Radiation processing today is being used to sterilize many hospital supplies, such as surgical instruments and catheters, and to help produce rugged wires and cables for telephone lines. (Credit: CEA)

Modern tools of the trade

Increasingly, industrial radiation processes are at work behind-the-scenes

by Vitomir Markovic

Almost popularly unheralded and unnoticed over the past several decades, ionizing radiation has become a valuable tool for efficiency in dozens of industrial and manufacturing processes making products used around the world.

Just during the last 15 years, for example, radiation processing – which refers to the use of gamma rays or high-energy electrons as industrial energy sources – has been growing steadily at about 10-to-15% per year. The main indicator of this growth is the number and total installed power of radiation sources.

Two types of radiation sources are commonly used today: radioactive isotope gamma radiation sources, cobalt-60 and caesium-137; and high-energy electrons produced by electron accelerators in an energy range of up to 10 megavolts. None of these radiations produces radioactivity in the materials processed.

Currently more than 130 industrial gamma irradiators are operating in some 41 countries, based on industry figures, and the total number of electron beam machines now approaches 400 worldwide. In various ways, these tools are being used to help produce products such as automobile tires, computer parts, and telephone cables, plastics and films for packaging, and to disinfect and sterilize disposable medical products for hospital and home health care.

Although the total value of irradiated products is difficult to estimate, the current worth probably is many times larger than the US $1 billion reported in *Business Week* in 1977. Though not spectacular compared to other industrial outputs, the volume indicates that radiation processing has become an established and accepted manufacturing method.

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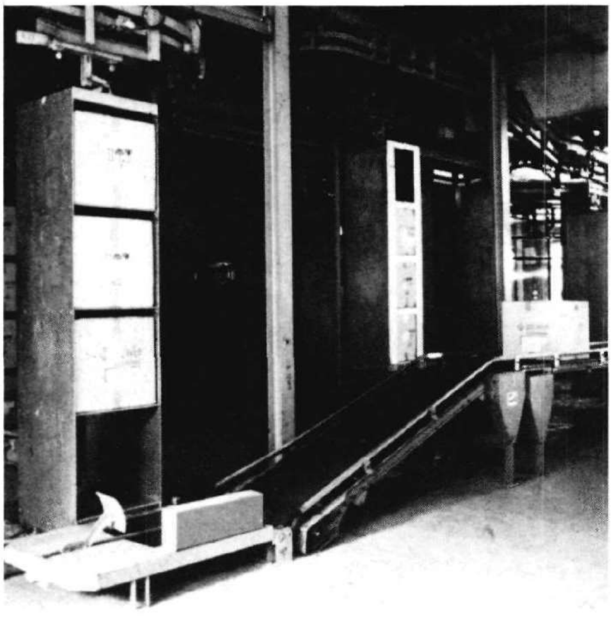
This review largely is based on information provided at the series of international meetings on radiation processing that were held at two-year-intervals from 1976 through 1984 in, respectively, Puerto Rico; Miami; Tokyo; Dubrovnik; and San Diego. These meetings have established themselves as the principal points of exchange for information related to science and technology in this field. The San Diego meeting, for example, was attended by about 470 participants from about 32 countries, and 120 papers were presented in 23 sessions covering all areas of established and developing applications, including aspects of radiation engineering, safety, industrial radiation dosimetry, development of industrial radiation sources, and regulation and legal aspects.



This gamma irradiation facility in Yugoslavia is one of 135 now operating in some 41 countries.

reached the stage of commercialization due to its technical and economic benefits.

Of course, not all applications were equally successful in the past. Success stories on one side are abundantly counteracted by lack of success, disappointments, and outright failures on the other side. Radiation processing for textiles, for example, has been tried, but never matured as hoped. Polymerization induced by radiation also has failed to take root, even though it offers advantages over traditional high-temperature, high-pressure catalytic processes. Similarly, radiation chemical synthesis offered opportunities, but found little industrial interest.

To clarify the picture, then, it is important to differentiate between:

- *Established technologies* – those that have been in industrial operation for many years around the world.
- *Emerging technologies* – those that have more or less passed through the research and development (R&D) stage, reached pilot or semi-industrial level, but have not yet become fully commercialized.

How the process basically works

Basically, the technology relies on the use of radiation energy to initiate chemical reactions, induce biological changes, or modify chemical and physical properties of materials. In a typical low-absorbed dose application, one kilowatt of radiation power can be used, for instance, to slow sprouting, and hence spoilage, of potatoes at the rate of about 10 tonnes per hour. On the other extreme, in a high-absorbed dose application, it can be used for sterilization of medical products at the rate of about 2000 syringes per hour, or about 15 to 20 million per year.

In these and other common applications, radiation processing typically holds important edges over alternative industrial processes dependent on the use of chemicals and heat. In almost every type of application using radiation processing, energy savings are reported to be significant in comparison with competing technologies. Other general advantages include reliability and simplicity of process control; reduction or complete elimination of industrial pollutants; and superior or even unique quality of products.

Another point frequently not properly emphasized is the high standard of safety at industrial radiation installations, as based on an extremely good safety record that has been established in the many industrial radiation installations operating over the past years.

On a cost comparison basis, radiation processing is no miracle technique: it can be cheaper, comparable, or more expensive than alternative methods. Yet the favorite scapegoat in the past – that radiation is expensive – has been disproved many times. Radiation is not cheap, but the number of different successful applications has shown beyond doubt that it has long

Projects in action

Through a number of avenues, IAEA continuosly has supported various projects in radiation processing around the world.

In Hungary, India, the Republic of Korea, and Yugoslavia, the Agency has executed projects jointly with the United Nations Development Programme (UNDP) that have led to radiation sterilization facilities and production of a long list of different articles for medical use. A similar project in Iran is near completion.

Projects based on the use of electron accelerators for radiation crosslinking and surface applications also have been implemented in the Republic of Korea and Yugoslavia, where products include wires and cables.

In Asia and the Pacific, one large UNDP/IAEA project in this field has 13 participating countries, and radiation techniques are among primary activities. In Indonesia, irradiation facilities on a pilot scale have been put into operation for vulcanization of natural rubber latex and for surface-coating applications. Training and demonstration centers have been established in the Republic of Korea, as well as in India, for radiation sterilization. Soon, another center, for radiation crosslinking applications will be set up in China.

In several other countries, Agency technical assistance projects are directed at installing radiation sources and operating research and pilot programmes in radiation technologies. The countries include Bangladesh, Bulgaria, Ecuador, Malaysia, Peru, Philippines, Portugal, Romania, Sri Lanka, Viet Nam, and Zambia.

Co-ordinated research programmes are aimed largely at the use of radiation technology for immobilization of bioactive materials and radiation modification of polymer properties for industrial and medical applications.

As in all Agency efforts, these activities are supplemented by training courses, study tours, fellowships, and international meetings aimed at fostering and improving flows of technical information.

• *Development technologies* – those that are in the research & development stage with indications for future commercialization.

Established radiation technologies

Probably about 90% or more of all installed radiation power is used for very few industrial processes. Three main groups fall into this category: radiation sterilization, radiation crosslinking applications, and radiation curing and grafting applications.

Radiation sterilization: medical supplies

This was the first radiation application to reach industrial level in the early 1950s and 1960s, principally in Australia, France, the United Kingdom, and the United States. Since then, it has grown steadily almost without impediments. When enthusiasts in academia and industry first started to pave the way for radiation, another cold process for industrial sterilization of medical supplies – ethylene oxide (ETO) – was widely used and accepted. Arguments in favour of radiation processing centered on reliability and superior product quality, and were later supported by cost advantages stemming from engineering advances, greater availability of high-power radiation sources, and higher volume of products treated.

Currently other factors are at work. Use of ETO is disfavoured, not only on cost grounds, but also because exposure to the chemical is more difficult and more expensive to control than exposure to ionizing radiation. ETO is known to be dangerous, toxic, and carcinogenic, with mutagenetic effects on living organisms, and there is increasing concern over attendant environmental pollution and exposure to it by workers, as well as patients that use the medical items, since traces of the gas remain on products.

In comparison, occupational safety of personnel working at radiation installations is very well and easily controlled, and no traces of radioactivity are induced in irradiated products. If necessary, radiation sterilized products can be released for use immediately after sterilization.

Today about 120 to 130 industrial installations, most of them using cobalt-60, are used for radiation sterilization in about 40 countries. The total output is on the order of three million cubic metres a year.

This application is expected to grow even faster in the near future due to governmental restrictions imposed on ethylene oxide. For example, at present about 40% of all disposable medical products in the USA are sterilized by radiation, and this is expected to nearly double by 1990. Similar expansion can be expected in other countries. A key advantage radiation holds over other methods is that products can be sterilized *after* packaging, thus avoiding problems of recontamination.

Radiation techniques also are being used to preserve wooden statues, sculptures, and other art objects. (Credit: CEA)

Important to note is that many developing countries have successfully introduced this technology. The benefits go far beyond direct implications concerning the value of production, personnel employed, and so on. It has contributed significantly to standards of health care, by providing for local production and wider use of disposable medical products designed for one-time use. These include syringes, catheters, and blood transfusion sets, for instance. The transfer of this technology is relatively simple and free of many difficulties associated with other applications.

Crosslinking applications: wires, tires, plastics and foams

Radiation crosslinking basically refers to modification of polymer properties by inducing chemical links between individual macro-molecules. Especially effective in initiating this chemical process, radiation transforms the polymer into a molecular structure with two important characteristics: It does not flow at elevated temperatures; and above the melting point, rubber-like properties are developed.

The first effect is of great importance for applications that involve wire and cable insulation; the second for production of heat-shrinkable materials and polymer foam. In radiation crosslinking of wire and cable insulation, the product is upgraded for use at higher temperatures or for those applications where short or long exposure to higher temperatures (due to overloads, for example) could otherwise permanently damage the insulation.

This is essential for wirings for internal circuits in television and audio equipment, computers, signal lines, electric appliances, power transmission lines, and in the automotive, aero, and shipbuilding industries. In comparison with chemical crosslinking, radiation is more cost-effective and less energy-intensive, requires less floor space, and is more reliable for process control. Small dimension wires can be effectively crosslinked, for example, only by radiation.

On the other hand, the method does not work for high-voltage cables, above about 30 kilovolts, because the penetration of the electrons, which are exclusively used in this radiation application, is limited. Therefore, chemical and radiation techniques are to a large extent complementary, and most large wire and cable companies in developed countries have one or more lines for radiation and chemical crosslinking to cover a wide variety of products.

More than 100 electron accelerators with an average power of about 40-to-50 kilowatts are used throughout the world for this application.

Radiation crosslinking of polymers also is used for production of heat-shrinkable materials, such as tubings, film, and tape. The products are irradiated and cross-linked to a predetermined level. After irradiation, they are heated above the melting point, expanded in one or two dimensions anywhere from two to four times, and cooled to preserve this expanded shape indefinitely. Upon application, the product is again heated above the melting point of the polymer and returns to its original form before expansion.

Applications are numerous: food and product packaging, insulation of electrical parts and joints, connectors for telecommunication cables, insulation of oil pipelines. The technology is highly sophisticated and transfer highly restricted by patent problems, proprietary information, and other factors.

Several large manufacturers of rubber tires, notably in France, Japan, and the United States, are using radiation to crosslink unvulcanized rubber to improve its mechanical properties in one stage of the manufacturing process.

Radiation crosslinking of polymers also has other applications on a relatively large commercial scale. Among them are crosslinking as part of the production of polyethylene foam for packaging, and crosslinking of hot-water polyethylene pipes. Although some "ready-made" polymer formulations for insulation and radiation crosslinking are commercially available, supply is one basic problem for the transfer of this technology to developing countries, which lack their own R&D capabilities.

Radiation curing: video tapes, paper, and wood panels

This area covers a broad range of applications that include curing of coatings, inks, and adhesives on a wide variety of substrates, such as paper, metal, wood, and plastics; coating or laminating paper, film, and foil; curing magnetic coatings for audio and video tapes; and curing of pressure sensitive devices.

Advantages include high-speed application and very rapid and uniform curing; the use of solvent-free coatings to reduce the cost of coating and eliminate pollution; the absence of heat buildup during curing, which allows the process to be applied to substrates that are temperature sensitive; and the reduction of energy consumption and space requirements.

The technology is characterized by the use of low-energy electrons, usually in the range of energies between 0.15 and 0.3 megavolts. The main feature of these machines is that they can be manufactured in self-shielded form and installed in any environment without the necessity for expensive and bulky concrete structures, which are essential for safe utilization of higher energy electron beams or gamma radiation from isotopes.

In the typical process, the special mixture of coating (usually urethane-based, epoxy, or acrylated oligomer) is applied to the surface of the material and then cured by exposure to a curtain of high-energy electrons. The polymerization is initiated by formation of very reactive-free radical species and practically finished in extremely short periods of time, as compared with thermal curing, which is time-consuming and energy intensive. With modern electron beam accelerators and handling equipment, the curing speed is on the order of hundreds of metres per minute at widths of up to about two metres.

Radiation curing applications have experienced exceptionally high expansion during the last few years, especially in applications related to curing magnetic media. One manufacturer in the United States, for example, has reported the installation of more than 70 new low-energy, self-shielded accelerators worldwide between 1980–83.

Many formulations for different radiation curing applications are commercially available. The exact content is usually proprietary. This fact, together with very precise process control (such as speed, electron beam curtain, and environment), and establishing process parameters, present the main obstacles for technology transfer. On the other hand, investments in electron beam accelerators, handling equipment, and working space are moderate and can be quickly recovered.

Grafting and other processes: membranes, frying pans, wood products

This process is intended for applications to modify surface properties, most often of polymeric materials. By the action of radiation, the active free radical sites are formed on the surface of polymer. If they are brought in contact with reactive monomers, either after irradiation or simultaneously during irradiation, a different chemical functional group can be chemically bonded to the surface.

Industrial production based on this process is not very large compared with other radiation applications, but it is being successfully applied in many countries for production of biocompatible materials, ion-exchange membranes for different uses, and for thin perm-selective membranes for battery separators.

Automobile tires, electronic parts, household items, and paper are among products radiation processing helps to produce. (Credit: UK AEA)

Radiation degradation of teflon (polytetrafluoroethylene) has been in use on a large scale for many years. Here, radiation breaks the long molecular chain of polymer, reducing the molecular weight and converting it finally into fine powder. This has found many applications for production of special heat-resistant lubricants, frying pan coatings, and so on. The starting material most often is teflon waste.

Wood-plastic composites are produced by radiation-induced polymerization of monomer that impregnates the wood. As a result, wood products with superior mechanical properties are obtained, even when the starting material is low-quality wood. Not very large, but successful, use of this technique is being made in the US for flooring, furniture, and different utensils. Basically, the same process is used with great success in France and Czechoslovakia primarily for preservation of art objects made of wood.

Emerging radiation technologies

Over the past years, several other radiation processes have emerged as potential candidates for wider commercialization. Among them:

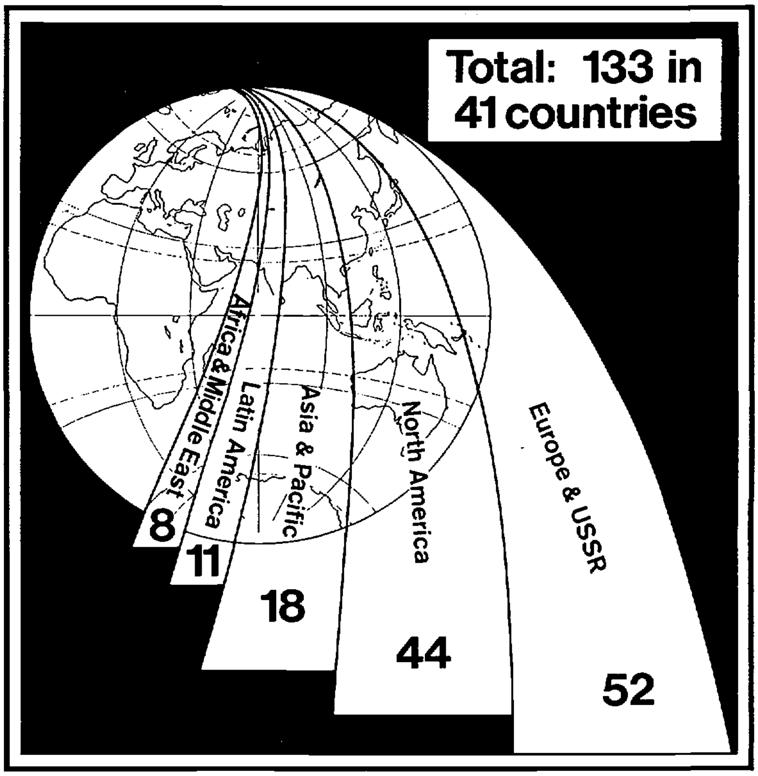
• *Food irradiation.* Currently being used in more than a dozen countries, food irradiation processing has established proven benefits to preserve foods and extend food supplies, especially in areas where spoilage is severe and rapid. Wholesomeness for human consumption has long ceased to be at issue. In view of its 40-year history, however, commercial progress has been halting. In terms of total quantities of irradiated foods (about 35 000 tonnes in 1983), industrialization remains limited for a variety of reasons. There are some indications that the outlook will change in the near future, particularly with regard to regulatory requirements. Today about 80 different commodities have gained governmental clearances for radiation processing. The application that appears to have the most immediate chance for food industry acceptance is radiation sterilization of spices, now beginning to take hold in the United States, for example. Overall, the general industry attitude over wider commercial prospects, at least as expressed at the October 1984 radiation processing meeting in San Diego, USA might best be defined as "cautious optimism", a view in part based on disappointments of the past.

• *Irradiation of animal feed.* This has reached an advanced level in Israel, for example, and is being considered as the most viable alternative to propionic acid in several other countries. Two types of applications generally are meant: radappertization (high absorbed doses) of laboratory animal feed, and radicidation (low absorbed doses) of farm animal feed. The first application, usually required only for small quantities, already is practiced at the semi-commercial level. The other one is used for capacities of tens of tonnes per hour, the main purpose being to decontaminate feed containing salmonella and other pathogenic micro-organisms. National regulations are becoming more and more aware of problems arising from such contamination and are requesting higher standards of microbiological quality.

• *Irradiation of sewage sludge.* This has been effectively demonstrated at several pilot-scale facilities in the US and the Federal Republic of Germany. Once decontaminated, the sludge can be used as fertilizer, as well as supplemental feed for ruminant animals. A number of different experimental facilities have been constructed using cobalt-60, caesium-137, and electron beam accelerators, and medium-scale plants are under planning or construction in Italy and India. Since most research on this technology is available in the open literature, introduction in developing countries could be relatively simple and straightforward.

• *Irradiation of stack gases.* This technique aims to simultaneously remove sulfur and nitrogen oxides from combustion gases in plants burning high-sulfur coal. One process developed in Japan by Ebara and tested in a pilot plant built in 1977 uses electron beams in the presence of ammonia. The polluting oxides are removed and ammonium salts are obtained as byproducts for use as fertilizers. Currently a demonstration facility in the

Gamma irradiators operating around the world



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Belgium	1
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France	3
German Democratic Republic	1
Germany, Federal Republic	5
Greece	1
Hungary	1
India	2
Indonesia	1
Iran	1
Ireland	2
Israel	1
Italy	5
Japan	7
Malaysia	1
Mexico	2
Netherlands	2
New Zealand	1
Republic of Korea	1
Saudi Arabia	2
Scotland	2
Singapore	1
South Africa	3
Spain	1
Sweden	2
Switzerland	1
Thailand	1
United Kingdom	8
United States	40
USSR	11
Venezuela	1
Yugoslavia	1

Design: W. Kalabis

Source: AECL

Radiation sources: future waves

Early day controversies about the relative pros or cons of gamma sources versus electron beam (EB) accelerators have been largely resolved by practice.

Today gamma sources are most often the preferred choice for radiation sterilization, food irradiation, and in general for treating bulky and voluminous products. On the other hand, EB machines are exclusively used for surface curing and radiation crosslinking applications. Most likely, they will be the preferred choice for applications that require large power throughputs and relatively low penetration, such as for irradiation of animal feed and grain disinfestation.

In some overlapping areas, both radiation sources can be used and the final choice may depend upon detailed technical-economic analysis and other side factors.

Current developments in the design of EB machines point to several advances ahead. For example, filament-free electron gun systems for low-energy EB accelerators are being developed, as are high-speed electron processing systems with increased irradiation zone length and a cooled drum technique for low-energy surface applications. Also, linear electron accelerators (LINACS), which were less favoured by industry in the past, are now being advanced to the stage that enables construction of high-power machines that can double as X-ray generators at sufficiently high efficiency of conversion.

Regarding gamma irradiators, important strides also are being taken. These include development of high-activity cobalt-60 irradiators and pallet-type cobalt-60 irradiators for multi-purpose applications. Features include computer-controlled operation, split-source operation, and an incremental dose system.

US is nearing completion and expected for operation in 1985, with testing planned to last one year. A possible impediment for development of this technology may be the need for high-power electron beam machines in moderate energy ranges (about one megavolt) but with very high beam powers (between 500 to 1000 kilowatts). This is well above present capabilities from machines with single electron guns, and engineering advances are needed.

Developing radiation technologies

Applied radiation research is being done at such a broad scale that any attempt to list all potential applications now at the R&D level risks leaving out important advances. With this in mind, the following methods are generating considerable interest:

- *Biomass conversion.* The final aim of research now underway in many countries is to use radiation – either alone or in combination with other processes – for degradation of lignocellulosic materials, most often agricultural waste, to sugar and alcohol. Another objective, as evident in Brazil, is radiation treatment of wood chips to improve grinding efficiency in production of fine wood powder. Energy use can be significantly reduced and smaller wood particles can be obtained that have been shown to be excellent fuel for suspension firing systems. The powder also can be used as raw material for continuous feeding of hydrolitic processes.
- *Immobilizing bioactive materials.* Several different techniques can be used to physically or chemically entrap biologically active species in gels, or attach them to an immobilized medium, for production of enzymes, antibodies, cells, and drugs, for example. By immobilization, high enzymatic activity can be sustained over a longer period of time, or the delivery of drugs can be slowed or programmed, to achieve beneficial industrial or medical results.
- *Rubber vulcanization.* Radiation vulcanization of natural rubber latex is proving much simpler and more energy efficient than sulfur vulcanization, with comparable physical and mechanical properties. Pilot-scale projects are now being performed in Indonesia and commercialization is expected in the near future.
- *Biocompatible polymers.* Radiation grafting techniques are being used to synthesize biologically compatible polymers from different hydrophilic and functional groups. Blood compatibility, for example, is one important focus of research. Products that can be developed from this technique include devices designed for implantation in the human body, as well as those designed for prolonged contact with tissues or used externally. Some of these applications already are at small stages of commercialization.