INDUSTRIAL APPLICATIONS OF LOW-ENERGY LINACS

J. Ungrin
AECL Research, Chalk River Laboratories
Chalk River, Ontario, Canada K0J 1J0

Abstract

Low-energy linacs are now used routinely in a large number of non-research applications. It is estimated that, in addition to the more than 3500 linacs used in well-known medical treatments, an additional 600-800 accelerators, with an integrated beam power of 30 MW, are used worldwide in industry. Low-energy (<50 MeV) ion beams penetrate only short distances into most industrial materials and consequently ion linacs are used directly mainly in processes that improve the surface properties of materials. They are also used indirectly in industry to induce nuclear reactions, which produce penetrating by-products (neutrons and gamma-rays) or radioisotopes. Electron linacs find practical applications either in the electron or bremsstrahlung mode. The beams can penetrate significant distances in materials in either mode and can be used to deliver energy or induce chemical reactions throughout the volume of products. For some applications electron linacs are in competition with radioisotopes. At the electron beam energies typically used in industrial processes (<15 MeV), very few nuclear reactions occur in most materials. The absence of any significant inventory of radioactive material in an industrial facility after completion of the process has been an important factor in the rapid acceptance and growth of the use of electron beams.

Introduction

Accelerators have become relatively common "tools" in a diverse array of industrial processes. Their use in industry has been extensively discussed previously, both at this series of conferences [1,2] and at the "Denton" and ECCART conferences, which are devoted largely to applications of accelerator technology [3,4]. Also, some excellent books and articles have been published on the subject over the past decade [5-8]. This paper focuses on the applications of accelerators that occur in the production of "consumer products", but which are not common knowledge. The technology discussed is restricted to linear accelerators (both dc and rf-driven) with energies below 20 MeV for electrons and 50 MeV for ions. Induction linacs, which have shown promise for the past decade, but which have not yet had industrial application, are not covered in this survey.

Because electron accelerators predominate in industry, both in number and in the total installed power, a larger portion of the discussion treats electron beam (EB) applications. Recent applications of both electron and ion accelerators that show a high probability of growth are discussed.

Medical Applications

The largest non-research application of low-energy accelerators has been in cancer therapy. The high beam quality and small physical size that are characteristic of the beams from high-frequency rf electron linacs make them ideal for medical installations. The availability of both electron and photon modes of operation, as well as a range of energy from the same apparatus, have led to linacs displacing ^{60}Co as the preferred treatment machine, and they now dominate the medical therapy market. Latest estimates indicate that between 3500 and 4000 electron linacs are used in medical clinics worldwide. The design and control of medical therapy linacs have improved significantly since they were first introduced in medical treatment in 1953 [9]. Recent improvements have incorporated the careful design of beam delivery systems that allow intraoperative radiotherapy, whereby internal organs containing tumours are exposed in an operating theatre and irradiated directly with electrons at energies of 6-20 MeV [10]. Also, fast, laser-guided, computer-based control systems can ensure tumour targeting accuracy of 0.3-0.4 mm on a patient, thereby avoiding the trauma associated with rigid immobilization systems; the small size and mass of X-band linacs allow them to be mounted on highly-responsive robotic arms [11]. Because of the low penetration of ions into human tissue, most medical applications of low-energy ion linacs have been restricted to the production of secondary products, specifically radioisotopes and neutrons. Although several ion linacs have been designed and built for isotope production [12], the preferred accelerator has been the cyclotron, and numerous compact versions have been developed specifically to meet the needs of the radioisotope market. The recent revival of interest in Boron Capture Neutron Therapy (BCNT) has led to a flurry of proposals for low-energy linac-based systems, but it is not expected that this application will have a significant impact on the accelerator market for several years.

Another growing area for linacs is cancer therapy with higher-energy proton and heavy-ion beams. Several dedicated facilities are under construction/commissioning, and it is expected that this application of linac technology will gain wide acceptance in the next decade.

Sterilization

The sterilization of materials with electron accelerators is closely linked, but not restricted, to medical applications. The largest application is the treatment of prepackaged, disposable medical supplies, such as hypodermic syringes, needles, catheters, surgical gloves and sterile dressings. The penetrating power of higher-energy beams is normally needed and a number of 5-10 MeV linacs, working either in the electron or photon mode, have been installed. Typically, the composite specific density of packaged and boxed medical products is in the 0.15-0.2 range. Using 10 MeV beams and double-sided irradiations, sealed cartons up to 40 cm in thickness can be quickly sterilized in the electron mode. The accelerators used are often in competition with ^{60}Co radiation sources, but for some products, particularly those based on polypropylene, the longer irradiation times required with the lower dose-rate radioisotope sources result in unacceptable chemical degradation of the product.

Electron accelerators are also being used increasingly in the sterilization of diverse items, such as antibiotics and other pharmaceuticals, bone marrow or human organs for immediate transplanting or long-term storage, and materials to be used by hospitalized persons whose immunity to infection has been reduced during chemotherapy.

Accelerator-generated radiation is also being used to sterilize packaging materials, such as fruit-juice containers and coffee creamers, and for an increasing line of cosmetic and personal hygiene products.

A rough estimate of the installed capacity of electron accelerators for the sterilization market is about 1000 kW.

Production and Treatment of Polymeric Materials

The most widely used, non-medical application of electron accelerators is the production and modification of man-made materials. Because the detailed processes are often highly guarded industrial secrets, it is difficult to assess the number of accelerators and the total beam power involved in the diverse applications. But, based on data from 1988 and 1994 [13,14], it is estimated that more than 500 accelerators and more than 35 MW of beam power are now installed worldwide for these applications. Most of these accelerators are in the 0.1 to 1.5 MeV range; less than 25, with a total installed beam power of less than 500 kW, are rf linacs of the type familiar to this conference.

Table 1 lists some of the important, well-established industrial applications. It has been estimated that the value added by radiation processing to the annual sales of these products is 2.5 to 3.0 billion $ (U.S.) [15].

The largest application is the cross-linking of insulation for the wire and cable industry, and for the production of heat-shrink film and tubing. Radiation cross-linked polyvinyl chloride, which has good electrical properties, and good heat and chemical resistance, can be made thinner than other insulating materials for the same voltage hold-off, and it has gained widespread use in the wire and cable industry. Cross-linked polyethylene is the most widely used consumer product that has an elastic memory; the irradiated material, which is stretched during manufacture, shrinks to its normal size after heating. It is widely used to produce heat-shrink tubing in diameters of from several mm to more than 1 m and, in the form of film, for applications ranging from food packaging to heat-shrinkable, water-tight covers for off-season storage of recreational vehicles. EB processing is also used to cross-link a variety of feed materials for the plastics-manufacturing industry, to improve strength and tailor the properties for improved extrusions.

TABLE 1
Established Applications of EB Processing

Cross-linking	- wire and cable industry - heat-shrink film and tube - manufacture of rigid foams - natural and synthetic rubber
Curing/Polymerization	- surface coatings - adhesive tapes - printing - fibre/resin composites
Grafting	- film layers - textiles - water absorbents
Degradation	- Teflon waste - butyl rubber - cellulose

Another well-established application is the polymerization or radiation curing of a wide array of specially formulated, solvent-free liquid media. The high penetration of energetic electrons allows uniform curing throughout the thickness of a product without the release of volatiles to the environment. Table 2 lists some curing and drying applications used in industry. The largest are the curing/drying of thin coatings and the partial vulcanization of the various polymer layers used in the manufacture of automobile tires. For the latter, the treatment permits a more balanced distribution of the layers and at the same time improves the cohesion strength.

Although most of the more than 130 accelerators used in the curing industry [16] are in the several hundred keV energy range, a number of 10 MeV rf linacs have recently been put into service to treat thick materials, particularly those involving carbon-fibre-based composites. The high-power industrial versions of rf linacs that have recently been developed [17] permit the treatment of large assemblies of these materials in both the electron (thickness less than 5 g.cm^{-2}) and bremsstrahlung modes.

TABLE 2
EB Curing Applications

Composites	- wood/organic impregnates - carbon-fibre/organic impregnates - wood/cement panels - polymer layers in automobile tires
Surface coatings	- paints/inks/varnishes - metallic coatings on tiles - anti-static film - silicone release coatings - metallized film, labels - security printing of stamps/currency
Magnetic recording media	- floppy discs - compact discs - aligned magnetic media
Flocked products	- automobile components - shoes
Adhesives	- pressure-sensitive coatings - laminating films - peelable labels

EB-initiated grafting of polymers is also well established in industry. The process, applied mostly to thin films of organic materials, facilitates the graft of one molecular group unto another, producing a new, higher-quality product. The process is used in the paper industry to produce materials with specialized surface properties, and in the textile industry to produce textiles that are flame-retardant, water-resistant, more easily dyed and have a greater resistance to shrinking or creasing. The process has also recently been applied in the disposable diaper market, where biodegradable materials with high water-absorption properties are manufactured by EB grafting suitable polymer additives to natural materials, such as starches.

Although the main application of EB processing has been to upgrade materials properties, several industrially relevant, materials-degrading applications have been developed as well. The degradation of waste Teflon to a powder form that is used as an additive to lubricants, and the desaturation of butyl rubber from discarded tires and inner tubes for recycling, are well-established industrial processes. Another application with even wider potential application is the EB degradation of cellulose. This degradation leads to a significant reduction in the energy required to produce pulp, the raw product for the huge paper and viscose industries.

Radiography/Inspection

The industrial use of rf linacs as "super X-ray" devices has been well established and it is estimated that more than 400 accelerators with energies in the 2-20 MeV range are in service [5]. The modest beam power required for these accelerators is similar to that required for cancer therapy machines, and it is therefore not surprising to find that the favoured accelerators for this application are rf linacs with operating characteristics not unlike those of the radiotherapy linacs. Because of the extreme size of some of the industrial components, high-frequency, gantry-mounted linacs are used for many of the radiographic inspections. Steel up to 600 mm thick is inspected using this technique, as are 2 m diameter, assembled rocket motors up to 8 m in length. A facility was assembled to detect defects as small as an 0.08 mm crack in rockets of this size [18]. The compact size of accelerator-based, high-energy photon sources has led to numerous proposals for mobile systems that can be used in the field for various applications. A number of units have been built to examine concrete bridges, assay waste (including radioactive waste) and examine military components.

The use of both photon and neutron radiography to detect contraband and explosives has received a very high profile over the past decade [19]. The requirements of the application in terms of cost, throughput speed and accuracy are very demanding, and accelerator-based systems have had stiff competition from chemical-based and high-resolution, conventional X-ray systems. The advantages of the accelerator-based systems are in the selective detection of low-density, hydrogen, nitrogen, oxygen and carbon-based compounds, which are the common ingredients of explosives. Compact RFQs have been the leading candidates for the generation of energetic neutrons, which are used for the neutron-scattering techniques, while dc columns are the main contenders for the resonant absorption technique requiring proton energies with high precision (energy of 1.7476 MeV). While the neutron-based techniques have tended to concentrate on smaller items, such as luggage, photon-based systems have been considered for inspecting the contents of larger shipping containers [20]. The international acceptability of this latter application is uncertain, because human stowaways are a common form of contraband transported internationally in ship containers. The potential high-dose irradiation of the stowaways will probably prevent this application from becoming reality.

Environmental Applications

The use of accelerators in environmental applications, which has been proposed and tested in prototype facilities for the last three decades, has recently experienced a resurgence. Although some use has been made of ion beams in the characterization of wastes, most applications have involved electron accelerators as high-power sterilizers that can disinfect waste streams.

The major waste materials that have been targeted for EB treatment are waste water, sewage and the associated dewatered sludge. Successful tests demonstrating the applicability of the technology for sewage were conducted as early as 1976 using a 750 keV, 50 kW accelerator [21]. Several other demonstration units have been put into service since, but the technology has not yet been accepted on a large industrial scale. The main barriers are economics and political will. Despite the growing concerns of global pollution, much of the world continues to accept the less-effective but cheaper treatment by chemical means, or the direct dumping of untreated sewage sludge. The economics of scale that arise with the development of higher-power accelerators [22] and the potential use of the treated sludge for agricultural applications and animal feed could lead to a wider use of this technology over the next decade. A factor hindering the use of the sludge, however, is the illicit disposal in urban sewage of industrial process fluids containing a range of metals. These metals lower the value of the product and generally limit the use of the sewage-based fertilizers to application on recreational land such as parks and golf courses.

Tightened regulations governing the transport and incineration of wastes from medical facilities and international airports have led to the proposed use of EB treatment to sterilize the material at the specific facility. The disinfected wastes can then be safely and cheaply disposed of as standard industrial waste. At present, this application appears to be economically viable only if one irradiator can service a group of large facilities. No accelerator-based sterilizer for this application is known to be in service.

A second important environmental application of EB processing is the decomposition/precipitation of chemical pollutants or hazardous materials from contaminated soil or liquid and gaseous discharge streams. Successful demonstrations involving the removal of up to 99% of the trichloroethylene and benzene from aqueous solutions have been reported [23]. Another application of EB processing that has attracted significant attention over the past two decades is the removal of sulphur and nitrogen-based pollutants from the flue gases emitted by coal- and oil-burning electricity-generation plants. A number of pilot plants have been put into operation to demonstrate the process, some as early as 1972. Because the density of the flue gases is very low, the electron beam energy required is typically 1 MeV or less, and efficient dc accelerators can be used. Although the process appears to have been technically proven at small-scale facilities in Germany, Japan and Poland, and economic assessments indicate that it should be financially viable [24], it has not yet been installed on a full industrial scale. One of the reasons is the technical challenge to produce the enormous EB power that is needed to effectively remove the pollutants. To remove 90% of the nitrogen and sulphur pollutants from the emissions of a large power station burning standard-quality coal, most assessments indicate that the installed EB power must be 3-5% of the electrical output of the station [5,24-26]. For a single, large multi-unit power station that generates 2000 MW of electricity, the installed EB capacity would then be 60-100 MW, which is 2-3 times the total EB power presently installed worldwide for all applications! Meeting these beam power requirements with economic, reliable accelerators is certain to provide a continuing challenge for all accelerator suppliers.

Materials Modification

The use of accelerated particles to modify material properties is well established. Because most of the properties are changed by the rearrangement or addition of atoms, ion accelerators producing beams with energies of 200 keV or less tend to dominate electron linacs in these applications.

Table 3 lists the main applications of both electron and ion beams used industrially at present [27]. The main application is ion implantation, a process for which more than 800 low-energy accelerators are installed in Japan alone [28]. Although the vast majority of these applications use low-energy beams, at least five accelerator suppliers now have higher-energy (0.5-3 MeV) implanters available [14]. Recent designs have been proposed that use variable, high-energy RFQ's [29].

TABLE 3
Materials Modification Applications

Ion implantation	- wear resistance - improved film adhesion - semi-conductor doping - improved semiconductor switching "lifetime-killing"
Thin layer activation	- wear, corrosion-rate monitoring
Gemstone enhancement	- topaz, beryl
Damage simulation	- electron, proton, and neutron-based
Radiation hardening	- identification of sensitive components - simulation of outer-space conditions

While ion-beam applications predominate in Table 3, significant use of electron beams also exists, particularly for gemstone enhancement. Electron beams have been used to convert "colourless" topaz to "blue" topaz for several decades. The quantity of topaz irradiated worldwide in 1987 was estimated to be of the order of 4000 kg (20 million carats), having a retail value of more than 300 million $ (US) [30].

Accelerator-generated beams have been used for some time to investigate radiation-related damaged observed or predicted to occur in fission- or fusion-based power systems. A series of high-intensity neutron generators, such as FMIT, have been proposed and partially built for materials investigation over the past decade. Although proton and electron beams do not exactly duplicate the material changes induced by neutrons, they are beginning to gain increased acceptance, because of the higher flux that can be achieved using focussed beams. A series of experiments at Chalk River have recently shown that 12 MeV electrons can simulate the same changes in reactor-core alloys that are induced by neutrons. The advantage of the electron irradiation is that the treated material is not radioactive, and that the same induced atomic change that takes place over one year in the reactor core (~1 displacement per atom) can be induced in representative samples with a modest power (4 kW) electron beam in 300 hours. Low-energy proton beams have also been used for this application, but their low penetration produces changes only in a thin surface layer.

Conclusion

Accelerators have been used in other diverse applications, such as food and water sterilization, oil and mineral exploration, materials analysis and atomic mass spectroscopy. Although in most cases these applications have been largely R&D or pilot-plant based, all have significant potential for expansion. Growth in these activities and in the areas of application discussed above indicate that a continued rapid increase in the number of industrial linacs, now estimated to be over 5000, is likely to occur.

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