28 Industrial Electron Accelerators

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28.1 Introduction

Started in the early 1930s, and in full development during the last 30 years, electron accelerators are now useful tools in industry for many applications. This is due to the numerous capabilities of the electron beam in a wide variety of commercial applications. Several thousands of different products are processed daily throughout the world, creating energy savings and high added value. A rough idea of industrial electron accelerators (of the electrostatic and cascade types) and their use is given in this chapter.

28.2 Interaction of Electrons with Matter

The principal effect of high-velocity electrons is to produce ions in the material treated, resulting in the liberation of orbital electrons. These electrons form the chemical bonds between the atoms of most materials, whether liquids, gases or solids. Since chemical bonding energies are lower than the energy of ionization of an orbital electron, an energetic electron beam can break these bonds, producing ions, free radicals and other excited states. As a result, the original molecule is modified and the free radicals or other excited species can combine to form new molecules. The net effect is the breaking of chemical bonds with attendant chemical reactions, destruction of organisms by disorganization of their DNA chains, or dislocation of atom migration.

28.3 Industrial Applications of Electron Beam Processing

Electron beam processing is now utilized by many major industries, including the plastics, automotive, rubber goods, petrochemical, wire and cable, electrical-insulation, textile, semiconductor, gem, medical, packaging and pollution control industries. A partial listing of proven industrial applications for electron beams includes:

– crosslinking of wire and cable insulation
– disinfection of sewage sludge and waste water
– power plant pollution control (DeSOx, DeNOx)
– modification of bulk polymers
– rubber vulcanization
– cellulose depolymerization
– crosslinking of plastic film, foam and tubing
– food preservation
– curing of coatings
– textile modification
– graft polymerization on film, fiber and paper
– semiconductor modification
– sterilization of medical supplies.

The net effect of electron treatment is that physical properties, chemical structures and biological structures can be changed. For example, the molecular weight of bulk polymers can be tailored by polymerization or depolymerization with electron beams. Also, the creation of free-radical sites by electron treatment provides grafting possibilities in the production of copolymers and converted materials.

Disinfection of sludge, pasteurization of foods, and sterilization of surgical supplies, pharmaceutical and packaging containers can all be achieved by the destruction or inhibition of microorganisms by electron treatment. Electrons have the advantage of preserving the nutrient value inherent in food and waste because electron treatment does not cause significant heating of the processed material. Disinfected sludge can be used for its nutrient value as fertilizer for soil and ocean enrichment. Animal feed can be disinfected so that harmful microorganisms are not passed on in the food chain, while maintaining the nutrient value of the feed.

Polymer and elastomer crosslinking by electron beams results in products which are more resistant to heat, stress and environmental decay. In the case of polyolefin film and tubing, electron beam treatment also induces an elastic memory, allowing uses such as shrink-packaging material and heat-shrinkable electrical insulation.

Curing of coatings and adhesives on wood, metals and polymers with electron beam processing eliminates the need for chemical catalysts or solvents and eliminates the pollution and occupational-safety problems associated with corrosive or toxic agents. In addition, the use of heat in conventional curing ovens has become cost-prohibitive and is an uneconomic utilization of a declining resource. Electron treatment is an energy-efficient alternative. Electron beam technology, throughout the scope of industrial applications, offers significant benefits on the basis of speed, convenience, energy economy and the fine control of the process or product.

The potential of electron beam processing can literally make the world food supply feed more people, turn waste into a life-cycle resource, eliminate sources of environmental pollution and save energy in getting consumer goods to the marketplace. In Table 28.1, the best of the main industrial applications of electron beam processing are summarized.

Table 28.1. Industrial applications of electron beam processing

Industries	Processes	Products
Chemical Petrochemical	Crosslinking Depolymerization Grafting Polymerization	Polyethylene Polypropylene Copolymers Lubricants Alcohol
Coatings Adhesives	Curing Grafting Polymerization	Adhesive tapes Coated paper products Veneered panels Thermal barriers Wood/plastic composites
Electrical	Crosslinking Heat-shrink memory Semiconductor modification	Building, instrument and telephone wires Power cables, insulation tapes Shielded cable splices Zener diodes, ICs, SCRs, IGBTs
Health Pharmaceutical	Sterilization Polymer modification	Medical disposables Powders and ointments Ethical drugs Membranes
Plastics Polymers	Crosslinking Foaming Heat-shrink memory	Food shrink-wrap Gymnastic mats, toys Plastic tubing and pipes Molded packaging forms Flexible packaging laminates
Pollution control	Disinfection Precipitation Monomer entrapment DeSOx/DeNOx	Agricultural fertilizers from sewage sludge Safe stack gas emissions Safe sludge disposal Ocean-life nutrients from sludge OSHA and EPA compliances Worker safety
Pulp Textiles	Depolymerization Grafting Curing	Rayon, permanent-press textiles Soil release textiles Flocked and printed fabrics
Rubber	Vulcanization Green strength Graded cure	Tire components Battery separators Roofing membranes

28.4 Process

a. *Features.* An electron beam processing system should offer in-line production capacities that meet the requirements of modern industrial practice. The electron beams are directed at the product and can be spread uniformly over the product area, with minimum energy waste.
b. *Parameters.* Four major factors require great consideration: dose, penetration, efficiency and production capacity.

28.4.1 Dose

The average dose is the total amount of energy absorbed by a material divided by its mass. The applications of electron beam processing are numerous, and the selection of a proper dose level is important for each. For instance, the treatment of potatoes to prevent sprouting may need only 0.001 of the dose needed for the improvement of the temperature resistance of polyethylene. The dose required for a given process, then, is a major determining factor in establishing processing costs and in selecting equipment power (Fig. 28.1). The unit of dose is the gray, defined as an energy absorption of 1 joule per kilogram of material. Absorbed dose can be transposed into more common industrial terms associated with heat and electrical energy.

28.4.2 Penetration

The penetration is a function of the thickness and density of the product and the energy of the electron beam. The thickness of material that can be penetrated by a high-energy beam is directly proportional to the energy of the beam and inversely proportional to the density of the material being treated. Thus, for a given electron energy, the penetration may be expressed in terms of the weight of material treated per unit area. For this reason, electron beam penetration is commonly expressed in g/cm^2. The electron beam energies of particular interest for processing applications range from 300 kV to 10 MV. A 1 MV electron beam has a maximum penetration of about 5 mm in water. Figure 28.2 shows the relative range of the electron beam as a function of voltage and its relative dose as a function of depth. The curves in Fig. 28.2 demonstrate two characteristics of electron beams. First, at the surface, the dose is about 60% of the maximum or greater, it builds up to a maximum within the thickness of the material and then it declines. Second, the depth at which the ionization does not fall below 60% of the maximum is between 1/2 and 3/4 of the total range. This is often referred to as the "optimum thickness" for electron beam penetration. At this optimum thickness, the best balance is obtained between minimizing overdoses and maximizing the beam's penetration capability.

If a minimum dose must be delivered to all parts of the product, the optimum thickness – where the dose does not fall below 60% of the maximum –

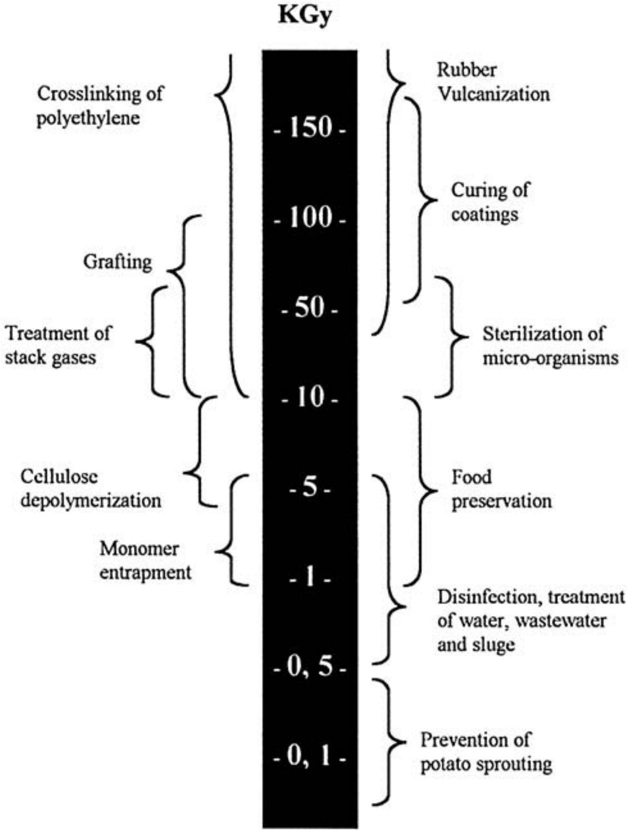

Fig. 28.1. Dose ranges for various applications

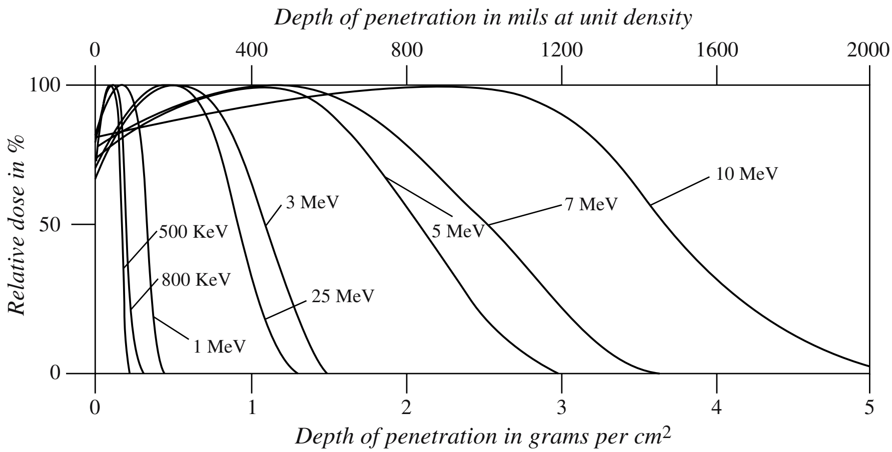

Fig. 28.2. Ranges of electrons for different energies

can be increased by about 2.4 times when electron beam processing is done from both sides of the product – a technique called double-sided treatment. In the case of a solid material, the product can be turned over after exposure on one side and passed through the beam a second time. With liquid or powder products, which could not be "turned over" without internal mixing, simultaneous cross-firing with two electron beams is required. In either case, the effective penetration is more than doubled because the doses obtained from the opposed beams are additive, as shown in the penetration curves for double-sided treatment (Fig. 28.3).

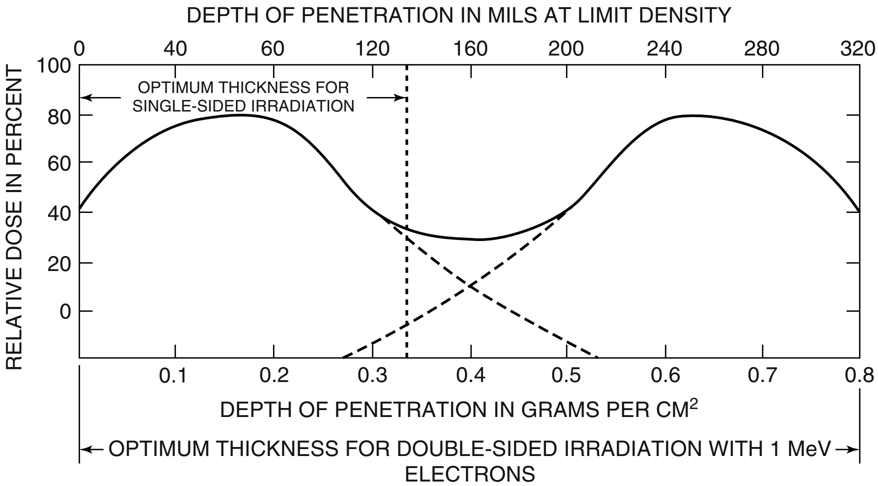

Fig. 28.3. Penetration curves for double sided treatment

28.4.3 Process Efficiency – Production Capacity

The size and shape of the product and the presentation technique influence the efficiency with which the electron beam can be used. For maximum efficiency and minimum cost in an electron beam process, it is necessary that as much of the electron beam power be absorbed in the product and the dose level in all parts of the product be as uniform as possible, with little overdosage or wasted energy.

For maximum efficiency, two factors are of importance:

- first, the uniform distribution of the beam over the product
- second, the absorption of the beam through the product thickness.

There is a dose variation with depth inherent in the process that should be taken in account, and estimated. Thus an estimate of the production capacity for a given situation can be obtained through the formulation

$$\text{Capacity(kg/h)} = 3600 \frac{\text{Power(kW)}}{\text{Dose(kGy)}} \frac{\text{Absorption efficiency in \%}}{100}$$

and similarly when the product is a film.

28.5 Technology

The main parts of an electron beam processing system includes firstly the accelerator, and secondly the scanner and a system adapted to handle the products to be irradiated. On the accelerator side, there exist several ways to obtain the high voltage. For the beam, the electron gun and the accelerator tube are similar to those in a research accelerator. The electron gun is usually a tungsten filament adapted in to a cathode. The optics for the electron beam are similar to ion optics. The delivered beam could be from some 10 µA up to 100 mA or more. Its size, ranging from some mm to tens of mm, does not normally need any adjustment for focusing. In most applications, the electron beam is swept in a scanner chamber in two directions at frequencies of the order of 200 and 1000 Hz, over a thin titanium window of 25 to 50 µm thickness.

The electrons passing through the scanner window then hit the products, which are conveyed at a certain speed under the scanner. Multiple types of conveyors have been adapted to different products, such as cables, film, heat-shrinkable materials and tubing. Depending on the required dose, their speed is automatically linked to the electron beam through a computer. Among the multiple applications, there are some voltages more specifically suitable for each product, as shown in Table 28.2, with a range up to 5 MV.

28.6 Different Types of Electron Accelerators

As mentioned above, the accelerators used differ mainly in the type of their power supply.

28.6.1 Electrostatic Accelerators

In many laboratories, electron beam irradiation projects have started with the use of an electrostatic accelerator. Owing to the voltage easily obtained from this type of accelerator, several of these are still in use. The limited beam current depends on the belt, which allows a beam of up to 1 mA for production in industry, usually at 3 or 4 MeV, and currently beams of 250 µA obtained with smaller 2.5 MV machines are mainly used for producing X-rays on a tungsten target. The X-ray application is broadly utilized for flow detection in welding and radiographic inspection of various products, and even for containers in airports and harbors (Fig. 28.4).

Table 28.2. Usable energy ranges for electron beam applications (MeV)

	0.1–0.3	0.3–0.8	0.8–3	3–5
Wire and cable				
Insulated wire	*	*	*	
Multiconductor cable			*	*
Plastic products				
Food wrapping	*	*		
Electrical tubing		*	*	
Shrinkable tapes	*	*	*	
Molded encapsulation			*	*
Irrigation tubing		*	*	
Plastic foam		*	*	
Molded gaskets			*	
Hot-water pipes			*	*
Solvent-free coatings				
Metal finishing	*			
Wood finishing	*			
Textile finishing	*	*		
Printable surfaces	*			
Magnetic tapes	*	*		
Adhesive tapes	*			
Perselective films	*	*		
Metallized films	*	*		
Rubber products				
Automobile tires		*	*	*
Roofing sheet		*	*	
Elastic bands		*	*	
Conveyor belts			*	*
Industrial hose			*	*
Profile gaskets		*	*	
Rubberized fabrics	*	*		
Weatherstripping			*	*
Latex products	*	*		
Bulk chemicals				
Polyethylene crosslinking		*	*	*
Polypropylene scission			*	*
Teflon degradation			*	*
Rayon pulp aging		*	*	*
Cellulose hydrolysis			*	*
Butyl rubber degradation			*	*
Crude-oil cracking			*	*
High-purity polymers			*	*
Reinforced plastics		*	*	*
Impregnated wood			*	*

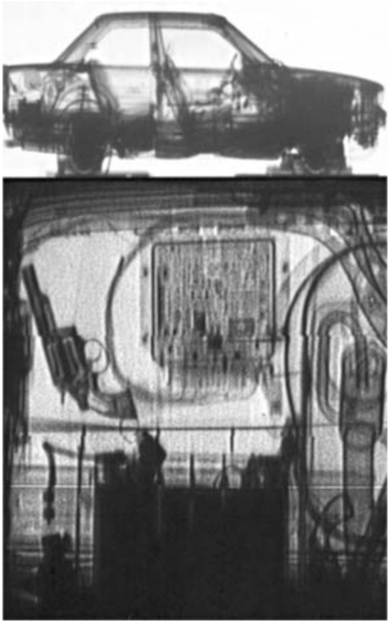

Fig. 28.4. Radiography inspection

28.6.2 Cascade Accelerators

Cascade accelerators of various types (asymmetric (Cockcroft–Walton), symmetric, parallel (Dynamitron), and isolation core transformers (ICTs)) are commonly used for irradiation. These devices are described in Box 3. For the ICT (see Fig. 28.5), the most used version has a three-phase transformer, which operates at 50 or 60 Hz directly from the mains power. The standard power for such a device is between 50 and 200 kW but in principle there is no limitation on power. The high voltage can reach 5 MV with an efficiency of around 85%.

28.6.3 Accelerator Technology

All types of accelerator tubes for electrons are in principle similar and not fundamentally too different from the technology of positive-accelerator tubes. They are constructed from ring insulators placed between highly polished metal electrodes. A uniform voltage gradient along the tube is achieved by column resistors that connect to each of the tube electrodes. The electron beam is focused and accelerated within the evacuated tube, reaching an energy corresponding to the output voltage of the power supply. Usually there is no need for special focusing.

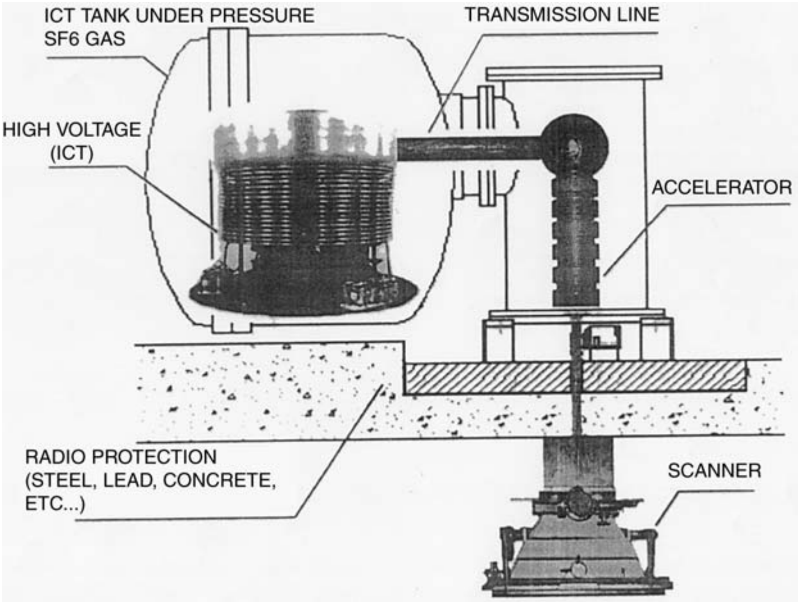

Fig. 28.5. ICT for industrial applications

28.6.4 Arrangement

Various arrangements are used for the complete electron beam system. Usually the accelerator tube and power supply are either together in the same tank under SF_6 pressure, with the tube coaxial with the generator, or separated in different tanks and connected through a transmission line. In one specific arrangement, one or two accelerator tubes and the corresponding scanners are connected to one power supply (Fig. 28.6). For voltages up to 900 kV, one power supply can be connected to one, two or three accelerators through special DC HV cables, to allow more flexibility in the process.

28.6.5 Scanner

After emerging from the accelerator tube, the electron beam enters a stainless steel scanner, where it is subject to an oscillating magnetic field, which causes the beam to be rapidly scanned through a certain angle. This angle can normally be varied up to $\pm 30°$. The scan width is automatically held constant. The scanned beam passes through a thin titanium window and bombards the material being processed. Low pressure is maintained in the accelerator tube and scanner by suitable pumping with ion pumps or turbomolecular pumps.

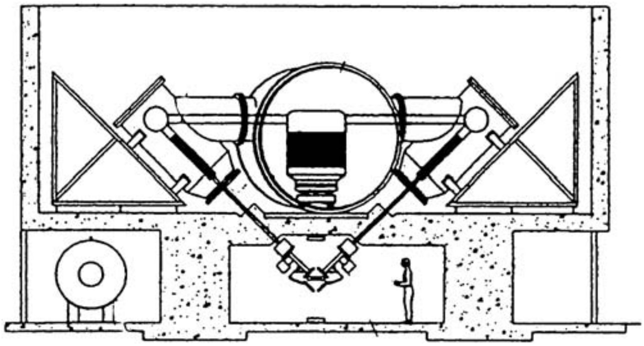

Fig. 28.6. Two scanners on one ICT power supply

28.6.6 The System Under the Beam – Conveyors

Crosslinking of polymers is one of the main applications of electron beams. Various materials such as cables, tubing, films and also heat-shrinkable materials are processed by various techniques and more or less specialized conveyors, as seen in Fig. 28.7.

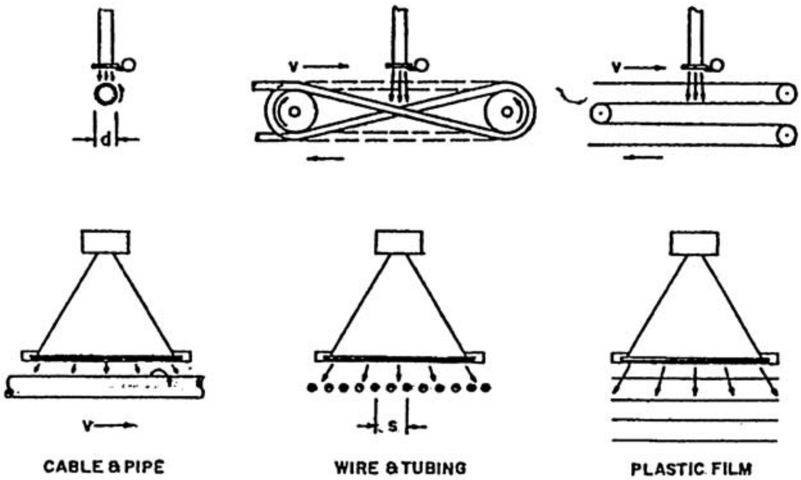

Fig. 28.7. Electron beam processing techniques

An important future application is emerging in the control of environmental pollution by treatment of liquid effluents, waste streams and stack gas, where numerous toxic substances can be removed in an economic process. Many stations are already processing effluents on an experimental basis. In contrast, some flue-gas-cleaning plants using an electron beam process are already operating on an industrial basis in Russia, Japan and China (Fig. 28.8).

Fig. 28.8. A flue-gas-cleaning plant in Chengdu, China (Courtesy of IAEA, publication TECDOC-1386)

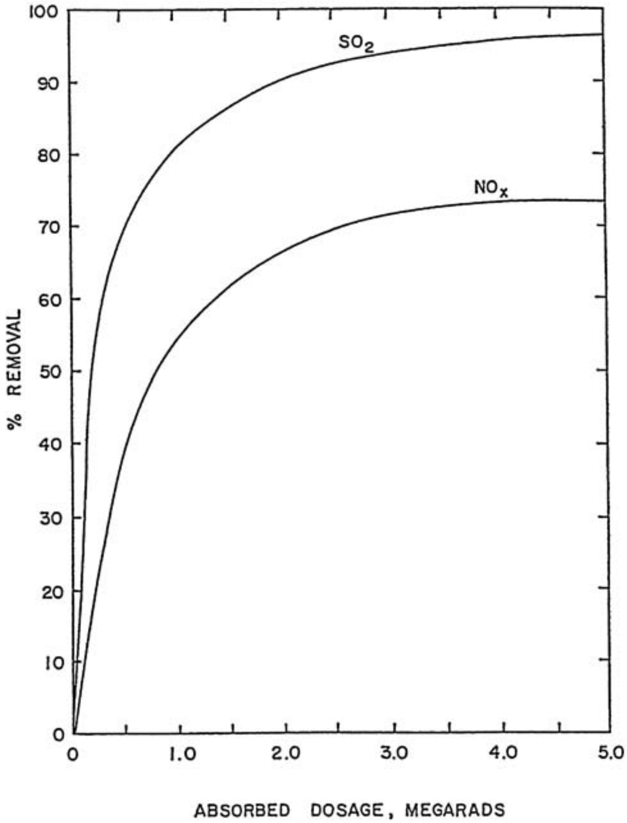

Fig. 28.9. Removal of SO_2 and NO_x as a function of irradiation dose

For example, in China, where coal is the main contributor to thermal power plants, and millions of tons of SO_2 are emitted yearly, a dedicated effort is being made in order to remove simultaneously, by electron beam processes, SO_2 and NO_x, which are the origin of acid rain. The removal of SO_2 and NO_x reaches close to 90 and 65%, respectively, as seen in Fig. 28.9.

It should also be mentioned that in a few cases, sterilization of medical products and food is being performed with an electron beam from electrostatic accelerators.