PROSPECTS AND CHALLENGES FOR THE INDUSTRIAL USE OF ELECTRON BEAM ACCELERATORS

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Abstract. There are >1400 high-current electron beam (EB) accelerators being used in industrial manufacturing operations around the world. The traditional market segments of the use of EB crosslinking for wire and cable jacketing, the crosslinking of heat shinkable tubings and films, and the partial crosslinking of components for use in tire manufacture as well as for the curing of inks, coatings and adhesives are outlined. The emergence of industrial EB processing is put into an historical context. The fastest growing market segment for industrial EB equipment has been that in the low-energy area. This has contributed to the major environmental impact of industrial EB processing: the near-elimination of the use of volatile organic compounds (VOCs) and their consequent elimination of greenhouse gas emissions from high speed coating and printing operations that use low-energy EB processing. The major low-energy EB equipment suppliers have down-sized accelerators making them more affordable for product development and industrial use. A new end-use area using low-energy EB has emerged. That is the use of low-energy EB for the surface decontamination of packaging materials that will be used for food and medical products just prior to these materials entering aseptic packaging equipment. Mid-energy accelerators have also been down-sized, with more beam power being offered in self-shielded accelerators. The development of very high power (300 kW to 700 kW), high-energy accelerators (5.0 MeV to 7.0 MeV) has made X-ray conversion a viable industrial process. Equipment that will be used exclusively in the X-ray mode for medical device sterilization is being installed. Studies of the industrial EB market over several decades have been expanded to include uses in Eastern European countries. The prospects for industrial EB processing depend upon the industry meeting a number of challenges: 1) the need to address the market in a coherent manner; 2) the need to be more astute in the selection of areas for applications development; 3) the need to emphasize energy efficiency; 4) the need to develop trained professionals; and 5) the need for enhanced industry wide communication. These points are elaborated upon in this paper.

1. The Industrial Electron Beam Market – 2009

There are >1400 high-current electron beam (EB) accelerators being used throughout the world in industrial manufacturing operations. The high productivity and controlled energy transfer from this electrically sourced equipment continues to provide added product value to crosslinked wire and cable jacketing, to heat shrinkable tubing and films and in the manufacture of automobile tires. The fastest growing market segment has been the use of EB curing for inks, coatings and adhesives. Excluded in this count are low-current accelerators, such as Van de Graaff generators and pulsed microwave linacs that are used in many research facilities. The pie chart in Figure 1 illustrates the estimated end-use market shares for this equipment. The accelerator energies typically needed for given end-use applications are presented in Table I for unit density materials [1].

Table I. EB Penetration – Market End-Uses

Market Segment	Electron Energy	Typical Penetration
Surface Curing	80 – 300 keV	0.4 mm
Shrink Film	300 – 800 keV	2 mm
Wire & Cable	0.4 – 3 MeV	5 mm
Sterilization	3 –10 MeV	38 mm

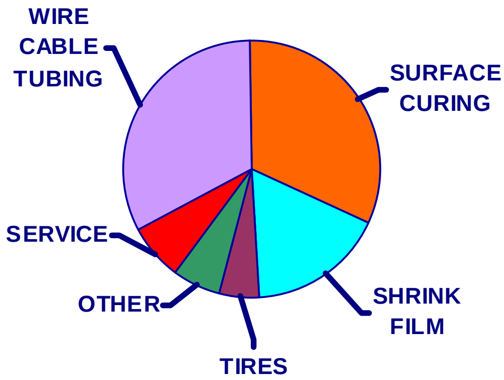

FIG. 1. Industrial Electron Beam End-use Market Distribution

Most EB accelerators have some common features: 1) electrons are emitted from heated tungsten filaments; 2) electrons are focused into a beam with an extraction electrode; 3) electrons are accelerated within an evacuated space with a strong electric field; then 4) electrons pass through a thin titanium-foil window into air. Industrial electron accelerators operate between 70 keV and 10 MeV, accelerating electrons, which have mass and charge, well beyond the ionization potential for organic or polymeric materials, ~10 eV. This electrically sourced ionizing radiation generates free radicals along a polymer chain which in turn lead to desirable effects such as crosslinking or killing bioburdens. The accelerating potential dictates the depth of electron penetration into matter.

All accelerators are shielded to prevent X-rays that are generated when electrons hit matter from entering the work area. For energies at 800 keV and below, that can be used in the production of heat shrinkable films, low-voltage wire jacketing, sheet rubber and in surface curing, the accelerator and exposure area are housed in a lead or steel lined chamber, especially those at ≤300 keV. At higher energies, up to 10 MeV, accelerators are housed in concrete vaults with restricted ingress and egress, often with portholes that facilitate product entry and exit. Higher beam energies require greater shielding thickness [2].

2. Emergence of Industrial EB Processing Equipment

The early industrial uses of high-current EB accelerators relied upon the resonant transformer developed at the General Electric Company (GE) by Willem Westendorp, a protégé of William Coolidge, the pioneer in EB equipment development at GE [3, 4, 5, 6]. EB accelerators developed by Robert Van de Graaff and Roy Emanuelson at the High Voltage Engineering Company, their insulating core transformer systems (ICTs), and the Dynamitron® developed by Marshall Cleland at Radiation Dynamics, Incorporated (RDI, now IBA Industrial Inc.) are used in these wire, cable, tubing, shrink film and tire applications [7, 8, 9].

In 1970, Sam Nablo cofounded Energy Sciences Incorporated (ESI) and developed a low-voltage accelerator (≤300 kV) based on the ideas of an ESI engineer, Bertram Quintal, that relies on self-shielding of the accelerator and under-beam conveyance with lead (or steel) to protect the work environment from X-rays that are generated when electrons impinge upon materials [10, 11]. A technique of using parallel segmented filaments for low-energy accelerators was developed by Sherman Farrell in 1975, which was adopted by RPC Industries, now PCT Engineered Systems [12]. Low-energy, modular EB equipment was developed by Tovi Avnery in the late 1990's and lead to the formation of Advanced Electron

Beams [13]. This technology has become particularly amenable to small sized, moderately priced, self-shielded laboratory units.

In the late 1980s, a novel accelerator design that could deliver high electron energies, up to the commercially acceptable 10 MeV, was developed [14]. This was licensed to Ion Beam Applications where Yves Jongen and Michel Abs brought these systems to very high beam currents, with total emitted beam powers of 700 kW having been attained. This design has become known as the Rhodotron® [15]. At these higher beam powers, X-ray conversion has become an industrially viable technology [16].

3. Emergence of EB Processing in Industry

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. They found that polyethylene (PE) crosslinks upon exposure to ionizing radiation [17, 18, 19, 20]. In January 1957, Paul Cook founded Raytherm Wire and Cable to take commercial advantage of the EB crosslinking of PE for wire and cable insulation. Later that year, he formed Rayclad Tubes to produce EB crosslinked PE heat shrinkable tubing [21]. These businesses were consolidated into the Raychem Corporation in 1960 and are now part of Tyco Electronics [22]. These wire and cable and shrink tubing applications now account for ~33% of the market use of high-current, industrial EB installations. In 1956, Bill Baird from the Cryovac Division of what was then Dewey & Almy (which became part of W. R. Grace and is now part of the Sealed Air Corporation) visited Cook at his Sequoia Process Corporation in California (an antecedent of Raytherm). Cryovac licensed Cook's process for EB crosslinking PE and producing heat shrinkable products [23]. Baird then developed a process for producing heat shrinkable food packaging films based on EB crosslinked PE [24, 25]. This application accounts for ~17% of the industrial EB accelerators now in use. Raychem/Tyco Electronics has long been acknowledged to have more installed kilowatts of EB power than any firm, whereas Cryovac has more installations (>125 EB units in manufacturing operations) [26]. Multi-billion dollar businesses have developed based on the use of EB to crosslink PE. Such end-use applications represent about half, if not more, of the industrial use of EB processing.

The industrial use of EB processing in the coatings area developed in the early 1960s. Bill Burlant at the Ford Motor Company used low-energy electron beams (400 keV or less) to cure automotive coatings using cable connected scanned beam accelerator produced by RDI [27]. The use of EB in curing printing inks was launched by Dan Carlick of Sun Chemical [28]. Substantial businesses have evolved based on providing the raw materials, monomers and oligomers, used in EB curable inks, coatings and adhesives, and formulated systems.

4. Economic and Environmental Impact

The profitability of industrial EB processing and its ability to produce high value-added products at reasonable cost depends on high product through-put. Industrial EB manufacturing processes, such as the crosslinking of wire or cable jacketing, of shrink tubing or films or the curing of coatings or printing inks, run at hundreds of meters per minute. The ability to attain such effective process speeds is dependent upon high beam current, as illustrated in the equation below for flat substrates. The factor k is the linear processing coefficient, typically ~10 to 30 depending on electron energy, web width, window thickness and air gap between the window and product. Reasonably high beam current is essential to high production through-put [1].

$$\text{Speed, meters/minute} = k \cdot \text{beam current, mA/dose, kGy}$$

The major environmental impact of EB processing has been to eliminate volatile organic compounds (VOCs) in the coating and printing industries. The EB curable materials used in these industries have near-zero VOCs. As a result, air pollutants, such as the solvents that have historically been used as diluents, do not exist in these EB processing operations. EB itself is a more efficient means of energy transfer, in contrast to heating, Table II shows the order of magnitude difference in energy consumption when comparing EB curing with solvent or waterborne technologies for the same amount of dried/cured material [29].

Another way to illustrate this environmental benefit is to compare the total energy consumption needed to produce a given quantity of product at a given coating weight, for example 20 g/m^2. In Table III, low-energy EB is compared with a "high solids" solvent based system. The total energy needed to air dry the solvent system is compared with the needed energy to operate the low-energy EB system. A comparison is also made between potential greenhouse gas emissions. EB curing also eliminates potential greenhouse gas emissions, lowering the carbon footprint of the process.

Table II. Energy Demands to Dry/Cure Coatings

System:	Solvent	Solvent	Water	EB Curable
Solids:	30%	40%	40%	100%
Diluent:	heptane	toluene	water	none
Boiling point, ºC:	98	111	100	NA
Vapor pressure, 20ºC:	35mm Hg	22mm Hg	17mm Hg	NA
Heat of vaporization: (calories/gram solvent)	76	88	540	NA
Energy to dry/cure 1g dried coating: (calories/gram solvent)	177	132	810	7 (30 kGy)
Energy to dry/cure 1g dried coating, J/g:	740	555	3390	30

Table III. Comparison of Solvent Based Drying with EB Curing

System:	Solvent	EB Curable
Coating solids concentration:	60%	100%
Dried coat weight, g/m^2:	20 g	20 g
VOCs/m^2, grams: (0.9 density solvent)	12 g	0 g
Total force air system energy demand, kJ/m^2: (calculated 27.3 kJ/g to dry)	328 kJ	NA
Total EB energy demand, kJ/m^2: (30 kGy or 0.030 kJ/g at 70% electrical input to effective EB)	NA	0.86 kJ
Total energy demand/hour: (11,200 m^2/hour production)	~3,700,000 kJ	~9,600 kJ
Total energy demand/hour:	1,030 kWh	2.67 kWh

Greenhouse gas emission potential

CO_2 from solvent combustion:	37 g/m^2	none
Facility CO_2 emission potential:	415.8 kg/hour	none

5. Equipment Trends

Two trends have emerged for industrial EB equipment: 1) the down-sizing of mid- and low-energy EB equipment and 2) the development of industrial processing based on the X-ray conversion from high-energy, high-powered (up to 700 kW) accelerators. Compact, moderate cost low-energy EB equipment is available for laboratory use and for integration into high speed coating, printing and surface treatment processes. Self-shielded, high-current mid-energy (500 keV) EB units are available for use with wire and tubing that minimize floor space demands. Figure 3 shows the compact, moderate cost Application Development Unit from Advanced Electron Beams (AEB) which takes up less than two square meters of floor space; Figure 4 shows the down-sized EZ-Cure III™ from Energy Sciences; and Figure 5 shows the Broadbeam™ LE series from PCT Engineered Systems. All of these have lowered the lab or plant floor space needed to place an EB unit into operation; all offer high-current performance. Materials work done on the AEB Application Development Unit can be scaled up for use with higher energy EB or X-ray systems, such as would be used in the curing of fiber reinforced composites [30].

Integrated systems, such as Getinge Linac's STERSTAR™, based on multiple low-energy EB accelerators, are being used to decontaminate the surfaces of materials before they enter aseptic packaging areas for medical product use [31, 32, 33]. Similar surface decontamination systems developed by AEB are being used in aseptic food packaging lines.

FIG 2. AEB Application Development Unit

FIG 3. ESI EZ-Cure III

FIG 4. Broadbeam LE series

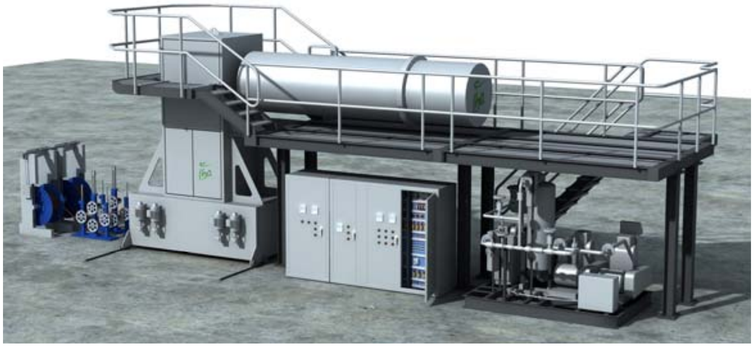

FIG 5. IBA Industrial Inc. Easy-e-Beam™ wire/tubing 800 keV, 100 ma unit

A high-current, mid-energy self-shielded EB unit has been developed by IBA Industrial, Inc. that can be installed in a production facility and not require the design or construction of a concrete shielding vault. Figure 5 shows the IBA Industrial Easy-e-Beam™ unit that operates at 800 keV and 100 ma. This unit is suited for high speed production of EB crosslinked wire jacketing and tubing.

The development of very powerful accelerators based on the Dynamitron® and on the Rhodotron® designs have enabled IBA Industrial Inc. to demonstrate that high power penetrating X-rays are a viable, electrically sourced, industrial alternative to the use of radioactive isotopes for medical device sterilization and food treatment [34]. In the United States, high power X-rays have been used since 2002 to decontaminate selected mail for the US Postal Service, which demands fast turn-around schedules. A Rhodotron can have multiple beam lines, for example at 5.0 MeV or 7.0 MeV, operating one at a time, that are aimed at X-ray targets to provide the most effective X-ray conversion for a given end-use application. Figure 6 shows the X-ray targets and product totes in a facility in Bridgeport, New Jersey, USA, that uses X-ray treatment to decontaminate parcel post.

FIG 6. Totes Ready for X-ray Processing

6. Market Prospects

A study by SRI International in 1979 and an expert panel review eight years later at the 6th International Meeting on Radiation Processing (IMRP) gave estimates as to the prospects for industrial electron beam processing [35, 36]. The 1987 IMRP-6 panel consisted of representatives from the major suppliers of EB accelerators and industry consultants. The growth of low-energy, self-shielded equipment was anticipated while mid-energy, high-current equipment continues to be the mainstay of the industrial market.

Perspectives have now changed to include an understanding of the use of EB processing in Eastern Europe. Unanticipated was the downsizing of low-energy equipment, making EB processing more economically attractive, and the development of very high power equipment, which makes X-ray processing practical. One major end-use application has emerged: the use of low-energy EB for the surface decontamination of packaging materials for food and medicinals. Implicit in the combination of EB surface decontamination and aseptic packaging is the reduced need for terminal or finished product treatment or sterilization.

7. Market Challenges

The prospects for growth in industrial EB processing depends on the industry's response to a number of challenges. The challenges facing the industrial EB are:

- **The need to address the market in a coherent manner**. With a diversity of equipment options and very heterogeneous market uses, industrial EB processing is a very fragmented business. Even the metrology used in EB processing, dosimetry, lacks coherence and a unified approach to measurement.

- **The need to be more astute in the selection of areas for applications development.** Considerable precious technical resources have been devoted to areas, which, while proven to be feasible and appealing in themselves, face non-technical societal barriers. Food irradiation and large scale environmental projects, such as stack gas and waste water treatment, have not yet generated market demand, despite decades of very sound technical achievement.

- **The need to emphasize energy efficiency.** Energy transfer efficiency is inherent in the excitation of materials by ionizing radiation derived from EB and X-ray sources. When compared to EB, all thermal processes are very energy inefficient. Even in areas where EB processing has been proven to be cost-effective and profitable, some companies remain committed to thermo-chemical processes.

- **The need to develop trained professionals.** Personnel are needed who can carry on in areas in which industry has accepted EB processing and who will have the initiative to explore areas that present market driven potential. This can be achieved by greater use of industry-academia partnerships, through the fostering, but with industry guidance, of academic endeavors involving EB processing.

- **The need for enhanced industry wide communication.** In many ways, programs involving other disciplines, not just those involved in radiation processing, may be more beneficial to the growth of the EB processing industry. Outside of the radiation processing industry, little is known about this profitable technology. Out-reach complemented by closer communications within the industry is needed. Such out-reach should be extended to developing economies which have not yet invested in the more effective EB technologies.

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