Development in Low Voltage EB Curing For High Product Throughput Applications

Im Rangwalla

Energy Sciences Inc.

42 Industrial Way

Wilmington MA 01887

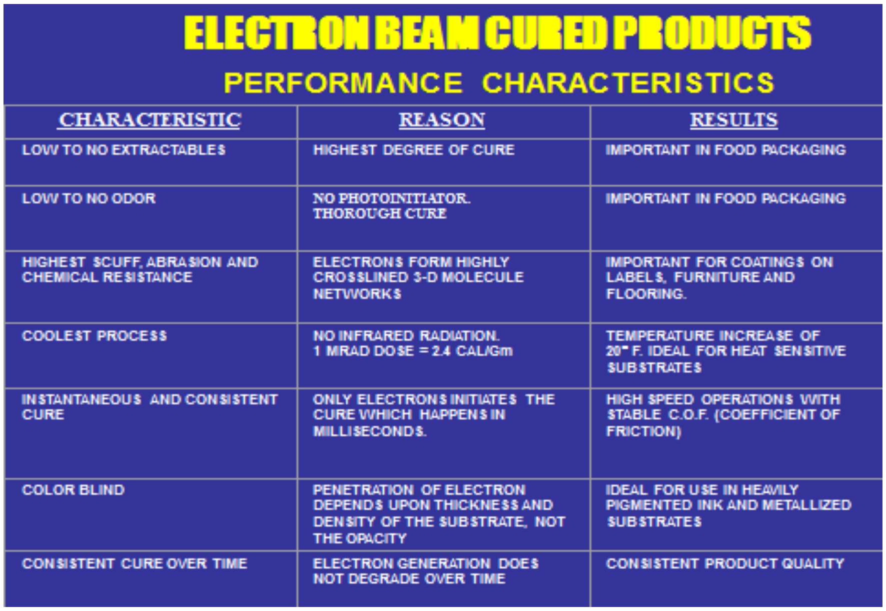
Abstract:

Sustainable Packaging, lowest carbon foot print, are some of the mandates being required by brand managers and end users. Recent developments in EB curing equipment provides the required dose to cure at highest product speeds and at lowest input power. These developments have resulted in further reduction of the size of the equipment and the cost. Details of these developments will be presented.

Introduction:

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 Co^{60} gamma sources or very high voltage scanned type electron beam accelerators. Both these high-energy curing options were not suited for commercial applications because of prohibitive capital equipment cost. The development of low energy (150-300kV) EB equipment was considered a breakthrough in the curing technology especially since the oil embargo of the mid-seventies made thermal curing options not as attractive. Large chemical companies jumped at the opportunities to synthesize special raw materials that could be EB curable. Opportunities were cited for various markets like 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 eighties. However, this growth was short lived and the rapid growth enjoyed in the eighties stayed quite flat in the nineties. EB processing was restricted to very large converters for niche market applications and did not broadly penetrate industry[1].

Table: 1



ELECTRON BEAM 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 CROSSLINED 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 INITIATES THE CURE WHICH HAPPENS IN MILLISECONDS.	HIGH SPEED OPERATIONS WITH STABLE C.O.F. (COEFFICIENT OF FRICTION)
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

The main reasons attributed to this limited growth were as follows:

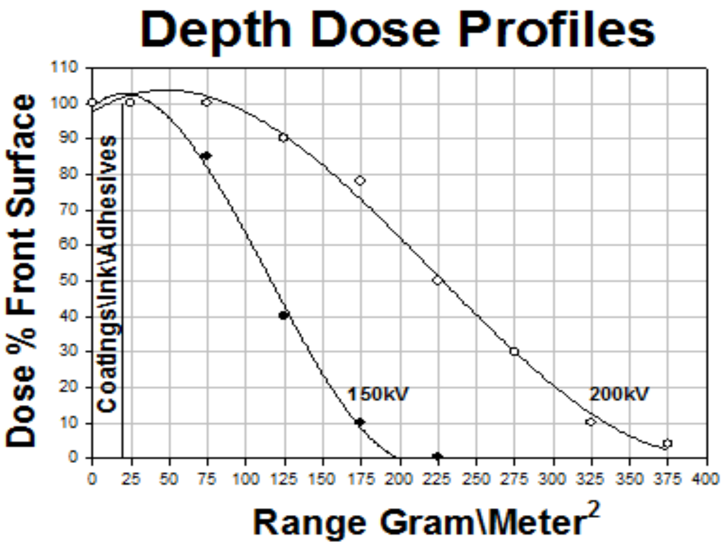
- EB equipment was quite large and expensive, especially for cost sensitive industries like flexible packaging and converting. In addition the operation and maintenance cost of these accelerators was quite high.
- EB equipment generated higher than required electron penetration. These electrons damaged radiation sensitive substrates like 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 lack of an industrial EB accelerator meeting the broader market requirements. Electron beam curable inks, coatings, and adhesives were available but at a premium cost and for certain niche applications. Lack of chemistry, and curing equipment was the main reason for a flat to negative growth of EB processing in the nineties.

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 electron beam systems operating at less than 125 kV first introduced in 1999, enable users to obtain all the benefits of EB curing at a price they can afford. This was because the low voltage EB equipment are approximately half the price of the old high voltage EB units and also consume less power and can result in higher production speeds.

A technology break-through in late 1990's permitted to realize electron beam processors with accelerating voltage less than 150 kV. Up to this time accelerating voltages of 150kV and higher were used to cure inks, coatings and adhesives less than 20 microns thick. These 150 kV EB units to cure thin materials were quite inefficient, because the effective penetration of 150 kV EB unit was at least 3 X higher. As shown in Fig: 1 at least 90% of the energy is not utilized. It was imperative to operate at low energies. But how remained the question?

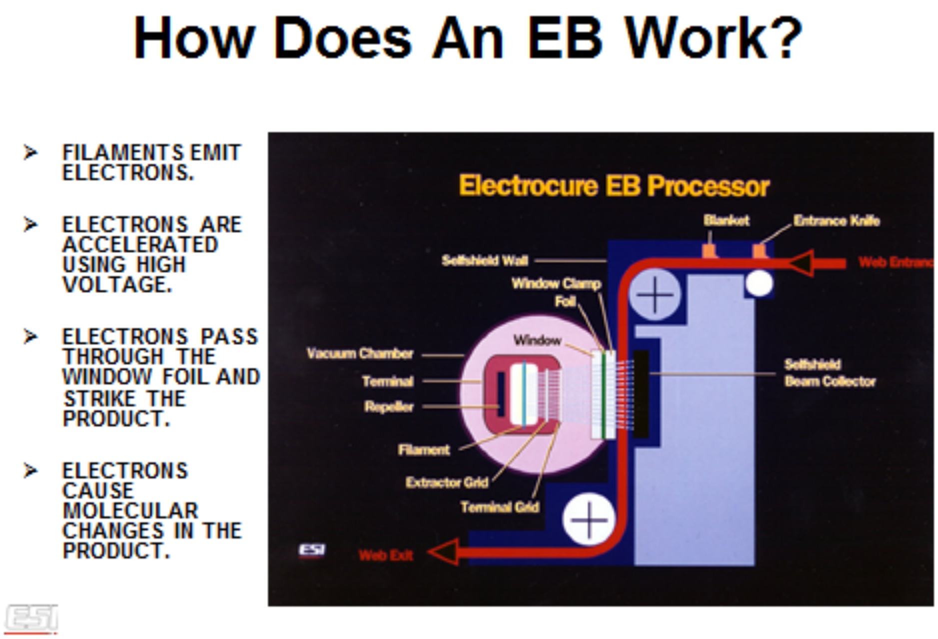
Fig: 1



EB Equipment Theory of Operation:

Let us review how the electron beam accelerator works.

Fig: 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.

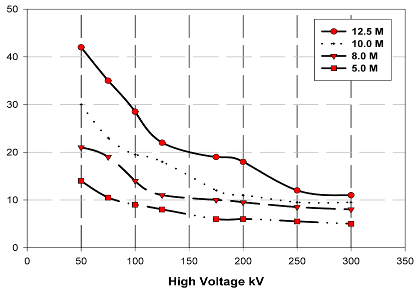
As shown in Fig 2, electrons are created by heating a Tungsten filament to very high temperatures 2400 K over its thermionic emission temperatures. At these temperatures electrons are boiling out of the thin filament forming a cloud of electrons around it. By applying a positive voltage these electrons 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 which is continuously maintained. The accelerated electrons then come out of the vacuum chamber by passing through a thin foil made of Titanium which acts as a barrier between the high vacuum and atmospheric conditions 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 (>150kV) EB equipment was thicker in the order of 12.5 microns or higher.

As mentioned above 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. Let us review, energy deposited in the 12.5 micron titanium foil when operating at lower voltages. This is as shown in Fig: 3[3].

Fig: 3

Energy Absorbed By Various Titanium Foils as a Function of High Voltage (kV)



As observed 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

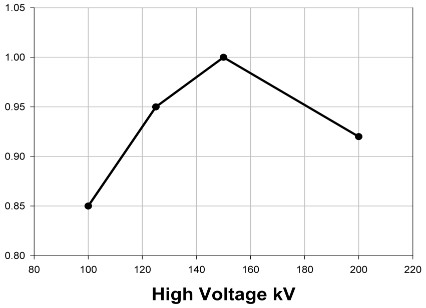
Power kW = High Voltage absorbed dkV X Beam Current I mA

One needs to operate at lower mA to keep the same absorbed power in the foil to prohibit pre mature foil failure and maintain at least 1500 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 with 12.5 micron Foil. As observed in Fig: 4 is the chart of machine yield as a function of high voltage for these various thickness foils.

Fig: 4

Typical Machine Yield as a Function of High Voltage



Since the dose to cure is directly proportional to the beam current I in mA, and inversely proportional to the product speed S as shown in the underlying 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 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 way was to design EB accelerators to operate under industrial conditions at low voltages. The key four variables in descending order enabling one to operate at low voltages are as shown in Table 2:

Table: 2

Key Variables in designing low voltage EB accelerators

1. **Reduction of foil thickness**
2. **Reduction of product air gap**
3. **Improvement of the beam optics in transverse direction**
4. **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. This phenomenon is as shown in Table : 3.

Table: 3

Machine Yield at Various Foil Thicknesses at Optimum Operating Voltage

Machine Width = 1200 mm

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

The increased efficiency at lower foil thickness meant that fewer electrons were absorbed in the foil allowing one to run at higher beam currents thus permitting commercial speeds at low voltages[4,5,6,7].

Results is as shown in Table: 4

Table: 4

Total Power to Provide 10 kGy of Dose at 1200 mpm

Machine Width = 1200 mm

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

Note: The 5 Micrometer Titanium Foil is developmental only.

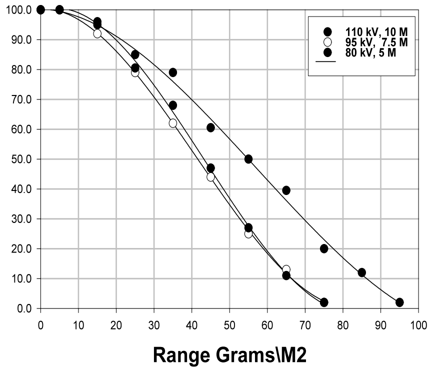
As can be seen from Table: 4 by using thinner thickness foil and optimizing the product gap one can reduce the power requirements by over 63 %. In addition to reducing the power the size and the price of the EB equipment is much less.

Let us now review the penetration profiles of the EB equipment using these thin foils and operating at its optimum lower voltages. This is as shown in Fig: 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.

Fig: 5

Depth Dose Profiles of EB Equipment at Optimum Operating Voltage as a Function of Ti Foil Thickness

Product Gap: 10 mm



Conclusion:

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

As discussed above already new EB equipment operating at 95 kV 7.5 micron foil requires about 25 % lower energy than the 110kV EB units and more than 50% less than the 150 kV EB units of the past. Developments in producing industrial even thinner foils in the 5 micron region will reduce the energy requirements to even lower. In addition making the EB equipment even smaller cheaper lighter, and the ultimate curing option.

References:

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