Application of electron accelerators in cable industry

Grażyna Przybytniak, Zbigniew Zimek, Andrzej Nowicki
Outline

• General information
• Electron accelerators for cable crosslinking
• Under beam facility
• Material composition
• Optimization of process parameters for EB crosslinking of cables by MC method
• Outlook
History

• Major commercial end-uses of ionizing radiation from electron beams are based on the discoveries by Malcolm Dole and Arthur Charlesby in the early 1950s.
• In 1957, Paul Cook founded Raytherm Wire and Cable to take commercial advantage of the EB crosslinking of PE for wire and cable insulation
• Raychem Corporation founded in 1960
• Now part of Tyco Electronics
• Wire, cable and shrink tubing applications now account for ~33% of the market use of industrial EB installations
Industrial EB end-use market
Electron Accelerators used in Japan 2007

“Growing Industrial Applications of Electron Accelerator in Japan” by S. Machi at ACCAPP09, IAEA 2009
Example of Wire & Cable applications

Automotive Wiring, Rail Cars/Rolling Stock and Lines, Solar, Aerospace

Example of Wire & Cable applications

EB crosslinking protects wire and cable insulation from the heat of soldering short-circuits as a result of high-temperatures in places such as near the engine or exhaust pipe of an automobile.

Electron accelerators in cable industry in the world

ELV accelerators are operating at LG cable Korea

Cable handling system for ELV accelerator in China

Low energy beams
- IBA (Belgium)
- Energy Sciences, Inc. (USA)
- Electron Crosslinking AB (Sweden)
- Advanced Electron Beams (USA)
- Wasik Associates (USA)
- Nissin High Voltage Corp. (Japan)
- PCT Prod. & Mfg., LLC, formerly RPC Industries (USA)

HUBER+SUHNER
Advantages and Drawbacks of Different Crosslinking Processes

<table>
<thead>
<tr>
<th></th>
<th>E-Beam</th>
<th>CV</th>
<th>Silane</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Floor Space</strong></td>
<td>Small</td>
<td>Large</td>
<td>Very Small</td>
</tr>
<tr>
<td><strong>Crosslinking Cure time</strong></td>
<td>Very Fast</td>
<td>Fast</td>
<td>Slow</td>
</tr>
<tr>
<td><strong>Scrap</strong></td>
<td>Very Low</td>
<td>High</td>
<td>Reasonable</td>
</tr>
<tr>
<td><strong>Investment Equipment</strong></td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Minimum Wire Size</strong></td>
<td>0.22 mm²</td>
<td>1.5 mm²</td>
<td>In theory for all cross sections possible</td>
</tr>
<tr>
<td><strong>Ecology</strong></td>
<td>Good Recyclable</td>
<td>Average Use of Peroxyde</td>
<td>Good Recyclable</td>
</tr>
<tr>
<td><strong>Compounds Cost</strong></td>
<td>Low</td>
<td>Average</td>
<td>High</td>
</tr>
</tbody>
</table>
Undrebeam facility

BARC-BRIT Complex

LS Cable, Korea

THE INDUSTRIAL AND ENVIRONMENTAL APPLICATIONS OF ELECTRON BEAMS
6-7 November 2014, WARSAW, POLAND
Favorable properties of EB crosslinked wire and cable insulation

Improved properties:
• Tensile strength increases, especially at elevated temperatures,
• Abrasion resistance
• Thermal resistance
• Stress cracking resistance
• Flame propagation resistance
• Deformation resistance
• Cut through resistance
• Chemical and oil resistance.
• Increased shear and compressive strength

Position 1: Compound cross linking
Position 2: Compound non cross linking (after 1 hour by 200 °C)

http://www.leoni-wind-solar-power.com
Crosslinkable Formulations

• Polyethylene PE
• Blends of PE and ethylene-propylene copolymers (EPR) or ethylene-propylene-diene (EPDM) elastomers.
• Polyolefins, EVA
• Chlorosulfonated polyethylene CSPE
• Polyvinylidene fluoride PVDF
• Ethylene tetrafluoroethylene ETFE
Composition of insulations and jackets

Other additives
- Antioxidants
- Plasticizers
- Lubricants
- Colorants
- Stabilizers
- Inorganic fillers
- Zinc oxide
- Silane as wetting agent
- Multi-functional monomers
- etc.

The current consumption of flame retardants in Europe (source: EFRA)
Conductor – insulation interfacial effects

- Dehydrogenation of polymers
- Thermal effects (heat transfer from copper to polymer)
- Corrosion

These adverse effects can be eliminated by controlling the parameters of EB suitable cable rewind under EB and intensive cooling.
Optimization of EB crosslinking

The economical condition of any industrial activity requires process optimization to reduce unit cost of the operation sustaining adequate quality of the final product. The computer simulation method becomes a very effective tool for optimization process providing necessary information in short time and reducing cost in comparison with conventional approach based on experimental dosimetry.

The simulations were performed using ModeCEB computer program (Lazurik et al., 2011).

Arrangement of radiation facility for electrical wire and cable processing: A—schematic diagram and B—beam extracting device and under beam equipment.
Monte Carlo method

The following interactions of electrons with matter and their modeling conceptions were included to the physical model of ModeCEB software:

• electron energy loss by inelastic collisions with atomic electrons and Bremsstrahlung;
• inelastic electron collision with atomic electrons leading to excitation and ionization of the atoms along the path of the particles (energy transfer);
• emission of the secondary electrons (model of the threshold energy)
• electrons participating in elastic collisions with atomic nucleus leading to changes in the electron direction (pulse transfer).
Parameters used for MC method

The following accelerator parameters and dimensions of under-beam irradiation zone configuration were used during MC simulation:
- beam current pulse parameters (amplitude, duration, repetition),
- electron energy with energy spread (defined energy spectrum distribution),
- beam spatial distribution (defined angular distribution “Space Spread”),
- accelerator window material and its thickness,
- accelerator scan parameters (width, deflection angle, frequency),
- distance between accelerator window and irradiation zone,
- dimensions and materials of irradiated wire and cable, and number of their passes under EB,
- distance between wire coils rewound under EB,
- one-, two- and four-sided irradiation processes.

- copper conductor, outer diameter: \( \phi = 7.5 \text{ mm} (2640.3 \text{ mm}) \),
- insulation thickness and material density: 1.0mm; 1.50g/cm\(^3\),
- jacket thickness and material density: 0.3mm; 1.62g/cm\(^3\).
Dose distribution in irradiation zone measured at a distance of 45 cm below exit window (electron energy 1.5 MeV; scan path 40 cm)

EB divergence angle versus electron energy for the distance 25–65 cm from the exit window.
Optimization of electrical cable irradiation

Cross section of electrical cable: (A) cable with segmented aluminum conductor; (B) equivalent dimensions of cable used for simulation of dose distribution. 1—Jacket; 2—insulation, 3—aluminum conductor.

Gel-fraction versus dose deposited in the polymer composition.
Optimization of electrical cable irradiation

Circumferential average dose distribution calculated (A) and measured gel fraction distribution (B) in polymer layer for one-sided irradiation

Circumferential average dose distribution calculated (A) and measured gel fraction distribution (B) in polymer layer for two-sided irradiation

electron energy 1MeV, energy spread ΔE/E 20%, beam divergence 30 deg

Dmax/Dmin = 1.057  Dmax/Dmin = 1.044
Optimization of electrical cable irradiation

Circumferential average dose distribution calculated for single (A) and double (B) polymer layers for two sided irradiation (1 MeV, $E/E = 20\%$, beam divergence 3 deg, $d = 1.5$ cm).

Effect of EB divergence angle on $D_{\text{max}} / D_{\text{min}}$ coefficients calculated for polymer layer divided on two separate sub-layers for two-sided irradiation (1 MeV, $\Delta E / E = 20\%$, $d = 1.5$ cm).
Optimization of electron beam crosslinking for cables

Spatial electron beam distribution in irradiation zone for different electron energies: A—1 MeV and B—1.75 MeV.
EB spatial distribution

Dose distribution along irradiation zone (electron energy—1.75 MeV, scan width—40 cm and distance to accelerator window—45 cm).

Dose distribution perpendicular to irradiation zone at center position (electron energy—1.75 MeV) distance to accelerator window: A—25 cm, B—45 cm and C—65 cm.
Optimization of electron beam crosslinking for cables

Electron trajectories of EB for extreme left, central and extreme right right position in the irradiation zone
Average dose and temperature rise of wire irradiated with electrons of different energies

<table>
<thead>
<tr>
<th>Electron energy (MeV)</th>
<th>Av. dose (insulation) (kGy)</th>
<th>Temperature rise (°C)</th>
<th>Av. dose (copper) (kGy)</th>
<th>Temperature rise (°C)</th>
</tr>
</thead>
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<tr>
<td>0.5</td>
<td>125</td>
<td>54</td>
<td>14.1</td>
<td>37</td>
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<tr>
<td>1</td>
<td>136</td>
<td>58</td>
<td>48.3</td>
<td>127</td>
</tr>
<tr>
<td>1.5</td>
<td>125</td>
<td>54</td>
<td>71.9</td>
<td>189</td>
</tr>
</tbody>
</table>

wire diameter 2.8 mm, insulation thickness 1.3 mm and copper conductor 1.5 mm

Specific heat:
copper 0.38 J/g °C - temperature rise 2.63 °C/kGy
polyethylene 2.30J/g °C – temperature rise 0.43 °C/kGy.
Experimental results of circumferential gel-fraction distribution in insulation layer of irradiated electrical wire that passed half way of the irradiation zone

Experimental results of circumferential gel-fraction distribution in insulation layer of electrical wire irradiated in two-side configuration after passing full irradiation zone
Optimization of electron beam crosslinking for cables

Circumferential dose distribution in insulation layer of electrical wire

Circumferential dose distribution in insulation of electrical wire divided into 5 sub-layers

<table>
<thead>
<tr>
<th>Symbols used</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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<tr>
<td>Energy spread (MeV)</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Beam divergence (deg.)</td>
<td>0</td>
<td>0</td>
<td>30</td>
<td>30</td>
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<tr>
<td>Two- or four-side irradiation</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
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<tr>
<td>Distance between wires (cm)</td>
<td>1.01</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
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Dose deposited in insulation layers

<table>
<thead>
<tr>
<th>Parameters</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Exp.</th>
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<tr>
<td>Av. dose (kGy)</td>
<td>78.0</td>
<td>73.3</td>
<td>75.5</td>
<td>75.5</td>
<td></td>
</tr>
<tr>
<td>Av. gel-fraction (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>57.9</td>
</tr>
<tr>
<td>Min. dose (kGy)</td>
<td>62.7</td>
<td>63.6</td>
<td>70.0</td>
<td>74.4</td>
<td></td>
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<tr>
<td>Min. gel-fraction (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>55.0</td>
</tr>
<tr>
<td>Max. dose (kGy)</td>
<td>107.9</td>
<td>83.4</td>
<td>79.6</td>
<td>76.9</td>
<td></td>
</tr>
<tr>
<td>Max. gel-fraction (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>69.5</td>
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<tr>
<td>Dmax/Dmin ratio</td>
<td>1.722</td>
<td>1.312</td>
<td>1.138</td>
<td>1.033</td>
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</tr>
<tr>
<td>Max./min. gel-fraction (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.100</td>
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</table>
Conclusions (1)

The simulation revealed significant inhomogeneous circumferential dose distribution in sub-layers of polymer whereas average depth dose distribution was quite uniform.

Performed calculations demonstrated relatively low influence of electron beam energy spectrum on homogeneity of irradiation and high influence of beam divergence on the circumferential dose distribution.
Conclusions (2)

- Two-sided irradiation of the electric cables might be carried out in such a way that the insulation is exposed to EB on all sides due to continuous changes in the angle of incidence of the electrons and their dispersion.
- The modeCEB program facilitates selection of the parameters that allow conducting the process optimally, ensuring homogenous dose distribution.
- Small distances between turning around cable segments transported under EB considerably disrupt dose uniformity, increasing its value in the regions close to passing in the opposite direction cable.
- Selected via computer simulations cross section of the conductor values ought to guarantee protection of the insulation against overheating, and subsequently thermal degradation.
Final conclusions

Issues related to further development EB crosslinking in cable industry

• Diverse, cost-effective accelerators
• Unified approach to dosimetry supported by MC calculations
• Energy utility, rewinding providing homogeneous dose distribution
• New generation of polymer based composites of enhanced ability to crosslinking
The R&D activity was supported by the European Regional Development Fund in the frame of the project UDA-POIG.01.03.01-14-052/09.