New Developments in EB Accelerators

By Thomas Lund, B. Laurell and E. Föll

The purpose of this presentation is to present an overview of the present state of industrial electron beam (EB) development. It is not possible to present all of the technical details which one might wish because of the need to protect the proprietary interests of the firms engaged in the production applications and technology development. Still, the general view can clearly be seen.

EB curing is a very fast, energy-efficient and environmentally friendly drying method that provides a particularly hard and chemically resistant surface with controlled curing throughout the depth.

Introduction

More environmental protection requirements force users of solvent-based coatings to look for an environmentally safe procedure that emits considerably fewer solvents or cracked products into the atmosphere and water.

Also, the new European Commission (EC) Super Directive regarding migration of less than 10 ppb into the food will force the packaging producer to look for new technologies.[28]

The chemistry has new groups of products to offer:

- Systems with low content of solvents and with high solid contents
- Coating materials containing water
- Coatings with solid resin in powder form
- 100% solid systems

A common feature of the first three methods is that heat is required for the formation of dry coating film. Interesting techniques that do not induce these disadvantages of thermal drying are the radiation curing methods—in particular, those involving ionising radiation such as ultraviolet (UV) or EB curing.

- Radiation curing
- Infrared system containing solvents
- Microwave water-based system
- UV light 100% system
- EB 100% system

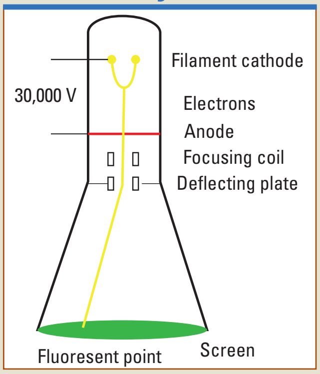
UV light can be used without problems for curing in those places that are accessible to "UV light" (i.e., the layers which the radiation must pass through must be thin and transparent at the appropriate wavelengths). The formulation will contain photoinitiators and other absorbing materials such as pigment and matting agents.

During and after the curing process, there should be no emission of harmful substances into the atmosphere, water or food. In addition, after the curing process is over, there should be no odor emissions from the surface. These requirements have already given EB curing the focus of even more attention, not the least because this technology has been used for a wide variety of applications in recent years due to the many other benefits it offers—it's an environmentally safe, heat- and solvent-free technique.

In spite of these benefits, success

FIGURE 1

Cathode ray tube



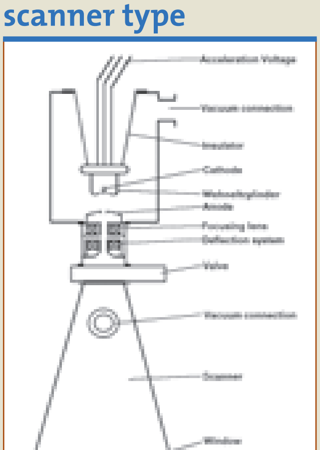
is only possible if the user, chemical supplier and plant manufacturer fully collaborate not only during the planning phase but also during the design of the curing line and later during initial operation.

The Accelerator

The functioning of the EB accelerator can best be compared with the cathode ray tube of a television. See Figure 1. The production of free electrons in a vacuum may be familiar to us all from the cathode ray tube and the television tube. A classic triode system is used for generating and forming a beam. A tungsten cathode heated in a high vacuum by an electrical current makes free electrons available on its surface and these are accelerated to the anode. In a television set, the electrons (negatively charged particles) are accelerated by a high-negative voltage toward the anode and then deflected to the screen or to the EB exit window in the EB accelerator. In the accelerator, these electrons then emerge from the vacuum through a thin piece of titanium foil into the air or an inert gas where they can act upon the material.

FIGURE 2

Electron crosslinking EB accelerator scanner type



In scanner accelerators (Figure 2), a tungsten heating cathode, Wehnelt cylinder and an anode (with focusing lens and EB deflection system) together form one unit. Absolutely linear current signals control the beam deflection in two perpendicular directions. Scanning frequencies are over 800 Hz. The EB exit window is designed to have a large surface area. A 7 to 20 microns-thick titanium foil is supported on the vacuum side by means of a special construction.

Linear or multicathode electron accelerators (Figure 3) in this cathode system contain several cathodes across the working area. A control grid accelerates the electrons and guides them out of the electron exit window of titanium foil. These accelerators can easily be manufactured up to larger working widths (2-3m). These accelerators provide a large electron current but are less accurate in the dosage and distribution, especially at low doses.

Cooling is affected by means of water and convection through a supportive copper plate. No additional window cooling from the outside is necessary by blowing either air or inert gas. This considerably simplifies window cooling and the inerting process. The electrons pass out of the vacuum into the air through a titanium foil stretched over a water-cooled support grid. The product treatment area is in front of the titanium foil. The large area window has a standard length in conveyor direction of 100 mm or 220 mm. The working width is adjusted correspondingly to the object to be irradiated.

Scanner accelerators have the highest accuracy in dosage and distribution but are less powerful in emitting electron current. Their exactness makes these types ideal for product development and experimental use as well as for production.

The linear accelerators provide a large electron current but are less accurate in the dosage and distribution, especially at low doses.

Effects of Electrons

Electrons are generated in a vacuum and accelerated, then proceed through the titanium foil from the vacuum to normal atmosphere and

FIGURE 3

Electron crosslinking EB accelerator linear type

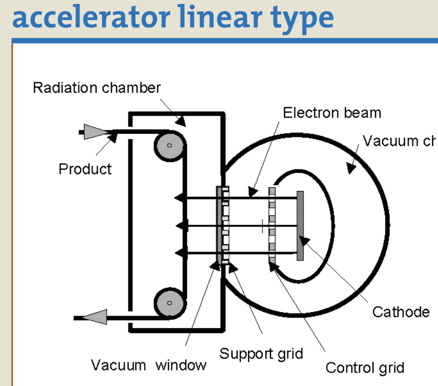
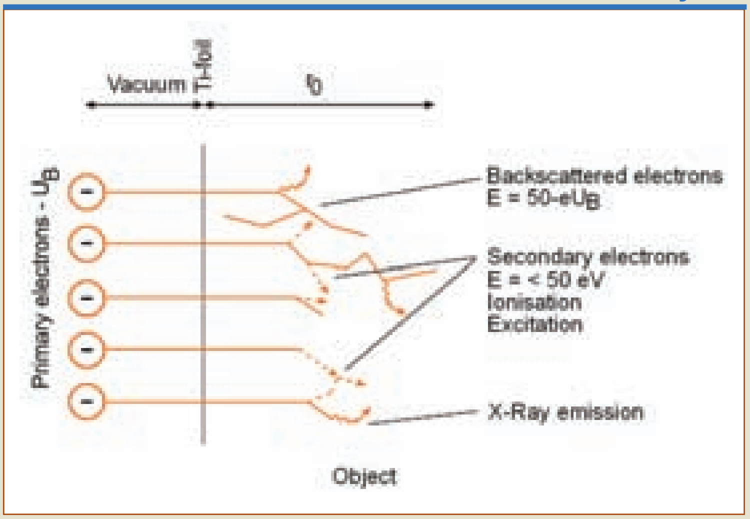


FIGURE 4

Electron interactions with matter (schematically)

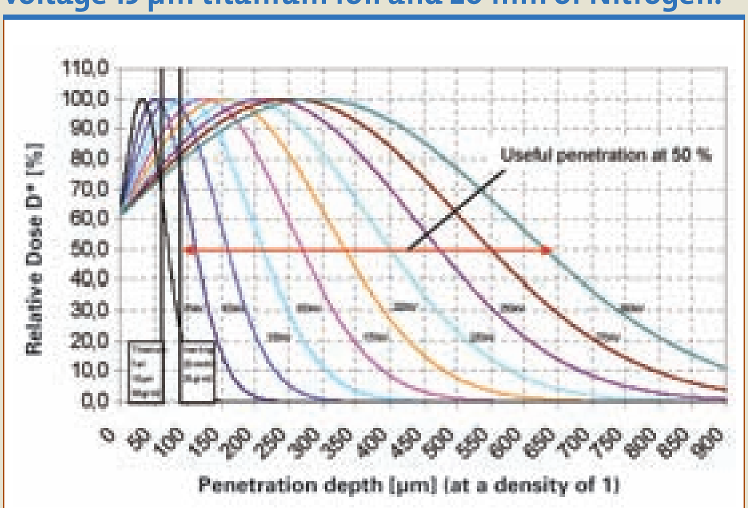


penetrate into the material with a range up to r_0.

After a distance of r_0 all electrons are retracted due to interaction with the material. Here, primary electrons and backscattered electrons are generated. Their energy exceeds 50 eV and has a maximum corresponding to the accelerating voltage. The fast primary and backscattered electrons do not lead to chemical reactions. Their activation cross section is too low—they cannot be caught by molecules and, thus, do not lead to radical formation, ionization or excitation.

FIGURE 5

Range of penetration with different accelerating voltage 13 μm titanium foil and 20 mm of Nitrogen.[22]



Important to us are the secondary electrons at energy levels between 3 and 50 eV. They are slow enough (i.e., their activation cross section is large enough to ionize molecules and to form radicals). Very slow electrons less than 3 eV only induce excitation. Ultimately, we only need the fast electrons to generate secondary electrons at the location outside the vacuum and/or deep in material.

A negative by-product of retarding accelerated electrons is the X-ray emission. Its energy cannot exceed the primary electron energy. This means that the electron-beam accelerator and the irradiation zone have to be shielded to prevent X-ray emission.

Energy Transfer

The transfer of energy from the electron beam into material is specified by four parameters:

- Depth of penetration
- Absorbed dose
- Beam uniformity
- Throughput

Depth of Penetration

The penetrating power of the electron beam is related to the accelerating voltage and the density of the processed material. Higher voltage causes deeper penetration and denser material reduces the depth of penetration. The Depth Dose Curves (Figure 5) are convenient aids for estimating the penetration depth. These curves show the penetration for different accelerating voltage to the depth of penetration in a material with mass density equal to that of water (i.e., p = 1 g/cm^3).

Penetration into materials of different density can be estimated by multiplying the penetration depth, found from the normalized curves, by the ratio of the density of water to the density of the material. For example, a 200 kV beam will have a 50% dose point at 0,246 mm in water and 0,123 mm in a material twice as dense (p = 2 g/cm^3).

At accelerating voltages of 150, 180 and 250 kV, respective curing depth of 86, 138 and 277 g/m^2 are achieved at 80% ionization.

Experienced values for industrial accelerating voltages are as follows:

- 80-150 keV thin layers in the field of printing inks or silicon-release materials, surface sterilization
- 165-180 keV furniture foil, pressure-sensitive adhesives
- 180-250 keV boards, parquet, panels, lamination
- 250-300 keV composite

The titanium foil and inerting space have influence on the depth dose distribution within the processed material in the low voltage region.

Absorbed Dose

Absorbed dose is defined as the amount of energy deposited into a specified mass of material. The unit of absorbed dose is gray (Gy), defined as the number of joules (J) of energy deposited into 1 kilogram (kg) of material. An older, but frequently used unit, is megarad (Mrad).

1 Gy = 1 J/kg
Heating of water 1 degree 4,2 J/g

1 kGy = 1 kJ/kg
Evaporation of water, at atm. 2250 J/g

1 Mrad = 10 kGy = 10 J/g = 2,4 cal/g
EB-curing of lacquer approx. 40 J/g

At a fixed electron accelerating voltage, the dose is directly proportional to the EB current. The dose D [kGy] is proportional to the electron current I [mA] and inverse to web speed v [m/min] as follows:

$$D = k \times \frac{I}{v}$$

The *k* factor depends on the equipment and the accelerating voltage.

The formula shows that:

- Dose and electron current are directly proportional
- If the ratio of electron current and speed are kept constant, the dose is constant, including startup and shutdown of the plant
- The accelerator uses only the quantity of power from the main supply needed for the used web speed
- Quality improvements

Typical values of the dose needed for practical applications are:

- Drying/curing of inks and coatings 15-30 kGy
- Crosslinking of plastic films 25-150 kGy
- Sterilization of medical products 7.5-35 kGy
- The certified dose to sterilize—7 log decrease is 25 kGy[27]

Beam Uniformity

Beam uniformity is a direct function of how the electron beam is distributed over the working width. It is specified as a percentage deviation from the average value, (e.g., 20 kGy ± 10%). In general, an electron crosslinking accelerator provides uniformity better than ± 5%; many applications can tolerate variations of ± 10% or more.

Throughput

Throughput is a measure of the energy deposition rate and relates directly to the amount of material that can be processed within a given time interval. It is measured in kilograys per second, abbreviated kGy/s. An accelerator specified at 10,000 kGy m/min can provide a dose of 25 kGy when the web speed is 400 m/min, or 50 kGy at 200 m/min, etc. The processor will automatically adjust the beam intensity as the web speed changes so that the dose remains constant.

Inerting

During EB curing, it is necessary to have an inert atmosphere. Oxygen concentration should be below 50 ppm for silicone coatings and below 150 ppm for web offset lithography. In order to keep the inerting gas consumption as low as possible, it is important to have an optimal design for the inerting system. Most of the inerting systems today are designed with an air block and then the remaining air is diluted to reach the required acceptance level for oxygen. With a high-speed web, it is important to have good laminar boundary layer separation.

Applications

EB-Curing and Surface Converting

The printing color must be dried after being applied on the substrate. The drying process can be made in various ways—through oxidation in air, removing the solvents or through chemical crosslinking. Each drying process has a name, such as cold-set, heat-set or UV-printing color. The printing color shows high variation in quality depending on the drying process. Die cold-set printing color that is basically absorbed into the paper is suitable only for new printing. When a higher printing quality is desired, heat-set printing is often used. The highest printing quality is achieved with radiation-curable printing color.

Radiation-curable printing color offers very high dot sharpness, high print gloss and high color brilliance. Besides the high print quality, the radiation-curable printing color has the advantage that it is extremely fast to cure and, thereby, immediately further workable. Furthermore, the system is 100% free from solvents and that means it's non-polluting.

EB curing is a very fast, energy-efficient and environmentally friendly drying method for paint, adhesives and

Figure 6

EC-LAB 400 batch system

Typical data for EC-LAB 400

Accelerating voltage:	80-300 keV
Electron current:	0-30 mA
Working width:	max 400 mm
Throughput:	4,500 kGy m/min
Exit window:	Titanium
Thickness:	7-20 µm
Cassette speed:	5-30 m/min
Max size (LxWxH):	600 x 400 x 250 mm
Web speed:	0-150 m/min
Max web width:	450 mm

printing ink. It provides a particularly hard and chemical-resistant surface with controlled curing throughout the depth. The EB-curing process is similar to the UV-free radical process—although the electrons are accelerated to a much higher energy and the electron has enough energy to start polymerization. The impact of these electrons is high enough to break chemical bonds and to generate ions. The ions then transform themselves into free radicals, which then initiate polymerization. Therefore, the EB-curing process requires no photoinitiator. EB accelerators can generate the radiant energy (80-300 keV) capable of curing thicker, pigmented resins as EB energy has greater ability than UV energy to penetrate through the material. EB is independent of the light transmission in the material.

Clear coatings of up to 500 µm and pigmented coatings of about 400 µm can be cured with EB equipment. The absence of a photoinitiator in the EB-curable coatings results in greater stability for the cured coatings. Benzophenone is perhaps one of the most common photoinitiators. Benzophenone is also often added to plastic packaging as a UV blocker.

Advantages of EB Curing

- It's environmentally friendly due to a 100% solid system. EB generates no emissions.
- There is no or low substrate heating.
- Energy consumption is low.
- There is a substantial production increase compared to conventional heat-treatment methods and UV technology, also with pigmented layers.
- Converted products can be further treated immediately without post curing.
- EB systems have smaller space requirements. It can be integrated into existing production processes without any problems.
- Exact repeatability of production conditions is obtained due to high dose accuracy. There is also no wastage when starting up and shutting down the plant.

In all applications, the EB accelerator remains the same—only the handling system differs such as:

- Material in solid forms (as sheet, board, panels, etc).;
- Flexible materials, roll-to-roll; or
- Laboratory equipment.

Solid Materials

In the surface converting of solid materials, the EB technology is successfully used in the following operating fields:

- Curing of top lacquer on doors[1, 2]
- All-around curing of coated profiles[3, 4]
- Curing of the coating on raw boards in the wood industry[5, 6]
- Curing of the coating on architectural claddings for outside applications[7, 8]
- Curing of the coating on wood-cement boards for outside and inside application[9]
- Curing of impregnation and top lacquer on laminated boards
- Curing of coated edges and panels in the wood and laminate industry[10]
- Curing of coatings on medium-density fiberboard (MDF)[11, 12, 13]
- Curing of coatings on three-dimensional parts (i.e., rims and pumps housings)
- Surface sterilization and disinfection

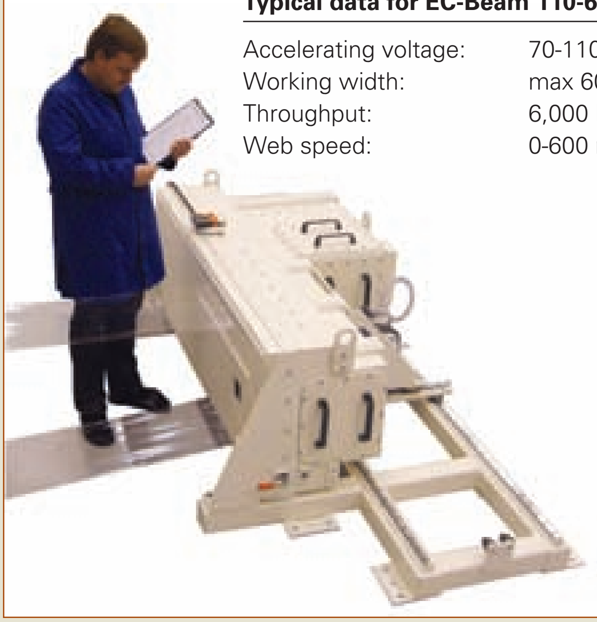
Flexible Materials

In the surface converting of flexible materials, the EB technology is successfully used in the following operating fields:

- Vulcanization or crosslinking of pressure-sensitive adhesives[14]
- Curing of high-gloss coatings of special papers (e.g., photographic paper)[15, 16, 17]
- Curing of release coatings
- Curing of web offset printing inks, finishing varnishes[18, 21]

Figure 7

The EC-Beam 110-600 is equipped with foil without pinholes



Typical data for EC-Beam 110-600	
Accelerating voltage:	70-110 keV
Working width:	max 600 mm
Throughput:	6,000 kGy m/min
Web speed:	0-600 m/min

- Crosslinking of films and foils
- Production of antistatic finish
- Crosslinking of flock adhesives
- Curing of intaglio prints[18, 19, 20]
- Post-crosslinking of binding agents of magnetic materials
- Metallizing of paper (e.g., curing of basic lacquer and adhesives for selective or plane transfer metallizing as well as curing of overprints)
- Curing of metal coating from roll-to-roll (coil coating)[24]
- Stabilization of rubber raw materials by partial vulcanization
- Crosslinking of laminating adhesives
- Crosslinking of thin insulation of wire and cables
- Coloring of textiles
- Surface sterilization

Laboratory Equipment

Laboratory scales serve as a basis for developing an in-depth fundamental physical and chemical understanding of the process and investigation of a wide variety of materials and methods for producing crosslink in materials and to develop more effective optimized treatments. Pilot plants are small processing systems that are operated to generate more detailed information required for scale-up-to-production plants. A detailed analysis leads to optimization of the process parameters.

Selection of material, paint and process design, etc., should be based on the laboratory data from large-scale experiments in a laboratory EB accelerator.

The EC-LAB 400 (Figure 6) is a compact, multipurpose EB laboratory with a variety of possibilities and applications. These include web transport with drum-and-batch applications and there is an option for continuous roller transport for adaptation in other processes and systems for continuous irradiation of cables, fibers and composites that will open many new possibilities. The highly modular design can easily be customized to meet unique needs and ambitions. The EC-LAB equipment is suitable for laboratory use or pilot-scale production, to develop new processes or insure production quality.

Process parameters and data from the EC-LAB 400 can be directly translated to a production unit.

EC Beam Printing System

The EC Beam 110 (Figure 7) is a compact EB accelerator, linear type suitable for all flexo-, screen- and roll offset-printing applications. It's designed for web speeds up to 600 m/min. The titanium foil and inerting space have influence on the depth dose distribution within the processed material in the low-voltage region. The costs for the HV transformer and screening can be reduced through lower accelerating voltage. The advantage of reducing the accelerating voltage is well known. However, this has not been implemented and there are no thin foils available in corresponding sizes for the printing industry. The window foils of titanium used until now are manufactured by through-rolling mill. Because of the high mechanical stress when making thin foil, "pin holes" can occur. New techniques make it possible to manufacture thin foils without pinholes.

EC Beam 150-250kV

This system (Figures 8 and 9) offers EB curing suitable for curing and surface converting of a variety of substrates, including:

- Wood materials as floor coverings, doors, wall plates, all-around curing of lacquers on mouldings

FIGURE 8

EC beam 250kV product width 1,250mm

Typical data for EC-Beam 110-600

Production unit made for 24/7 operations at 250kV

Accelerating voltage:	150-250 keV
Working width:	max 1,250 mm
Throughput:	13,000 kGy m/min at 150 keV
Web speed:	10-further m/min

- Façade plates for outside application, direct coatings of paper and foils
- Paper and synthetic foil coatings (furniture foils, lacquered foils for laminated boards in applications for high requests such as floor coverings or table surfaces)
- Vulcanizing of pressure-sensitive adhesives

The PLC system of the equipment controls and supervises the high voltage (penetration depth of electrons) and EB (dose/throughput of material). The unit can be equipped with inert gas recovery and recirculation.

The accelerator is running at 24-hour operation in many different types of applications. It is especially distinguished by short setup times following initial installation and service. Its uncomplicated construction, combined with a control system for automatic process control, enables the operator to quickly and easily replace cathodes and exit windows without assistance from the supplier. Replacing worn parts requires less than one hour.

EB Package Sterilization

The documentation of the radiation sterilization process rests on the ability to measure dose in all steps of the validation and routine control (Figure 10).

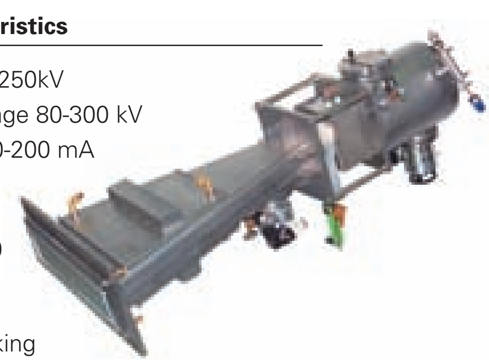
Aseptic Packaging

Consumer products such as aseptic packaging for food or cosmetics, which have to be microbe-free, can be sterilized by radiation. To sterilize the inside of the package, a packaging production plant moves a considerable part of the aseptic process from dairies and other beverage companies back to packaging production. The sterilization is performed with EB inline treatment, which is a safe method with a low environmental impact. This process

FIGURE 9

Electron beam accelerator, 250 kV accelerating voltage and 1,20 m working widths.

Operating characteristics



- EC Scanner 150- 250kV
- Acceleration voltage 80-300 kV
- Electron current 0-200 mA
- Working width 2,000 mm
- Throughput 9,000 kGy m/min
- Distribution of dosage over working width < $ 5 %
- No gas cooling of the electron exit window necessary
- The accelerator can be installed in any position whatsoever
- No measurable radiation outside the X-ray shielding

Figure 10

Ecolean® air aseptic

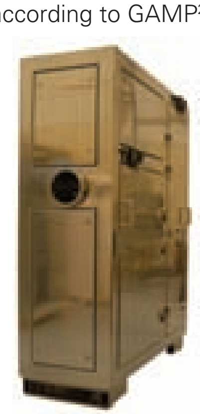
The packaging material is folded, shaped and sealed in proprietary Ecolean machines to produce roll stock of individual ready-to-fill packages. Each package is hermetically sealed and sterilized, and the process is monitored and traceable down to individual packages.

Figure 11

Medical device

EB 300-120 MD

Electron accelerator manufactured according to GAMP[29]



has no affect on material properties such as strength or color, nor does it generate any detectable odors. The package is sterilized throughout and the irradiation process follows the ISO standard for medical products, thus ensuring defined package sterility levels.

Producers of medical devices have a responsibility to ensure that their products are free from viable microorganisms. Sterile medical devices meet a Sterility Assurance Level of 10-6 or less (i.e., the probability of a single viable microorganism being present is less than 10-6.) A minimum irradiation dose of 25 kGy is considered sufficient to validate the sterilization of a medical product.[27] An irradiation dose of 15 kGy is acceptable when bio burden is lower then 1,5 cfu.[27]

Accelerated electrons in voltage ranges of 150-250 keV with penetration depth in material of density 1 of 70-300 µm are particularly suitable for:

- Surface sterilization; and
- Germ reduction in the depth of the packaging material.

Accelerated electrons are calculable in their penetration depth (Figure 5).

A key aspect for medical device equipment is well-written procedures. Procedures should be clear, concise and easy for employees to follow. Well-written procedures should not leave any room for misinterpretation. They should be written in such a manner that anyone who is properly trained and knowledgeable in the field could follow them as they are written.

Summary

EB curing is a very fast, energy-efficient and environmentally friendly drying method that provides a particularly hard and chemically resistant surface with controlled curing throughout the depth.

A laboratory scale serves as a basis for developing materials and methods for producing crosslinking in materials.

Pilot plants lead to optimization of the process parameters and ensure a successful transition to production. A compact 70-110 keV EB is suitable for all flexo-, screen- and roll offset-printing applications. (Web speeds up to 600 m/min.)

A linear multicathode electron accelerator works well for larger working widths with high web speeds.

Still, in order to carry this technology on to further success, there needs to be good cooperation between customers, chemists and plant manufacturers.

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—Thomas Lund, B. Laurell and E. Föll are with Electron Crosslinking AB, in Sweden.