

Development in Low-Voltage EB Curing for High Product Throughput Applications

By Im Rangwalla

Sustainable packaging and the lowest carbon footprint are some of the mandates being required by brand managers and end-users. Recent developments in Electron Beam (EB)-curing equipment provide the required dose to cure at the highest product speeds and at lowest input power. These developments have resulted in further reduction of both equipment size and cost.

The ability of energetic electrons to initiate polymerization reactions has intrigued polymer chemists

and engineers for a long time. Early development work was done with low-dose rate Co⁶⁰ gamma sources or very high-voltage, scanned-type electron beam accelerators. Both of these high-energy curing options were not suited for commercial applications because of prohibitive capital equipment costs. The development of low-energy (150-300 kV) EB equipment was considered a breakthrough in the curing technology—especially since the oil embargo of the mid 1970s made thermal curing options less attractive.

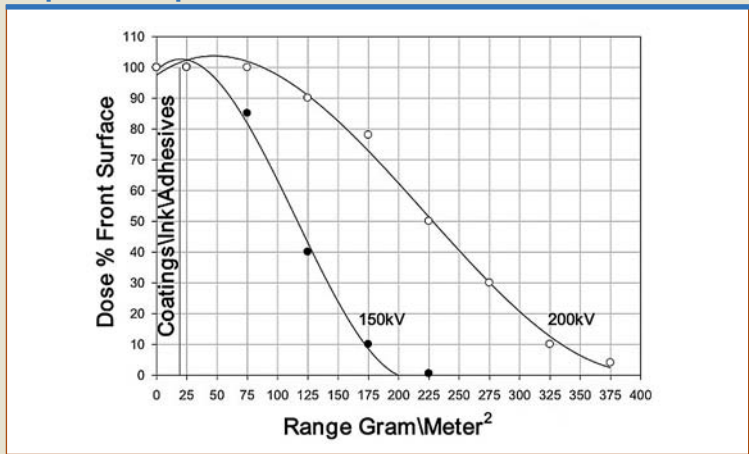
TABLE 1

EB-cured products

Performance Characteristics		
Characteristic	Reason	Results
Low to no extractables	Highest degree of cure	Important in food packaging
Low to no odor	No photoinitiator; thorough cure	Important in food packaging
Highest scuff, abrasion and chemical resistance	Electrons form highly crosslinked 3-D molecule networks	Important for coatings on labels, furniture and flooring
Coolest process	No infrared radiation; 1 MRAD dose = 2.4 Cal/Gm	Temperature increase of 20°F; ideal for heat-sensitive substrates
Instantaneous and consistent cure	Only electrons initiate the cure which happens in milliseconds	High-speed operations with stable Coefficient of friction (COF)
Color blind	Penetration of electron depends upon thickness and density of the substrate, not the opacity	Ideal for use in heavily pigmented ink and metallized substrates
Consistent cure over time	Electron generation does not degrade over time	Consistent product quality

FIGURE 1

Depth dose profiles



Large chemical companies jumped at the opportunities to synthesize special raw materials that could be EB-curable. Opportunities were cited for various markets such as printing (offset lithography), pressure-sensitive adhesives and silicone release coatings, to name a few. For most of the applications, the end product properties obtained by EB curing were quite unique and superior to products obtained from most other curing methods (See Table 1). Some very large converters saw the benefits that EB processing brought and widely

adapted the technology. As a result, EB technology saw good growth through the 1980s. However, this growth was short-lived and the rapid growth enjoyed in the '80s stayed quite flat in the '90s. EB processing was restricted to very large converters for niche market applications and did not broadly penetrate industry.¹

The main reasons attributed to this limited growth included:

- EB equipment was quite large and expensive, especially for cost-sensitive industries such as flexible packaging and converting.

In addition, the operation and maintenance cost of these accelerators was quite high.

- EB equipment generated higher than required electron penetration. These electrons damaged radiation-sensitive substrates such as PVC (discoloration), cellulose and paper materials (loss of physical properties due to chain scission), and certain polyolefin (off-odor and increase of seal initiation temperatures).

Chemistry suppliers restricted their efforts in developing EB-curable chemistry due to the lack of an industrial EB accelerator meeting the broader market requirements. EB-curable inks, coatings and adhesives were available, but at a premium cost and only for certain niche applications. Lack of chemistry and curing equipment were the main reasons for a flat-to-negative growth of EB processing in the '90s.

The energy of electrons expressed in kV determines the depth of penetration into a material and thus the thickness of the material that can be dried or cured. New low-voltage EB systems operating at less than 125 kV were first introduced in 1999, thus enabling

FIGURE 2

How does an EB work?

- Filaments emit electrons.
- Electrons are accelerated using high voltage.
- Electrons pass through the window foil and strike the product.
- Electrons cause molecular changes in the product.

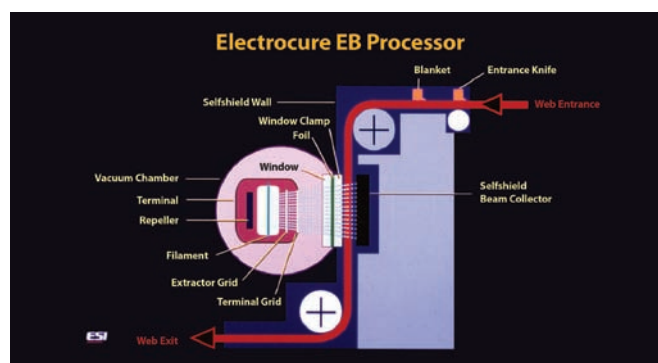
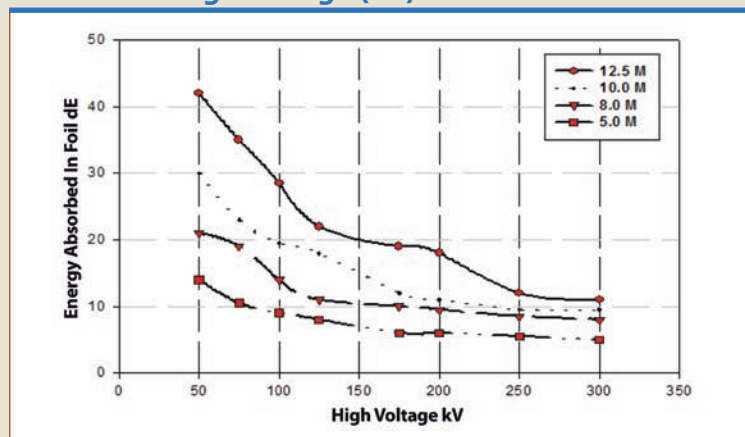


FIGURE 3

Energy absorbed by various titanium foils as a function of high voltage (kV)



users to obtain all the benefits of EB curing at a price they could afford. This was because the low-voltage EB equipment was approximately half the price of the old high-voltage EB units, consumed less power and offered higher production speeds.

A technology breakthrough in late 1990s led to EB processors with accelerating voltage less than 150 kV. Up to this time, accelerating voltages of 150 kV and higher were used to cure inks, coatings and adhesives less than 20 microns thick. These 150 kV EB units used to cure thin materials were quite inefficient because the effective penetration of a 150 kV EB unit was at least three times higher. As shown in Figure 1, at least 90% of the energy is not utilized. It was imperative to operate at low energies, but “how?” remained the question.

As shown in Figure 2, electrons are created by heating a Tungsten filament to very high temperatures—2,400 K over its thermionic emission temperatures. At these temperatures, electrons are boiling out of the thin filament, forming a cloud of electrons around it. By applying a positive voltage, these electrons are extracted from the filament and then accelerated

by high voltage (kV) to whatever depth is required for it to penetrate.²

The entire process takes place in a vacuum that is continuously maintained. The accelerated electrons then come out of the vacuum chamber by passing through a thin foil made of Titanium that acts as a barrier between the high vacuum and the atmospheric conditions of the “Process Zone.” In the process zone, the material (like an ink, coating adhesive, etc.) to be cured is transported on a web, usually at high speeds of around

350-400 meters/min. The titanium foil used in the higher voltage (>150 kV) EB equipment is thicker, in the order of 12.5 microns or higher.

As mentioned earlier, in order to make the EB units smaller and cheaper, one had to deposit the energy close to where active chemistry was taking place and not at an effective depth of 3X by operating at 150 kV. One intuitively would say, “why not just make an EB unit operate at < 150 kV?” But, like everything else, it is not that easy.

Energy is deposited in the 12.5 micron titanium foil when operating at lower voltages, as shown in Figure 3.³ As observed, when dropping the voltage down from 150 kV to 100 kV for the 12.5 micron foil, the energy absorbed in the foil increases from 20 keV to almost 30 keV. Since heat energy deposited in the foil is **Power kW = High Voltage absorbed dkV X Beam Current I mA**, one needs to operate at lower mA to keep the same absorbed power in the foil to prohibit premature foil failure and maintain at least 1,500 hours of foil life before changing, as required by industrial applications.

Now, besides energy absorption, there is also absorption of low-energy electrons when operating at < 150 kV

FIGURE 4

Typical machine yield as a function of high voltage

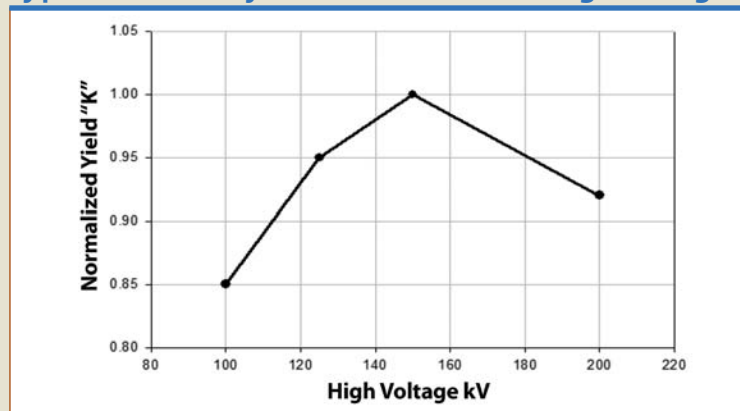


TABLE 2

Machine yield at various foil thicknesses at optimum operating voltage

High Voltage kV	Titanium Foil Thickness Microns	Machine Yield "K" Mrad/fpm/mA	Machine Yield "K" kGy/mpm/mA
150	12.5	7.30	2.20
110	10	8.45	2.60
95	7.5	9.71	2.96
80	5.0	10.50	3.20

with 12.5 micron foil. Figure 4 details the machine yield as a function of high voltage for these various thickness foils.

Since the dose to cure is directly proportional to the beam current I in mA and inversely proportional to the product speed, S is shown in the following equation:

$$\text{Dose (kGy)} = K \times I \text{ (mA)} / S \text{ (mpm)}$$

To maintain the same dose by operating at < than 150 kV using the older machines, one will need to operate at slower operating speeds making the process not commercially viable. Therefore, when using the thicker foils and the older EB unit, it was not possible to commercially operate at lower voltages.

Development of Low-Voltage EB Units

The only solution was to design EB accelerators to operate under industrial conditions at low voltages. There are key four variables in designing low-voltage EB accelerators that enable users to operate at low voltages:

- Reduction of foil thickness
- Reduction of product air gap
- Improvement of the beam optics in transverse direction
- Improvements of the heat transfer capability of the foil by modifying the window body (foil support and cooling structure)

By reducing the foil thickness and the product air gap, surprisingly, it was observed that the efficiency of the EB unit improved at its optimum voltage.

The increased efficiency at lower foil thickness meant that fewer electrons were absorbed in the foil, allowing users to run at higher beam currents, thus permitting commercial speeds at low voltages.^{4,5,6,7} Results are shown in Table 2.

As can be seen from Table 3, by using thinner thickness foil and optimizing the product gap, operators can reduce the power requirements by more than 63%. In addition to reducing the power, the size and price of the EB equipment is much less.

The penetration profiles of the EB equipment using these thin foils and operating at its optimum lower voltages are shown in Figure 5. From this graph, one can see that the product to be cured at 10-20 grams/m² receives the required dose. But the energy depletes very quickly with the thinner foils operating at lower voltages, enabling one to minimize energy deposition into the substrate. This feature is very important when one is curing inks, coatings or adhesives using radiation labile substrates.

Conclusion

As discussed before, energy curing, in particular EB curing, is already established as the lowest carbon footprint curing option.⁸ To further compliment that statement, recent developments in low-voltage EB curing equipment require even lower input energy.

As discussed above, new EB equipment already operating at 95 kV 7.5 micron foil requires about 25% less energy than the 110 kV EB units and more than 50% less than the 150 kV EB units of the past. Developments in producing even thinner industrial foils in the 5 micron region will reduce

TABLE 3

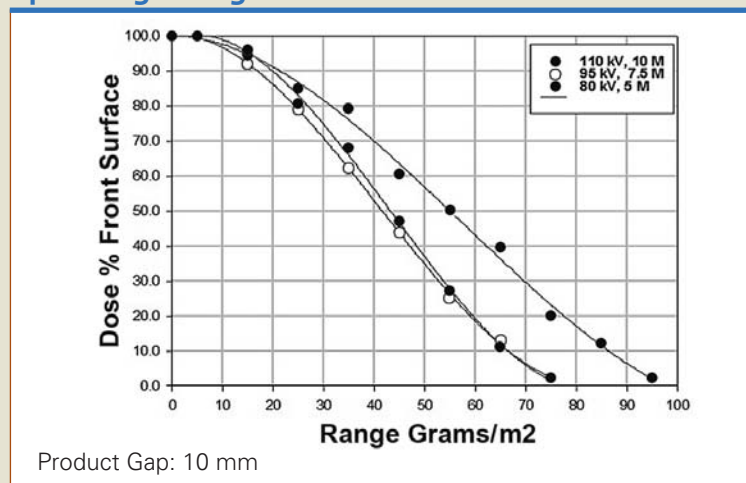
Total power to provide 10 kGy of dose at 1,200 mpm

Foil Thickness Microns	Optimum High Voltage kV	Beam Current I mA	Total Power kW
12.5	150	545	82
10.0	110	461	51
7.5	95	405	38
5.0	80	375	30

Machine Width = 1,200 mm
 Note: The 5 Micrometer Titanium Foil is developmental only.

FIGURE 5

Depth dose profiles of EB Equipment at optimum operating voltage as a function of Ti foil thickness



the energy requirements even lower. In addition, making the EB equipment even smaller, cheaper and lighter makes it the ultimate curing option.

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