Radioisotopes and radiation technology in industry

A report on some lesser known, but widely applied, industrial applications

by Jacques Guizerix, Vitomir Markovic, and Peter Airey

Industrial radiation processing is based on the use of radiation as a source of energy to induce specific chemical, physical, and biological changes. On the other hand, applications of *isotopes* in industry, either as sealed sources or as tracers, rely on the measurements of physical signals which monitor properties of interest.

Examples of applications abound: For example, thousands of nucleonic gauges are used in the paper and steel industry to optimize product quality and production efficiency by monitoring continuously the paper weight per unit area, or the thickness of steel. Many tens of thousands of level gauges often permit measurements in difficult conditions, e.g. in corrosive media, or to provide simple, reliable, and cheap solutions that compete favourably with those involving non-radioactive equipment. Non-destructive testing is developed worldwide, and gammagraphy is a classical component, in use with other, non-nuclear methods, of all modern laboratories specialized in this area.

Many of these applications, which involve sealed sources of low to high activities — say, a few millicuries up to several curies — are well known to the general public.* This article offers an overview of radiation processing and tracer applications which are perhaps lesser known, although widely applied for the benefit of industry.

Industrial applications of radiation

In industrial applications, radiation effects are produced at rates comparable to manufacturing output of other industrial techniques. Therefore, both the energy — to ensure proper penetration through products — and power — to ensure adequate throughput — play important roles. Other important factors for industrial applications are reliability of operation (usually not less than 90% of utilization), process control, efficiency, and safety.

Several types of radiation sources satisfy all these requirements. It can be safely stated that today's radiation source technology and engineering can match almost any industrial requirement. The principal sources of radiation are the radioactive isotope cobalt-60 for gamma radiation, and electron beam (EB) accelerators for high-energy electrons, from 0.15 to 10 mega-electron volts (MeV).

Gamma radiation sources and technology. Cobalt-60 has dominated this market almost exclusively. This situation is likely to persist, since another isotope once considered an alternative, namely caesium-137, is not available in quantities needed for industrial throughputs. Although one such commercial irradiator has recently been installed in the USA, it is unlikely that many more will be commissioned in the next decade.

Gamma radiation from cobalt-60 penetrates deeply through irradiated materials and is very convenient for the treatment of bulky and packaged products. Its main application is for industrial sterilization of single-use medical products and, to a lesser extent, for the sterilization of pharmaceuticals, spices, and other products.

About 140 industrial facilities are in commercial use worldwide (about 40 countries) for radiation sterilization. Total installed activity is about 3.10^{18} becquerels (Bq), or 80 megacuries (MCi). A typical industrial facility loaded with 3.7×10^{16}Bq (1 MCi) has a capacity equivalent to about 15 kilowatts (kW) of radiation power. It can sterilize (at 2 Mrad) about 25 000 to 30 000 cubic metres of materials per year. Facilities with total installed activity up to 2.2×10^{17}Bq (6 MCi or 90 kW) are in operation.

Other applications include food irradiation (several commercial installations and a number of smaller, demonstration units); disinfection of sewage sludge (one commercial irradiator in the Federal Republic of Germany) and several pilot facilities; and some other small-scale or special applications to, for instance, wood-polymer composites, polymerization, radiation grafting for battery separators, biomedical applications, and the vulcanization of rubber latex.

EB radiation sources and technology. Industrial applications of electron beams started in the 1950s with crosslinking of polyethylene film (to produce heat

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* The curie is a unit of the rate of isotope decay. One curie is equivalent to 37×10^9 disintegrations per second or 37 gigabecquerels (37GBq).

shrinkable film for packaging) and wire insulation. It has steadily expanded. At present, several hundred EB accelerators are used for different commercial applications. Two distinct classes of accelerators and applications have been developed:

- *Low energy EB accelerator.* In an energy range of 0.15 to 0.5 MeV, they have fully shielded product handling areas and radiation shielding is an integral part of the accelerator. They are relatively small in volume, with small space requirement, and can be easily and conveniently installed in any working area or in existing production lines. The useful range of electrons in this energy range is very small (less than 1 mm) and applications are limited to irradiation of the surface layers. Typical applications are crosslinking of thin plastic film; crosslinking of thin wire insulation; curing of coatings on paper, wood, plastics, metal, etc.; curing of silicon release coatings on paper and film; curing of offset inks; and curing of laminating adhesives.

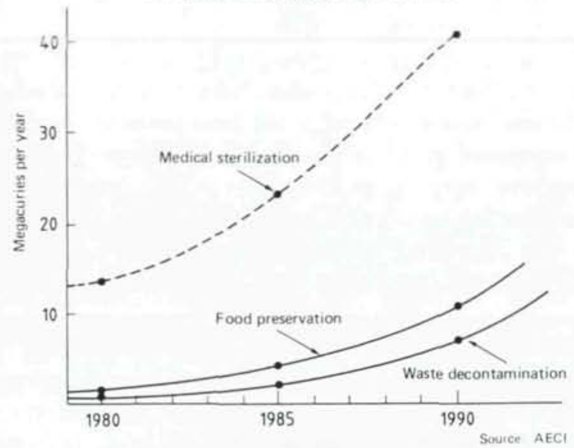
The radiation curing technology replaces the ultraviolet (UV) technology whenever pigmented coatings are used or very high production speeds are required. In many applications, such as the curing of laminating adhesive between wood panels and foil/paper with simultaneous curing of the protective top-coat, the use of radiation cannot be replaced by any other method. High power EB machines, 300-500 kW, are available with an energy range up to 0.3 MeV. Production capacities of the order of 1000 metres per minute (at 10 kilogray absorbed dose) are easily attainable with commercial accelerators. These machines have also been successfully tested for treatment of flue gases for environmental conservation. *(See the article on this subject in this edition on page 25.)*

- *EB accelerators in the energy range of 0.5 to 10 MeV.* These are commercially available with power ratings up to about 200 kW. Thick concrete shielding (1.5 to 2 metres) surrounds radiation areas. These machines are now used by many major industries, including plastics, automotive, rubber goods, petrochemical, and wire and cable. The main applications include radiation crosslinking of plastics (wire and cable insulation, heat shrinkable materials, hot water polyethylene pipes, foam, etc.); radiation vulcanization of rubber; and modification of bulk polymers (controlled degradation).

Most accelerators used for these applications are in the energy range of 0.5 to 4 MeV. A few are used for food irradiation (disinfestation of grain in the USSR and decontamination of animal feed in Israel). Attempts to use accelerators for decontamination of sewage sludge have not been very successful up to now, but no definite conclusions have yet been reached. The machines in the energy range of 600-800 kV appear to have great potential for use in environmental applications, namely for processing of combustion flue gases.

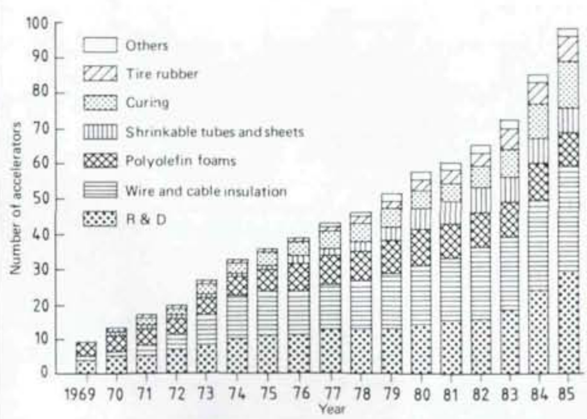
Several linear electron accelerators (LINAC) are used commercially for sterilization of medical products (in the UK, USA, France, Denmark, and Poland). However, due principally to high cost and low power levels, they have not found as widespread use as low-energy direct current (DC) machines. The steady growth of EB applications is well illustrated by the situation in Japan, as shown below.

Projected annual demand for cobalt-60 for different industrial applications



The trend for cobalt-60 demand in medical sterilization can be expected to follow or even surpass the prediction (as was the case in the period 1983-85). The development of food preservation and waste decontamination is subject to several external factors. Actual data for 1987 are probably below the predicted values.

Electron accelerators installed in Japan



Application	Electron accelerator		Number of companies
	Number	Total power (kW)	
Wire and cable insulation	30	1600	13
Polyolefin foams	10	338	3
Shrinkable tubes and sheets	7	480	5
Pre-vulcanization of tire rubber	6	410	4

Radiation processing in developing countries

The transfer of radiation technology to developing countries is taking place with a varying degree of success, depending on the technology, country, existing infrastructure, and many other external factors. Radiation sterilization is by far at the most advanced stage of development at the commercial level. About 20 countries now operate some 25 commercial cobalt-60 gamma facilities for sterilization of medical products.

The other areas of industrial applications are generally not well developed, with very few commercial installations in industrial use.

The Agency is continuing to provide active support in the promotion and transfer of radiation technology through various activities. One of the most effective means is through regional projects. An example is the project in Asia and the Pacific of the United Nations Development Programme (UNDP) and the IAEA under the Regional Co-operative Agreement (RCA). About 140 people have been trained in different subjects of radiation technology during the past 5 years. In 1986 alone, a series of eight national executive management seminars on radiation sterilization and radiation curing were held. More seminars and training courses are planned for the period 1987-91. As a result, several industrial projects have been identified and initiated in the region.

Nature of information from tracers

"Yes–No" type			proving the reality of connecting links between 2 populations
Analog type			establishing a quantitative relation between 2 populations
Questions	**Signal**	**Time dependency**	**Examples**
connection?	0 1 1	no	• leaks detection
connection? where?	0 1 0	no	• autoradiography
connection? where? how much?	0	no	• autoradiography + densitometry
how much?		no	**Dilution method** • weighting mercury in electrolytic cells
how much? when?		f(t)	• flow rate measurement
how much? when?		f(t)	**System analysis** • mass flux function
		h(t)	• transit time distribution
connection? where? how much? when?		f(t x y)	• mapping pollutant dispersion

Industrial tracer applications

In solving problems of material transport, engineers are frequently faced with the requirement for absolute "bulk flow" measurements. As this information is normally not available directly, they add an accurately known auxiliary flow of a substance that can be measured, a "tracer". But first, however, it is necessary to establish a relation between tracer flow information and the desired bulk flow.

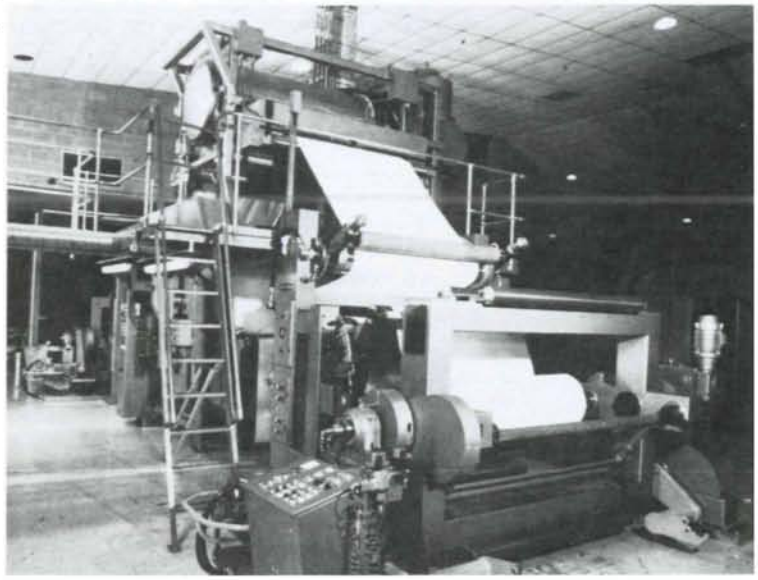
Tracer information is interpreted through a signal which can be electrical, e.g. the output of a detecting device, or the variation in the darkness of a nuclear emulsion, as in autoradiography. *(See accompanying diagramme for the type of information tracers provide.)*

As an example, consider the problem of leak detection in a heat exchanger, which consists of the flow of liquids in two circuits. A simple question may be posed: "Is there a connection between the two flows?" The response is yes or no, and the existence of a leak is proved when a tracer injected in the first circuit is detected in the second circuit.

More sophisticated tracer applications benefit from *systems analysis*, which is a method based on the exploitation of the response of a system to a stimulus applied at the entrance to this system. One imagines a constant flow of water in a mixer in a chemical plant. The concentration of a given species varies at the entrance to this system. A pulse of tracer of this species is injected at the system's entrance and the concentration is measured at the exit. This function defines the transit time distribution (TTD) of this material and constitutes the best "sample of mass transfer" that can be obtained. It can be used to calculate the variation of concentration at the exit of the system, knowing the variation of concentration at the entrance.

The TTD of a system can best be obtained through the tracer technique. It is easy to understand the importance of this function, which permits the incorporation of residence times and dispersion in analysing problems. One may choose to exploit these phenomena in industry, e.g. in mixers, or to minimize them, e.g. when many kinds of oil are transported, in series, in a pipeline.

Radioactive tracer techniques present advantages: First, their concentration can be measured with detectors located outside pipes or vessels. Second, measurement on samples taken from a flow are simple and independent of the matrix of samples. Third, a radioactive tracer is unique for labelling specific elements or chemical species. For example, sulfur in hot corrosion studies of steel alloys may be labelled with sulphur-32 and



Electron beam processor for radiation curing applications. (Credit: Energy Sciences, Inc.)

revealed at the grain boundaries by autoradiography. The information obtained from the radioactive tracer, for a given cost, is normally much more extensive than with non-radioactive tracers.

Radioactive tracer applications are regulated by the appropriate national authorities. The very low concentrations and the short half-lives of commonly used tracers normally make it possible to use levels much lower than the maximum stipulated in the regulations.

Status of industrial tracer applications

As illustrated by a guidebook now in preparation at the IAEA, tracers are of benefit to most industries. *(See box.)* The book is being prepared by 20 authors from eleven countries: Czechoslovakia, Finland, France, Federal Republic of Germany, German Democratic Republic, India, Israel, Netherlands, Poland, United Kingdom, and United States of America. Other countries are also making significant tracer applications. The guidebook's scope shows that practically all industries benefit from tracer applications — 68% of the content of this guidebook deals with chemical engineering, and the remainder is mainly devoted to metallurgy, mineral exploration, and environmental and sanitary engineering.

Tracer applications take place in laboratories, e.g. for kinetic and chemical reaction mechanism studies, as well as in plants for trouble shooting investigations (leak detection, pipe blockage); for the determination of circuit characteristics (flow rates, dead volume, branching ratio, bypassing); and for process optimization and process control. They are used in laboratories for research work, or by governmental or private institutions providing services on a commercial basis. Commercial organizations include the Physics and Radioisotope Services, ICI, in the United Kingdom; the French Atomic Energy Commission; a private company in India making only mercury inventories; and another one in Finland specialized in flow-rate measurements. The success of such enterprises, subject to the laws of supply and demand, is the best proof of the economic benefits induced by tracer applications.

In developing countries, the development of industrial tracer applications is very heterogeneous. Some countries are at the stage of the most advanced countries in this field, e.g. Chile, India, and Poland, and others are still submitted, as are some industrialized countries, to the law which states that a "time constant" of 15 to 20 years is always necessary for the application of a new technology. Some additional delays arise for economic reasons and also due to the lack of information. Nevertheless, much has been achieved. *(See the table on the next page for applications in Asia and the Pacific.)*

Guide to radioisotope tracers in industry

The IAEA currently is preparing a comprehensive guidebook on applications of radioisotope tracers in industry, covering subjects from tracer methodology to case studies in specific industries. Major headings and sections include:

- The concept of tracers
- General tracer technology
- Tracer methodology (tracer and system analysis; basic flow modelling; tracer information in modelling larger systems; tracer information in solving complex problems; processes with variable flows and volumes)
- Generalized applications (use of flow models; value of parameters; flow rate; mass balances; characteristics and use of solid tracers; mixing efficiency; trouble shooting; diffusion, permeation; particle size distribution; corrosion and surface phenomena; the use of isotopes in mechanistic and kinetic studies; two-phase flows; process control; kinetic parameters)
- Case studies (chemical industry; paper and cellulose pulp industry; petroleum industry; cement industry; metallurgical industry; energy industry; electronics industry; mechanical industry; environmental and sanitary engineering; mineral industry)
- Current trends in development and applications.

Further information on the guidebook may be obtained from the IAEA's Section on Industrial Applications and Chemistry.

Some industrial applications of radioisotopes in Asia and the Pacific

Industry	*Application*	*Isotope*	*Country*	*Comment*
Petroleum	water intake profiles in water injection wells	barium-131 (microspheres)	China	3095 wells tested to mid-1985; estimated 10 000 by 1990
Petroleum	leak testing in 140-kilometre Viramgam-Koyali crude oil pipeline	bromine-82	India	5 curies/kilometre; following 24-hour pressurization and flushing, leak was located to within 1 metre
Petroleum	leak testing		Sri Lanka	
Petroleum	leaks in underground wells	antimony-124 (triphenyl antimony) iodine-131-iodo benzene	China	5 field tests since 1968
Natural gas	distribution of corrosion retarding agent in pipeline	tritiated water	China	
Petrochemical	location of pipeline blockages	cobalt-60	India	3-metre curie source to locate blockages in naphthaline from Trombay refineries to NOCIL complex, New Bombay
Mechanical engineering	wear measurement studies on internal combustion engines	neutron activation (thin layer activation)	India	extensive programme involving wear in piston rings, bearings, fuel injection equipment, valves
Mechanical engineering	oil consumption measurements		India	effect of rated load and speed, brake, horsepower studied
Mechanical engineering	highest working temperature and temperature distribution of moving parts	krypton-85 (implantation)	China	
Power generation	dynamics of the migration of reinjected water (geothermal)		Philippines	
Power generation	measurement of turbine efficiency	bromine-82, tritiated water	India	volume flow by tracer dilution with other measurements to give ± 1% accuracy at hydrostation near Bombay
Power generation	carry-over test for steam generator at nuclear power plant	sodium-24	Rep. of Korea	
Iron and steel	effect of ladle lining on steel quality	calcium-45	China	inclusion of ladle lining erosion products in steel studied; estimated 1.3 million Yuan saved on lining material
Iron and steel	effect of calcium on nozzle clog during casting of aluminium killed steel	calcium-45	China	estimated savings of 52 000 Yuan annually
Iron and steel	hot corrosion behaviour of some alloys (nickel-based iron alloys; nickel-based niobium containing alloys)	sulphur-35 (sodium sulphate)	China	
Iron and steel	determination of wear of refractory linings in blast furnace; investigation of sources of refractory inclusions; determination of slag carry-over in molten metal		India	five major steel plants used radioactive tracers: Jamshedpur (TISCO); Rourkela; Durgapur; Bhilai; Bokaro (SAIL)
Coastal engineering	off-shore sand and sediment studies for harbour development, navigation channels	iridium-192 (glass)	Indonesia	extensive applications
Coastal engineering	silt movement to develop dredging strategies and assist with design of navigation channel	scandium-46, gold-198 (sand)	India	examples include studies at Chochin and Marmugao harbours
Coastal engineering	sand drift studies	cobalt-60 (glass)	Rep. of Korea	studies undertaken at Mukho Port, Sam Cheong Port, and Young Il Bay
Chemical	mercury inventory in electrolytic cells	mercury-197	India	offered as a commercial service
Chemical	mercury inventory in electrolytic cells	mercury-197	China	
Chemical	determination of a range of process parameters and plant operating characteristics		India	examples include residence time distribution; dilusion; flow rate at Century Rayon
Chemical	mixing characteristics of urea reactor	carbon-14 dioxide	Rep. of Korea	Chung Ju fertilizer plant
Water resources engineering	mapping seepage contours in the face of Pedu Dam	gold-198 tritiated water	Malaysia	major seepage areas and transit lines identified
Water resources engineering	location of mayor seepage areas in Kihung Reservoir	sodium-24	Rep. of Korea	
Water resources engineering	flow-rate measurements in sewer lines		Philippines	
Water resources engineering	discharge measurements in rivers and irrigation canals	technetium-99m	Malaysia	work undertaken on the Langat, Semenyih, and Lui rivers for the Department of Irrigation and Drainage and on canals for the Kemulen Agriculture Development Authority (KADA), Kelantan
Electronics	leakage in semiconductors	krypton-85	China	
Electronics	leakage in semiconductors	krypton-85	Thailand	

The table surveys some industrial applications of radioisotopes in developing Member States of the IAEA participating in the regional co-operative programme in Asia and the Pacific (Regional Co-operative Agreement). The survey is not exhaustive and excludes Australia and Japan, two donor countries of the programme. Excluded applications include "closed source" uses, such as radiography, nuclear gauging, and borehole logging, for example.