wiley Interscience, New York, USA (1990).
[5] R. J. Woods and A. K. Pikaev, Applied Radiation Chemistry: Radiation Processing, John Wiley & Sons, Inc., New York, USA (1994).
[6] K. Dawes and L. C. Glover, Effects of Electron Beam and γ-Irradiation on Polymeric Materials, Chapter 41 in Physical Properties of Polymers Handbook, James E. Mark, ed., AIP Press, American Institute of Physics, Woodbury, New York (1996) 557-576.
[7] J. G. Drobny, Radiation Technology for Polymers, CRC Press, Boca Raton, Florida, USA (2003).
[8] A. J. Berejka, Industrial Radiation Processing of Polymers Status and Prospects – August 2005, International Atomic Energy Agency, Vienna, Austria.
[9] A. Zamore, J. Hackett and S. E. Wald, Successful Applications of Electron Beam Processing in Wire and Cable Manufacturing, Technical Information Series TIS 01416, IBA Industrial, Inc., 151 Heartland Blvd., Edgewood, New York 11717, USA (1993).
[10] Anon, Raychem Corporation, http://www.answers.com/topic/raychem-corporation.
[11] L. D. Loan, Applications+ of Radiation Processing in the Wire and Cable Field, Radiation Physics and Chemistry, Vol. 9, Nos. 1-3 (1977) 253-259.
[12] E. Saito, Application of Irradiation Process for the Production of Thin Wall Wires, Radiation Physics and Chemistry, Vol. 9, Nos. 4-6 (1977) 675-684.
[13] P. G. Goavec, Plastic Materials and Acome's Use of High Energy Electron Processing in France, Radiation Physics and Chemistry, Vol. 14, Nos. 1-2 (1979) 61-67.
[14] E. W. Bennett, Jr., Applications of Irradiation to Industrial Wires and Cables, Radiation Physics and Chemistry, Vol. 14, Nos. 3-6 (1979) 947-951.
[15] R. G. Bruce Mitchell, Crosslinkable PVC Compounds for Wire and Cable Insulation, Radiation Physics and Chemistry, Vol. 14, Nos. 3-6 (1979) 937-940.
[16] I. Uda, Irradiated Wires for Internal Wiring, Radiation Physics and Chemistry, Vol. 14, Nos. 3-6 (1979) 941-946.
[17] A. Barlow, J. Biggs and M. Maringer, Radiation Processing of Polyolefins and Compounds, Radiation Physics and Chemistry, Vol. 9, Nos. 4-6 (1977) 685-699.
[18] N. M. Burns, The Radiation Crosslinking of Ethylene Copolymers, Radiation Physics and Chemistry, Vol. 14, Nos. 3-6 (1979) 797-808.
[19] Anon, 1967 USS Forrestal fire, http://en.wikipedia.org/wiki/1967_USS_Forrestall_fire.
[20] R. Timmerman, Crosslinking of Polyvinylidene Fluoride and Wire Coated with the Crosslinked Resin, U. S. Patent No. 3,142,629, July 28 (1964).
[21] B. J. Lyons, Radiation Crosslinking of Fluoropolymers – A Review, Radiation Physics and Chemistry, Vol. 45, No. 2 (1995) 159-174.
[22] H. P. Fisher, The Effect of Ionizing Radiation on Fluoropolymer Coatings, http://www.gloveboxsociety.org/files/tech_library/tech-14.pdf.
[23] J. G. Drobny, Radiation Processing of Fluoropolymers, http://www.radtecheurope.com/files_content/november%202004%20papers/drobnypapernovember2004.pdf.
[24] J. G. Drobny, Technology of Fluoropolymers, Second Edition, CRC Press (2008).
[25] L. Spenadel, Radiation Crosslinking of Polymer Blends, Radiation Physics and Chemistry, Vol. 14, Nos. 3-6 (1979) 683-697.
[26] L. Spenadel, Electron Beam Crosslinking of Ethylene Propylene Electrical Compounds, Journal of Industrial Irradiation Technology, Vol. 3, No. 1 (1985) 7-39.
[27] Anon, Vistalon Ethylene-Propylene Elastomers, Radiation Cured Electrical Materials, Product Report 82 ET-B 348, Essochem Europe, Inc. (1982) 16-19.
[28] Anon, Flame Retardance in Vamac Ethylene Acrylic Elastomers, Doc. Ref. VAM020925_2, v.1, E.I. du Pont de Nemours and Company, Inc.,September (2002).
[29] J. P. Christiano, Extrusion of Zero Halogen Flame Retardant Compounds for Wire and Cable Applications, International Polyolefins Conference, sponsored by the Society of Plastics Engineers, held in Houston, Texas, on February 22 – February 25, 2009.
[30] A. J. Berejka, M. R. Cleland, et al, Industrial Electron Beam Processing, International Atomic Energy Agency, Industrial Irradiation Associates (2009).
[31] R. Bradley, Chapter 9, Application: Wire and Cable, Radiation Technology Handbook, Marcel Dekker, Inc., New York 10016, USA (1984) 211-240.
[32] J. H. Bly, Chapter VI, Wire, Flexible Cable and Tubing, Electron Beam Processing, International Information Associates, Yardley, Pennsylvania 19067, USA (1988) 55-73.
[33] H. R. Studer, Irradiation of Insulation and Sheath for Large Wire and Cable, Radiation Physics and Chemistry, Vol. 14, Nos. 3-6 (1979) 809-819.
[34] M. Cleland, R. Galloway, F. Genin and M. Lindholm, The Use of Dose and Charge Distributions in Electron Beam Processing, Radiation Physics and Chemistry, Vol. 63, Nos. 3-6 (2002) 729-733.
[35] M. R. Cleland and R. A. Galloway, Accelerator Requirements for Electron Beam Crosslinking of Wire and Cable Insulation, Technical Information Series, TIS 01813 (2009), IBA Industrial, Inc., Edgewood, NY.
[36] Anon, ISO/ASTM 51649:2005, Practice for Dosimetry in an Electron Beam Facility for Radiation Processing at Energies Between 300 keV and 25 MeV, Annual Book of ASTM Standards, Vol. 12.02, ASTM International, West Conshohoken, Pennsylvania 19428, USA.
[37] Anon, ASTM E2232-02, Guide for Selection and Use of Mathematical Methods for Calculating Absorbed Dose in Radiation Processing Applications, Annual Book of ASTM Standards, Vol. 12.02, ASTM International, West Conshohoken, Pennsylvania 19428, USA.
[38] J. A. Halbleib, R. P. Kensek, T. A. Mehlhorn, G. C. Valdez, S. M. Seltzer and M. G. Berger, ITS Version 3.0, The integrated TIGER series of coupled electron/photon Monte Carlo transport codes, SAND91-1634 (1992), CCC-467/ITS Code Package (1994), Radiation Safety Information Computational Center (RSICC), Oak Ridge, Tennessee 37831 USA.