NEW DEVELOPMENTS OF ELECTRON BEAM ACCELERATORS

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1. FOREWORD

The purpose of this presentation is to present an overview of the present state of industrial electron beam 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 be seen clearly.

2. INTRODUCTION

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

Also the new EC Super directive regarding migration of less then 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 which do not induce these disadvantages of thermal drying are the radiation curing techniques methods – in particular those involving ionising radiation such as ultraviolet or electron-beam curing.

Radiation Curing

- IR Infra-red	System containing solvents
- Micro-wave	Water-based system
- UV Ultraviolet light	100 % system
- EB Electron Beam	100 % system

UV-ultraviolet 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 trough, must be thin and transparent at the appropriate wavelengths. The formulation will contain photo initiators and other absorbing materials like pigment and matting agents.

During and after the curing process there should be no emission of harmful substances into the atmosphere, water or into the food. In addition, after the curing process is over, there should be no odour emissions from the surface.

These requirements have already given Electron Beam curing (EB) the focus of even more attention, not least as this technology has been used for a wide variety of applications in recent years due to the many other benefits it offers.

EB is the abbreviation for an environmentally safe, heat and solvent free technique: **E**lectron-**B**eam curing.

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

3. THE ACCELERATOR

The functioning of the electron beam accelerator can best be compared with the cathode ray tube of a TV. Fig. 1.

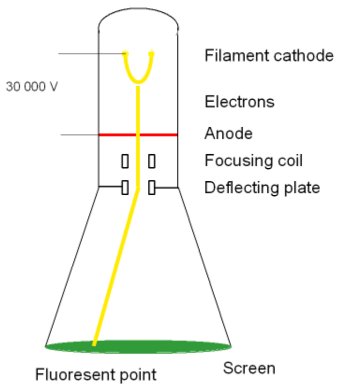

Figure 1 Cathode ray tube

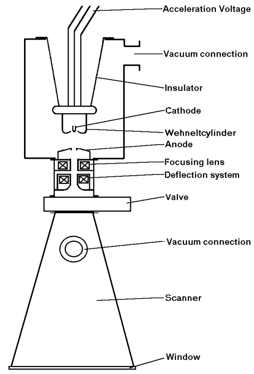

Figure 2 Electron Crosslinking electron beam accelerator Scanner type

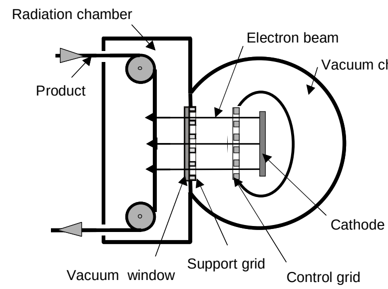

Figure 3 Electron Crosslinking electron beam accelerator Linear type

The production of free electrons in vacuum is properly 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 high vacuum by an electrical current makes free electrons available on its surface and these are accelerated to the anode. In a TV set the electrons (negatively charged particles) are accelerated by a high negative voltage towards the anode and then deflected to the screen, or to the electron-beam exit window in the electron-beam 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.

In a scanner accelerators (fig.2) a tungsten heating cathode, Wehnelt cylinder and an anode -with focussing lens and electron-beam deflection system- together form one unit. Absolutely linear current signals controlling the beam deflection in two perpendicular directions. Scanning frequencies are over 800 Hz. The electron-beam 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 multi-cathode electron accelerators (fig.3) this cathode system contains 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 effected by means of water and convection through this 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 of the 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 for production.

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

4. EFFECTS OF ELECTRON

Electrons are generated in vacuum and accelerated, then proceeds trough the titanium foil from vacuum to normal atmosphere and penetrate into the material with a range up to r_0.

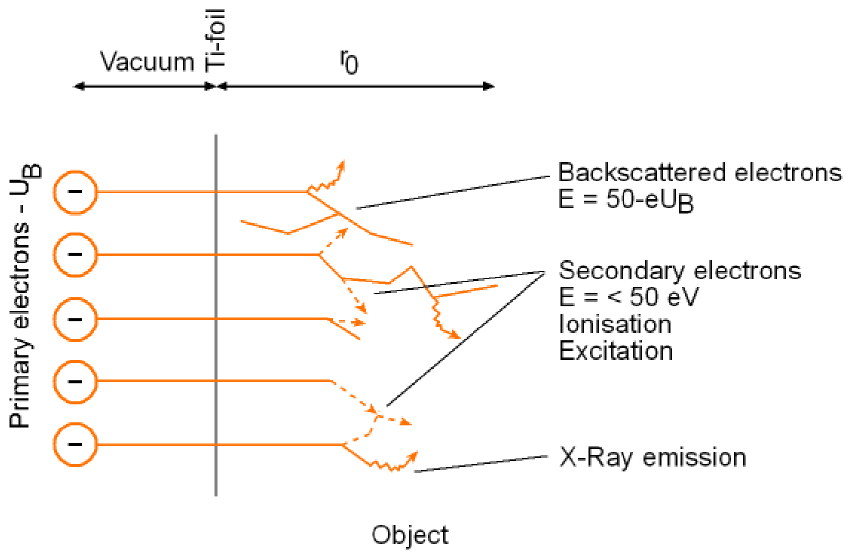

Figure 5 Electron interactions with matter (schematically)

After a distance of r_0 all electrons are retracted due to interaction with the material.

- Here Primary electrons / 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.

- 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.

5. 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

5.1. Depth of penetration

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 (Fig 6) 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).

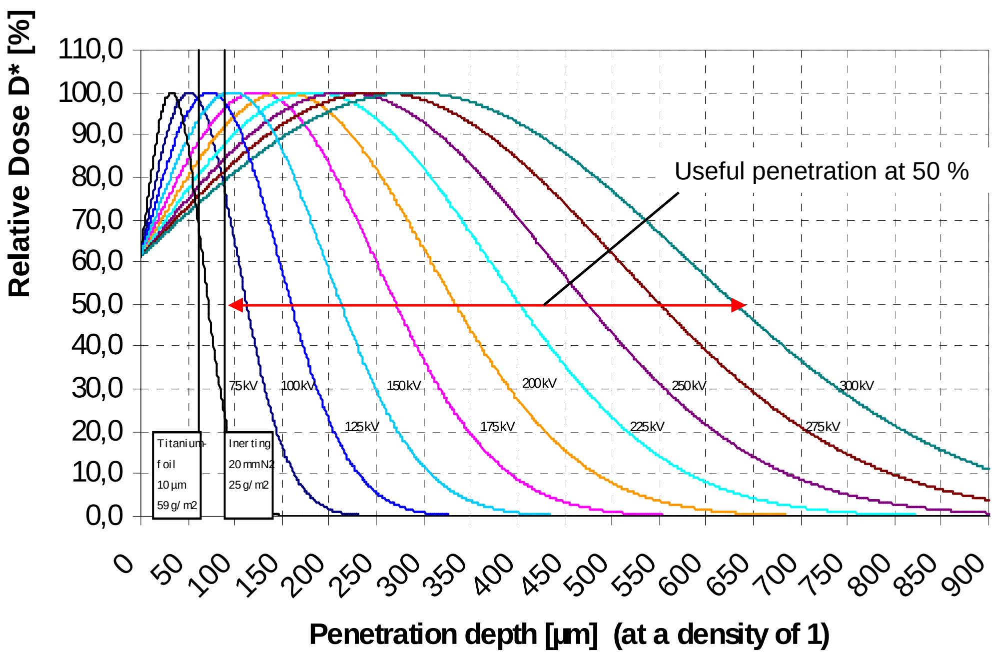

Figure 6 Range of penetration with different accelerating voltage 13 µm titanium foil and 20 mm of Nitrogen. [22]

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 sterilisation
- 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

5.2. 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 electron beam current. The dose *D* [kGy] is proportional to electron current *I* [mA] and inverse to web speed *v* [m/min] as follows:

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

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

The formula above shows:

- dose and electron current are directly proportional
- if the ratio of electron current and speed are kept constant the dose is constant including start up and shut down 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]

5.3. 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, Electron Crosslinking Accelerator provides uniformity better than ± 5%; many applications can tolerate variations of ± 10% or more.

5.4. 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 kilogray per second, abbreviated kGy/s.

An Accelerator specified to 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.

5.5. Inerting

During Electron beam curing is it 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 is it important to have an optimal design of the inerting system. Most of the inerting systems today are design with an air block and then diluting the remaining air to reach the required acceptance level for Oxygen.
With a high-speed web it is important to have good laminar boundary layer separation.

6. APPLICATIONS

6.1. EB –Curing and surface converting

The printing colour must be dried after have been applied on the substrate. The drying process can be made in various way, through, oxidation in air, remove the solvents or through chemical Crosslinking. Each drying process has name as Cold-Set, Heat-Set or UV-printing colour. The printing colour shows high variation in quality dependent of the drying process. Die Cold-Set printing colour that basically is absorbed into the Paper, suitable only for new sprinting. When a higher printing quality is desired there is the Heat Set printing application. The highest printing quality is achieved with radiation curable printing colour.

Radiation curable printing colour offer very high dot sharpness, high print gloss and a high colour brilliance. Besides the high print quality the radiation curable printing colour have the advantage, that it is extreme fast to cure and thereby immediately further workable. Furthermore is the System 100% free from solvents and by that means non-polluting.

Electron beam curing is a very fast, energy efficient and environmentally friendly drying method for Paint, Adhesives and Printing ink that provide particularly hard and chemical resistant surface with controlled curing throughout the depth. Electron beam curing process is similar to the UV-free radical process. Though, 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 cure process requires no photo initiator. Electron beam 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 photo initiator in the electron beam curable coatings results in greater stability for the cured coatings.
Benzophenone is perhaps one of the most common photo initiators. Benzophenone is also often added to the plastic packaging as a UV blocker.

Advantages of Electron Beam curing:

- Environmentally friendly due to a 100 %-solid system. EB generates no emissions.
- No or low substrate heating.
- Low energy consumption.
- Substantial production increase compared to conventional heat-treatment methods and UV-technology, also with pigmented layers.
- Immediate further treatment of converted products without post curing.
- Low space requirement. Integration 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 Electron Beam Accelerator itself remains the same but the handling system differs:

- material in solid form, as sheet, board, panels etc.
- flexible materials, roll to roll
- laboratory equipment

6.2. 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 MDF boards (Medium-Density-Fibre-board) [11], [12], [13] Curing of coatings on three-dimensional parts e.g. rims and pumps housings.
Surface sterilization and disinfection

6.3. Flexible materials

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

Vulcanisation or Crosslinking of pressure-sensitive adhesives [14]
Curing of high-gloss coating of special paper (e.g. photographic paper) [15], [16], [17]
Curing of release coatings
Curing of web offset printing inks, finishing varnishes [18], [21]
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]
Stabilisation of rubber raw materials by partial vulcanisation
Crosslinking of laminating adhesives
Crosslinking of thin insulation of wire and cables
Colouring of textiles
Surface Sterilization

6.4. Laboratory equipment

Laboratory scale serve as basis to developing an in-depth fundamental physical and chemical understanding of the process and investigating 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 plant. 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 Electron beam accelerator.

The EC-LAB 400 is a compact multi-purpose laboratory electron beam with a variety of possibilities and applications. These include web transport with drum and batch applications and there is option for continuous roller transport for adaptation in other processes and system for continuous irradiation of cables, fibres and composites that will open many new possibilities. The highly modular design it can easily be customized to meet unique needs and ambitions. The EC-LAB equipment is suitable laboratory use or pilot scale production, to develop new processes or to insure quality in production.

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

Typical data for EC-LAB 400

Accelerating voltage:	80 – 300 keV	Cassette speed:	5 – 30 m/min
Electron current:	0 – 30 mA	Max size (LxWxH):	600 x 400 x 250 mm
Working width:	max 400 mm	Web speed:	0 – 150 m/min
Throughput:	4500 kGy m/min	Max web width:	450 mm
Exit window:	Titanium		
Thickness:	7 – 20 µm		

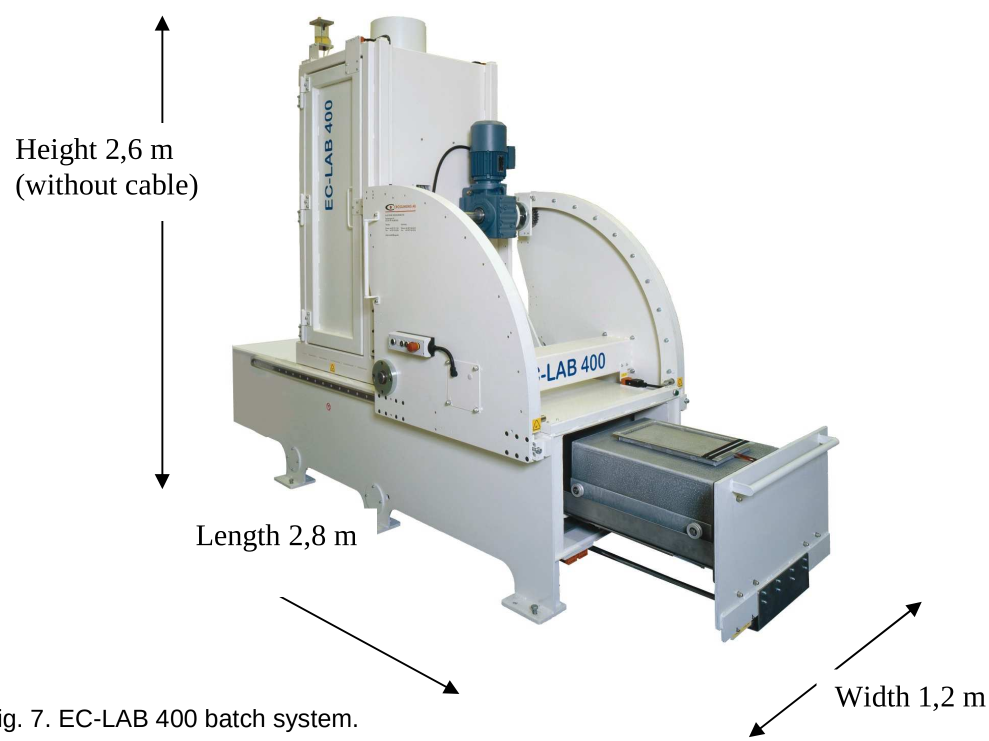

Fig. 7. EC-LAB 400 batch system.

6.4.1. EC Beam printing system

EC Beam 110 is a compact Electron beam accelerator Linear type suitable for all Flexo-, Screen- und Rolloffset- printing applications. Designed for web speed up to 600m/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 has this not been implemented, there are not any 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 be obtained. New techniques make it possible to manufacture thin foils without pinholes.

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

Picture 1 EC Beam for Web width 600mm

Typical data for EC-Beam 110-600

Accelerating voltage:	70 – 110 keV
Working width:	max 600 mm
Throughput:	6000 kGy m/min
Web speed:	0 – 600 m/min

6.4.2. EC Beam 150-250kV

Electron beam curing suitable for curing and surface converting of a variety of substrates, e.g.:

- Wood materials as floor coverings, doors, wall plates, all-around curing of lacquers on mouldings
- Façade plates for outside application, direct coatings of paper and foils
- Paper and synthetic foil coatings (furniture foils, lacquered foils for laminated boards in application for high requests like floor coverings or table surfaces)
- Vulcanizing of pressure sensitive adhesives

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

Picture 2 EC Beam 250kV Product width 1250mm

Typical data for EC-Beam 250kV 1250

Production unit made for 24/7 operations at 250kV

Accelerating voltage:	150 – 250 keV
Working width:	max 1250 mm
Throughput:	13000 kGy m/min at 150 keV
Web speed:	10 – further m/min

6.4.3. EC Scanner 150-250kV

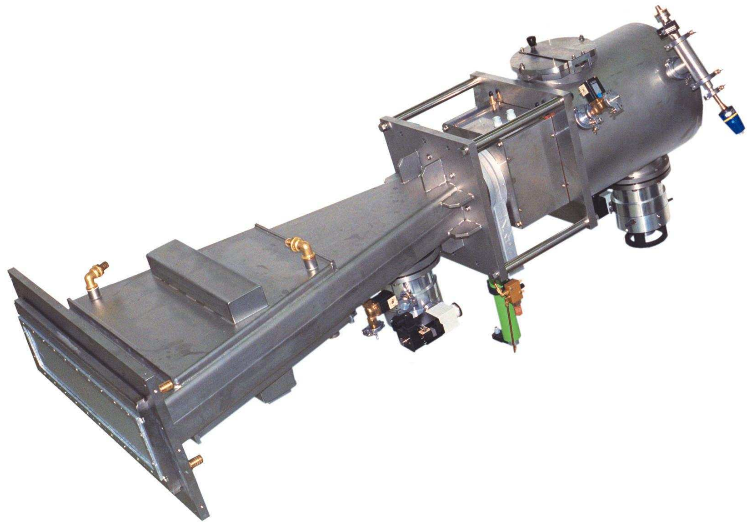

Figure 4 Picture of Electron Beam Accelerator, 250 kV accelerating voltage and 1,20 m working widths.

Operating characteristics EC Scanner 150-250kV

- Acceleration voltage	80 - 300 kV
- Electron current	0- 200 mA
- Working width	- 2000 mm
- Throughput	9000 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.

The accelerator is running at 24-hours operation in many different types of applications. It is especially distinguished by low set-up times following initial installation and service. Its uncomplicated construction combined with a control system for automatic process control enables the operator to quick and easy replacement of cathode and exit window without assistance from the supplier. Replacing wearing parts requires in total less than one hour.

6.5. EB –Package sterilisation

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

6.5.1. Aseptic packaging.

Consumer products such as aseptic packaging for food or cosmetics, which have to be microbe free, can be sterilized by radiation.

Sterilizing the inside of the package 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 electron beam inline treatment, which is a safe method with a low environmental impact. This process has no affect on material properties like strength or colour, nor does it generate any detectable odours. The package is sterilized throughout, and the irradiation process follows the ISO standard for medical products, thus ensuring defined package sterility levels.

Picture 3 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.

6.5.2. Medical Device.

EB 300-120 MD
Electron accelerator manufactured according to GAMP [29].

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 (SAL) 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
- Germ reduction in the depth of the packaging material.
Accelerated electrons are calculable in their penetration depth. Fig 6

Picture 4 EB 300-120 MD

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.

7. SUMMARY

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

Laboratory scale serves as basis to developing materials and methods for producing Crosslinking in materials

Pilot plants leads to optimization of the process parameters and ensure a successful transition to production.

A compact 70 – 110 keV EB suitable for all Flexo-, Screen- und Rolloffset-printing applications. Web speed up to 600 m/min

A Linear multi-cathode electron accelerator for larger working widths with high web speed

Still in order to carry this technology on to success, good cooperation between customer, chemistry and plant manufacturers is necessary.

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