Electron Beam Accelerators

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Electron beam accelerators can be made in a number of ways: cathode ray tubes (CRT) that sweep or scan the process area, electron wide-area curtains and sealed vacuum tube systems.

CRT systems (scanned beams)

The CRT type works much like older television picture tubes or computer CRT display screens. A filament or cathode provides a point source of electrons. These electrons become a beam when they are accelerated across a voltage potential and reach very high velocities. Inside the TV tube (which is under vacuum), the beam of electrons is scanned back and forth, according to the TV signal, and light is emitted when the electrons strike a phosphor coating on the interior of the screen giving rise to the picture image. With an electron beam that cures coatings and inks, the scanned beam leaves the vacuum by passing through an ultra-thin window and strikes the uncured ink or coating – instantly curing it.

Unlike UV cure, where the photons emitted by an ultraviolet lamp have only minuscule mass and are easily stopped at the surfaces of materials, electrons have much more mass and can penetrate films. Thick and opaque films can be cured with electron beams. As the EB voltage increases, so does the electron energy – and the depth of cure. Higher voltage accelerators – >300,000 volts (300 keV) – differ among suppliers in the kinds of transformer systems used. These higher voltage systems are quite large and almost always are set up as stand-alone operations and can require large concrete or steel shielding facilities.

As mentioned above, the CRT type beam is magnetically scanned in order to spread out the electron beam so it can interact with a greater cross-section of material. Scan widths of up to 1.8 meters (72") have been attained. This occurs while still in the vacuum. After passing through the thin window, the scanned beam is at atmospheric pressure in the curing chamber, where the inked and/or coated substrate is. The curing chamber almost always is inerted with nitrogen. The electrons now can cure the EB ink and/or EB coating.

Curtain systems

The majority of installations in the 150 to 300 keV range rely on linear cathode concepts. These accelerators have a number of common features:

a) Transformers and a DC power supply.
b) Linear filaments (differing in design configuration between vendors). Because the source is a linear source rather than a point source, no scanning is necessary.
c) An evacuated acceleration tube or chamber with a separate vacuum system (in some systems) to maintain said vacuum.
d) A beam transmission window and inerted curing chamber.
e) Lead or steel safety shielding around the acceleration tube and under beam transport systems.
f) Electrical control systems for interlocking beam operations with other process equipment.

Quick summary

One way to generate the high-energy electrons used in an EB process is a single point CRT tube, where the electrons produced by the source, are scanned across the item to be cured, similar to an old style CRT TV tube. Another way is to produce a curtain from multiple sources called filaments.

Compact EB units are usually filament type and operate in the 90 to 300 keV range.

When designing an EB unit, one has to consider four main components:

- Power supply
- Acceleration chamber
- Beam window
- Shielding (to absorb any secondary X-rays that may be produced)

The dose of electrons needed to cure an ink or coating is typically 1 to 3 megarads. By linking the electronics of the EB unit to the printing press drive system, it is possible to give the ink and/or coating the same "dose" of electrons no matter what the press speed is. This is important since it allows the final print properties to remain the same throughout start up and shut down of the press.

The power supply

Coil wound transformers are used to provide the voltages needed by linear cathode electron beam accelerators. These transformers rely on standard factory power. Depending upon the power level of the accelerator, relatively small transformers can be used as in small-scale, self-contained lab units. Larger transformers, sometimes occupying as much as 8 square meters of plant floor space, are needed for high current production units. These transformers may be oil-filled for insulation and cooling, or they can rely on sulfur hexafluoride (SF6) gas as a coolant/insulator. With production units, the transformer can be connected to the accelerator by a high voltage cable. Thus, the transformer can be physically located well away from the accelerator. Or, if space permits, the transformer may be directly coupled to the accelerator, thus eliminating the need for the high-voltage power cable.

Filament systems

The key to compact electron beam accelerator design in the low voltage range (90 keV to 300 keV) is the use of linear filaments, which eliminate the need to scan electrons. Two basically different approaches have been taken to designing filaments arrays, which traverse across a web.

Single cathode

In one approach, a continuous filament is formed and cut to length so the filament itself approximates the width of the application area. With this design, the filament is able to emit a shower or wide area curtain of electrons uniformly across a given area. Extending the target width of an accelerator becomes a matter of building longer filaments and the support structures needed to hold them and the accelerator housing. This curtain approach permits building accelerators capable of depositing electrons on webs up to 2 meters wide.

For some applications that require a high production throughput and a high level of beam exposure, long parallel filaments can be aligned within the same acceleration chamber. Acceleration heads with up to four such parallel filaments have been built to cross-link adhesives.

Multiple cathodes

The other approach to filament design is to run many short filament lengths in the direction of the web, which are, in turn, connected to each other in parallel. In this configuration, the filaments can broaden the beam of electrons impinging upon a substrate. Since these filament arrays are modular, a number of modules can be linked to permit the electron bombardment of webs approaching nearly 3 meters wide. Given the other design requirements of the acceleration system and its necessary lead shielding, structural considerations tend to limit the practical web widths, which can be treated with electrons to this 3-meter figure.

The acceleration chamber

The general construction of a low-voltage electron beam acceleration chamber is presented below. When positioned in a converting line, this chamber is the most obvious part of the accelerator. It can be around 40 cm in diameter or larger and traverse the entire width of a web.

Electrons are extracted from the filament or cathode and accelerated across a large voltage potential (90 to 300 keV). Care is taken in the design of this terminal so the electrons emitted from it flow toward the titanium foil beam window (F) and are not absorbed in the chamber walls.

In order to prevent any loss of energy as the electrons are being accelerated, the acceleration chamber is maintained at a vacuum of 1.0 x 10^{-6} mBar. This vacuum also enhances the life expectancy of the filaments by reducing the possibility of filament oxidation.

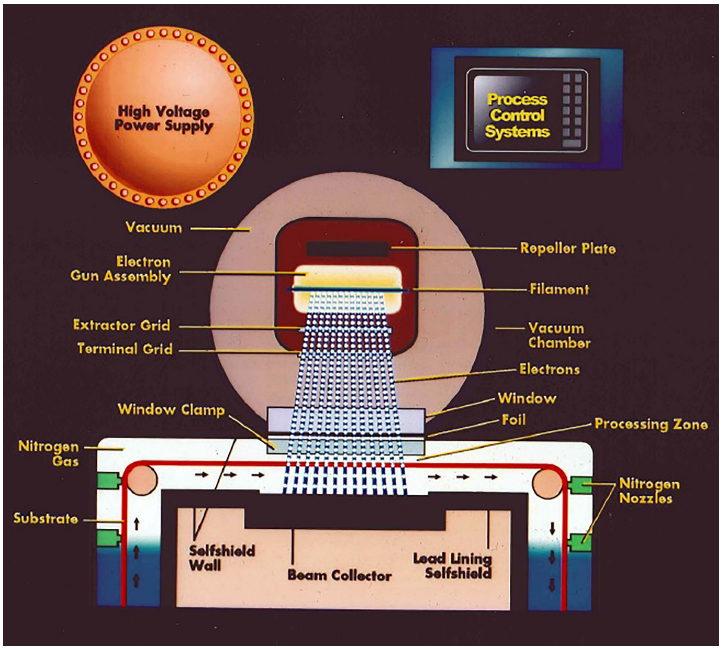

IMAGE 1. Electron beam diagram

Sealed tube systems

With CRT and most curtain systems, a separate vacuum pump and system is supplied with the accelerator. The vacuum system is a user serviceable design. Sealed tube systems require no vacuum system, but they must be returned to the manufacturer periodically for refurbishment.

Beam windows

The accelerated stream of electrons seeking ground is directed within the acceleration chamber toward the beam transmission window. This window is a thin gauge (typically 25 microns or thinner) titanium foil. Its main function is to maintain the vacuum within the acceleration chamber itself. Being extremely thin, this foil does not absorb much of the electron beam (<2%), and it permits most of the accelerated electrons to travel through the foil and impinge upon a substrate or target below.

The window, however, does absorb some energy, and it does become hot during accelerator operation. Both water-cooled grids or air cooling are used to keep the beam window near ambient temperatures. In the course of use, the electron beam can imprint a heat pattern on the window. To avoid an implosion, which could carry materials and unwanted dust into the acceleration chamber, it is good practice to change the beam window as part of a routine preventative maintenance program. The inability to hold vacuum within the acceleration chamber can be indicative of a pinhole. Care also should be exercised to see that components of coating materials do not collect on the window over extended periods of time.

The titanium foil beam window, rubber gasket O-rings and accelerator filaments are the only three components of an electron beam accelerator, which require routine replacement in user serviceable designs. Accelerator manufacturers estimate 10,000 hours of service use for a filament under normal production use. The thermal cycling of repeated on and off switching with accelerators used for experimental work will shorten this life expectancy. After more than six months of in-service use, it is also good practice to change the titanium foil beam window.

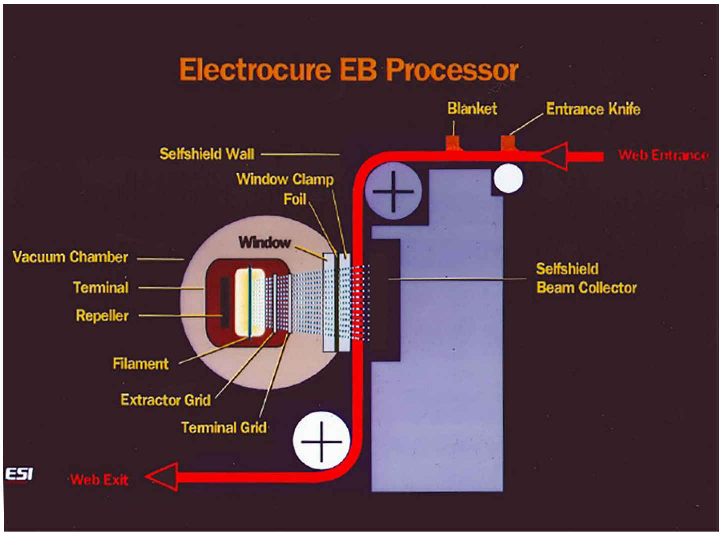

IMAGE 2. How an electron beam works

Shielding

The electrons being emitted by an accelerator flow in a straight line from the beam window toward a target or substrate. When accelerated electrons strike a target material, they can interact with the material and create a desired chemical effect. However, given their high speed and kinetic energy, accelerated electrons may also pass through the substrate. Whether the high-energy electrons hit the substrate or pass through the substrate and hit the material beneath, they also will generate long penetration X-rays. These X-rays will scatter in every possible direction.

Lead and safety

To eliminate any possible worker exposure to these so-called "secondary X-rays," the manufacturers of low-energy electron beam accelerators encase the critical areas of their equipment in lead. Typically, 1.0 cm (0.4 inch) of lead is sufficient to stop any X-rays generated by a 150 keV accelerator. Such lead casing is used around the entire accelerator chamber and around the under beam components used for material transport. Arranging the angle and length of such openings also enables the EB manufacturer to eliminate any possible X-ray emission. Electron beam accelerators will come equipped with X-ray detection devices, which will read the background level and will be interlocked with the accelerator to shut it down instantly should an increased level of background X-rays be detected.

It should be noted that lead shielding is practical up to the 300 keV level. At higher acceleration voltages, above 600 keV, separate concrete or steel vaults must be constructed in order to eliminate any X-ray emissions. Thus, these 90 keV to 300 keV accelerators often are called self-shielded.

When the stream of electrons emitted by an accelerator is absorbed in a target, heat is generated. Care is taken to see that the area immediately under or opposite the beam is cooled. In most situations, a water-cooled metal plate is positioned directly below the beam. When drum curing is being used, the drum beneath the beam also is water-cooled. Inert gas atmosphere that is introduced in order to enhance the reaction rate of a material exposed to electrons, also can help serve as a coolant.

In general, the operating voltage range of an electron beam accelerator is set during the design and construction of the unit. Accelerator manufacturers provide a voltage adjustment feature that permits operating the accelerator at less than the maximum rated voltage. Thus, an accelerator capable of delivering 200 keV electrons can, with a simple keypad or touchscreen, be turned down to deliver 100 keV electrons. This lower power system consumption permits more economic conversion of thinner gauge materials. As an example, 300 keV electrons, which effectively can penetrate 0.5 mm (20 mils) of unit density material need not be used if 0.01 mm (0.4 mils) penetration (which can be generated from only 100 keV) is sufficient to thoroughly cure a given material. Some work has been done using two low-voltage accelerators to irradiate webs from both sides.

Exposure and dose

The total absorption by a target material of an electron beam is called the dose. Dose is often expressed in megarads wherein one rad equals 100 ergs per gram of absorbed energy. One megarad is also equal to 10 kilograys (10 joules per gram). The gray is the internationally used unit of dosimetry for EB. The curing of most coatings, inks and adhesives requires dose exposure in the range of 1 to 3 megarads (10 to 30 kilograys) to exhibit full cure.

In contrast to electron beam exposure, ultraviolet exposure is often in the range of 0.1 to 0.5 joules. Because of differences in web speeds and lamp intensity vs. beam currents, it is difficult to establish any exact correlation between the exposure dose under an electron beam and that under a system of ultraviolet lamps.

Here are some useful dosimetry relationships:

Dose = energy absorbed per unit mass
Rad = unit of dose equal to absorption of 100 ergs per gram
Megarad = MR or MRad = 1 x 106 rads = 10 kilograys = 10 joules per gram = 2.39 calories per gram = 4.3 BTU per pound = 10 watt-seconds per gram = 4.54 kW-seconds per pound
Gray = unit of dose = absorption of 100 rads = 1 x 104 ergs per gram
Kilogray = 1,000 grays = 0.1 megarads = 1 joule per gram
1 megarad = 1 x 108 ergs per gram absorbed energy = 10 kilograys

System controls

In actual practice, one usually operates an accelerator strictly by controlling beam accelerating voltage, beam current and line speed. The relationship between the line speed of a moving web and the beam current dictates the dose. For any given material, there is an optimum relationship between these two controllable parameters, which will ensure the desired state of cure. Being a completely electrical device, the beam current of an electron beam accelerator can be electrically interlocked with the drive systems. Thus, an increase in web speed would result in a corresponding increase in beam current, keeping the substrate exposure level constant. This permits minimum use of materials during start-ups and shut downs. The equation below shows that accelerator current and line speed are directly proportional.

$$\text{Dose} = \frac{k \times I\ (\text{mA})}{\text{line speed (m/min)}}$$

Dose is expressed in megarads, "I" is the beam current in milliamps, line speed is in meters per minute and "k" is an empirically derived proportionality constant (often called the "production constant.") Although the production constant is empirically derived, it is a function of various beam design features, including line width, geometry and the distance to the beam window.

Other uses

In relying on linear cathodes (filaments), many electron beam systems are suited for use with flat sheet or web-fed materials. Because of the need to maintain vacuum in the acceleration chamber and the consequent use of a foil window, complex beam configurations are not usually practical. This does not necessarily preclude the use of electron beams with 3D objects. Sophisticated under-beam transport devices occasionally have been developed, which permit the controlled rotation of objects under the beam, especially if they are transported down the length of the beam window. Besides inks and coatings, electron beam cross-linking is being used with adhesives, as well as bulk cross-linking of film products and wire insulation. ■