

ELECTRON BEAM IRRADIATION APPLICATIONS

Sunil Sabharwal[#]

Radioisotope Products and radiation Technology Section
International Atomic Energy Agency
Vienna, Austria

Abstract

The irradiation of materials with electron beams or X rays is used extensively to enhance or modify their physical, chemical or biological properties. These electron beam “irradiators” cover a very wide range of accelerators technology, beam current and energies to produce a wide variety of products, mostly with polymers. They also are used for curing ink, coatings, and adhesives as well as for the sterilization of medical products, disinfection and preservation of food. The emerging applications include treatment of waste waters and flue gases, and degradation of plastics for use in coatings and inks. The status of applications and the role of IAEA in enhancing these will be presented.

INTRODUCTION

High energy ionizing radiation has the unique ability to produce reactive species like free radicals in a variety of materials that can be used to modify physico-chemical properties of materials for a variety of industrial applications. Over the last 50 years, the subject of radiation chemistry and accelerator physics have developed simultaneously and from industrial applications point of view, the progress in one area has generally led to the advancement in the other area. While the basic radiation chemistry studies using the pulse radiolysis studies using nano-scale pulse electron beam accelerators led to understanding the basic fundamental aspects of radiation chemistry, the commercial applications based on radiation crosslinking of polymers or inactivation of pathogenic bacteria emerged as the driving force for developing high energy high current accelerators to ensure that the fruits of radiation chemical research are utilized for industrial applications. Radiation technologies based on electron beam accelerators today are used for applications such as crosslinking of wire & cables, producing heat-shrink materials, surface curing of materials, sterilization of medical products and for food irradiation [1]. Currently, world-wide, there are over 1400 industrial electron accelerators in operation that are being widely used for applications such as polymer processing, surface curing, sterilization of medical products and food irradiation [2]. A conservative market survey indicates that these high current EB units are providing an estimated over US \$85 billion value added unique high-value products for mankind in an environmentally friendly manner [3]. Pollution of air, water and land resources due to industrial and human activities constitutes a major threat to sustainable development.

[#]S.Sabharwal@iaea.org

While burning of fossil fuels lead to formation of sulphur oxides (SO₂ and SO₃), nitrogen oxides (NO_x), water resources are being polluted with industrial and human waste. The industrial effluents carry chemical contaminations like heavy metals, organic pollutants, petro-chemicals, pesticides and dyes while discharge of sewage and sludge giving rise to microbiological and chemical contamination of the water bodies. In the last few years, extensive work has been carried out for utilizing radiation technology for environmental remediation. Pilot or plant scale electron beam facilities have been set up to demonstrate the application of this technology for treatment of such pollutants in an effective and efficient manner [4,5]. This paper presents the present status of the established as well as emerging applications and the challenges that the accelerator technologists need to address for further implementation of this technology in these emerging areas.

TYPICAL CHARACTERISTICS OF ELECTRON ACCELERATORS FOR INDUSTRIAL APPLICATIONS

For industrial radiation processing, the two main characteristics of an electron beam accelerator are energy and current. While energy of the accelerator determines the thickness of the product that can be uniformly processed, the current determines the productivity or the throughput of the process that can be achieved. A wide range of electron beams with energies varying from 0.15 to 10 MeV are used in radiation processing for varying applications (Table 1). The electron beam accelerators used in the industry typically have beam power (the product of electron energy and current) ranging from 5 to about 100 kW, although more powerful accelerators (400 kW and higher) have also been set up in recent years to demonstrate certain applications or for commercial irradiation. Low-energy accelerators having energies from 0.15 to 0.5 MeV, are generally constructed as self-shielded systems in the production. They are used mainly for the treatment of surfaces and the irradiation of coatings and thin materials, such as polymeric films. Medium-energy accelerators produce electrons with energies of 0.5 – 5 MeV at powers of up to 300 – 350 kW. High-energy accelerators, which for processing purposes generate electron beams with energies of 5 – 10 MeV, are linear accelerators giving pulsed beams of up to 50 kW. Such accelerators are used for radiation sterilization of medical products and, to a lesser extent, for the radiation treatment of foodstuffs. The applications of electron accelerators are summarized in Table 1.

Table 1: EB Penetration for End Application

Application	Electron Energy	Typical Penetration (mm) for unit density product
Surface Curing	80–300 keV	0.4
Shrink Film	300–800 keV	2
Wire & Cable	0.4–3 MeV	5
Sterilization	3–10 MeV	38

FUNDAMENTAL PRINCIPLES FOR DEVELOPING ELECTRON BEAM TECHNOLOGY APPLICATIONS

Generation of radiation energy through electron beams is an expensive form of energy. It can therefore find applications under following conditions:

- (i) Substantial benefits or change occur with a small input of energy. Polymerization reactions which are generally chain-reactions constitute one such class of reaction where radiation technologies can be used to initiate the chain reaction for a variety of industrial applications.
- (ii) The small change produced results in a large change in the properties of the substrate. For example: in case of polymeric materials, the free radicals produced on polymer backbones can result in either joining of polymeric chains (crosslinking) or chain breakage (scission) resulting in dramatic change in the properties of the polymeric material. Similarly, the small change induced in the DNA structure may stop the reproduction of the microbial cell.
- (iii) Situations where the value addition to the product is so high that cost of irradiation is not relevant
- (iv) Where radiation is the only method of choice for the treatment process.

Based on these considerations, polymerization (surface curing), polymer modification, sterilization of medical products and food irradiation are the major established applications of electron beam technology.

ESTABLISHED APPLICATIONS OF ELECTRON ACCELERATORS

Polymer Modification

These applications are based on the ability of some polymeric materials, such as polyethylene to undergo crosslinking reaction between adjacent polymer chains, resembling vulcanization, resulting in improved thermal and mechanical properties as well as introduction of “memory effect” in polymeric materials after controlled irradiation. The electron beam crosslinking of the insulation jacketing on wire and cable is one of the most well established industrial uses of EB processing. Crosslink formation results in a three dimensional network structure in the polymeric material that prevents

insulation from dripping off an overheated wire in case of a short circuit, or when exposed to elevated temperatures as in the case of an automotive engine or in case of a fire accident. The polymers that are typically used for such applications include polymers that cross-link on irradiation such as polyethylene, EVA or EPDM depending upon the end use application. Absorbed doses of the order of 100-150 kGy or higher are required to cross-link polyethylene wire and cable insulation. Crosslinking imparts two main properties to wire jacketing. If the wire become heated due to an electrical short circuit, the crosslinked jacketing will not melt off of the wire and thus will maintain its insulation. This is very important for under-the-hood wires used in automobiles. Second, when exposed to flames, the jacketing will not burn away nor drip and prevent or delay propagation of a fire.

Polymer cross-linking also forms the basis of radiation processing in the manufacture of heat-shrinkable plastic films and tubes. This application is based on the principle of “memory effect” in the crosslinked polymeric material. The crosslinked polymer deformed under stress at elevated temperatures, when reheated above its melting temperature remembers the shape before deformation and regains the shape before deformation. In a typical application, such materials are used to produce connectors for joining the wires or tubing. The crosslinked plastic behaves as a weak rubber that can be stretched or expanded by controlled mechanical or pneumatic differentials inside and outside the tubing. The stretched tubing is then quickly cooled to temperature below its melt transition temperature to allow the crystalline domains in the polymer to form again and hold the plastic in the stretched or expanded state. This tubing is then used to cover wire connections to be joined. When the tubing is heated during application, it contracts and conforms to the connector or object inside it. This simple application has resulted in forming a variety of high technology products such as heat recoverable closures for telecommunication splices, wraps for welded pipe joints and heat shrinkable food packaging film.

Radiation curing for printing inks especially with wide web presses for high volume production and for printed items requiring high quality graphics and colour highlights constitutes one of the most important applications of low energy electron beam accelerators and over 500 accelerators are used in the industry. Electrons from the accelerator generate free radicals in polymerisable monomers leading to simultaneous polymerization and crosslinking of the monomer onto the substrate. Since electron beam processing takes place at near ambient temperatures, drying of inks can be implemented even on heat sensitive plastic substrates. Absence of extractable initiators in EB curable inks and over print system allow development of over-print materials that are compliant with US Food & Drug Administration regulations for direct food contact and could replace film laminates used atop printed materials

to prevent leaching of extractable for compliance with direct food contact regulations [6].

Sterilization of Medical Products and Food Irradiation

The use of electron beams for sterilization of medical products constituted one of the first commercial applications of radiation technology in 1950s. Since then, high energy 10 MeV accelerators have been used for many decades for sterilizing packaged medical devices. Mid energy accelerators at 3.0–5.0 MeV have also been used for medical device sterilization especially for products having a low bulk density so that the penetration of electrons is sufficient. The packages can be also be irradiated from two sides, thereby increasing the beam penetration to 2.4 times.. In recent years, X radiation produced from high energy high power electron beam accelerators (7 MeV, 700 kW). Even with a low conversion efficiency (typically 10%) for conversion to X rays, the facility allows production of 70 kW of X ray power that allows economic benefits for treatment of medical products by gamma radiation.

Food irradiation was one of the very first proposed uses of Roentgen's discovery of X rays and the subject has been investigated in details world over. The efficacy, minimal effect on nutritive value and general safety of irradiating food has been demonstrated over and over again. The World Health Organization (WHO) has long been on record as supportive of this method for processing food [7,8]. The industrial high energy electron beams (10 MeV) have been successfully used in irradiating food and foodstuffs to eliminate pathogens [9]. With increasing acceptance of food irradiation in many parts of the world, it is apparent that the use of electron beam accelerators for treatment of food is expected to increase in coming years.

EMERGING APPLICATIONS OF ELECTRON BEAM ACCELERATORS

The realization that the environmental problems associated with the development of human activities do not remain confined to local region, but also may affect people living far from contaminated sites has resulted in developing economically and technically feasible technologies for controlling solids, gaseous and liquid effluent streams. Radiation technology with electron beam accelerators with its unique ability to produce highly reactive species in an efficient manner has the capability to alleviate some of these problems and may play an important part in offering sustainable solutions. The unique features of this technology, being a room temperature and additive free process, makes radiation technology an environment-friendly process as compared to conventional thermo-chemical processes. Considerable efforts have been made in demonstrating use of radiation technology for environmental remediation. This includes application of radiation technology for simultaneous removal of sulphur oxides (SO_x) and oxides of nitrogen

(NO_x) from flue gases. The electron beam technology for flue gas treatment has demonstrated very good removal efficiencies for the pollutants SO_x and NO_x . The by-product yield is of good quality with less moisture and is good for commercial fertilizer [4, 10].

Radiation processing of wastewater is non-chemical and uses short-lived reactive particles that can interact with a wide range of pollutants. Such reactive radicals are strong agents, oxidizing or reducing, that can transform the pollutants into liquid wastes. A pilot plant with an electron accelerator for treating textile dyeing wastewater was constructed in the Daegu Dyeing Complex (DYETEC) [11], and later an industrial plant for treatment of 10,000 m³/day has been constructed and in successful operation [12]. A study on sludge hygienization using radiation is ongoing, and the experience of the research has shown that the process is simple, effective and easy to integrate with an existing sewage treatment plant, and that the radiation-hygenized sludge can be utilized as a fertilizer in agriculture [13].

CONCLUSION

The use of ionizing radiation has led to development of advanced polymeric materials for a wide range of applications in various industries. These include industries such as insulated wire and cable production, heat-shrink materials, surface curing, sterilization of medical products and food preservation. The commercial success of the technology is evident from the number of such machines operating and value added products that have emerged using this technology. The demonstration of electron beam based processes for treatment of flue gases and treatment of waste waters on an industrial scale is expected to offer unique solutions for environmental remediation in coming years. The development of reliable very high power electron beam machines will be crucial to extend the use of electron accelerators in these emerging applications.

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