Applications of radioisotopes and radiation technology in industry: current status and prospects

H. J. Pant, Y. K. Bhardwaj, Umesh Kumar and P. K. Pujari*

Radiochemistry and Isotope Group, Bhabha Atomic Research Centre, Trombay, Mumbai 400 085, India

The Bhabha Atomic Research Centre (BARC), Mumbai, over the last five decades has made pioneering contributions in the development and applications of radioisotopes and radiation technology for industry, medicine and agriculture leading to significant benefits to the society. This article briefly discusses various applications of radioisotopes and radiation technology in the industry presently being pursued at BARC. The main areas of application include radiotracers and sealed sources for industrial troubleshooting, radiography and tomography for NDT applications, and nucleonic gauges for quality control in industrial processes. The radiation processing technology, on the other hand, is an effective, economical and environmentally friendly alternative to conventional methods used for various industrial processing applications. Presently, 24 gamma irradiators and 18 electron-beam machines are commercially operating in India for various radiation processing applications.

Keywords: Nucleonic gauges, radioisotopes, radiometry, radiotracer, radiation processing, sealed sources, tomography.

Introduction

SOON after its independence in 1947, India realized the importance of atomic energy for power and non-power applications and established the Atomic Energy Commission (AEC) in 1948 with Homi Jehangir Bhabha as its Chairman. Later in 1954, the Department of Atomic Energy (DAE) was established with the primary mandate of developing nuclear technology for the production of nuclear power and radioisotopes for application in healthcare, industry and agriculture. Radioisotope production in India started on a modest scale soon after the APSARA reactor at Trombay became critical in 1956. The commissioning of the 40 MW CIRUS reactor in 1960, the setting up of modern radioisotope processing laboratories in the late sixties and the production of cobalt-60 in power reactors in mega curie quantities (in the late seventies) made India self-sufficient in radioisotope production. The radioisotope production received a major boost in 1985 with the commissioning of the high-flux 100 MW DHRUVA reactor, which provided the opportunity to extend the range of radioisotopes available in the country, both in quantity as well as in specific activity. The CIRUS reactor was decommissioned in 2010 after 50 years of successful operation and the APSARA reactor was upgraded to 2 MW and renamed APSARA-U in 2018. Presently, there are two research reactors, i.e. DHRUVA and APSARA-U operating at BARC for production of different radioisotopes. The produced radioisotopes are used in industry, healthcare and agriculture across the country. The Board of Radiation and Isotope Technology (BRIT), Mumbai, a commercial organization of the DAE, supplies radioisotopes/radiopharmaceuticals as well as equipment and provides various services to the Indian industry. The industrial applications of radioisotopes and radiation technology are primarily classified into two categories, i.e. radiotracer and sealed source applications which are discussed below[1,2].

Radiotracer applications

Radiotracers have been widely used for troubleshooting and process optimization in the industry all over the world because of their specific advantages over conventional tracers. The main advantages of radiotracers are physico-chemical compatibility, high detection sensitivity, *in situ* detection, availability of a wide range of radiotracers for different phases, stability in the harsh industrial environment and limited memory effect[1–3]. Table 1 lists the commonly used radiotracers in the industry[3].

Figure 1 illustrates the principle of the radiotracer technique[1]. It involves an instantaneous injection of a suitable radiotracer into the system at the inlet and monitoring its passage at the outlet or at strategically selected locations along the system using collimated radiation detectors. The monitored tracer concentration data are plotted as a function of time and interpreted to obtain information about process parameters, hydrodynamic behaviour of the system and occurrence of malfunctions if any. The common radiotracer applications in the Indian industry include[3–5]:

- Leak detection in buried pipelines and industrial systems
- Blockage location in buried pipelines

---

*For correspondence. (e-mail: pkpujari@yahoo.com)

Table 1. Commonly used radiotracers in industry[1]

Isotope	Half-life	Radiation and energy (MeV)	Chemical form	Tracing of phase
^{3}H	12.6 yrs	β: 0.018 (100%)	Tritiated water	Aqueous
^{24}Na	15 h	γ: 1.37 (100%), 2.75 (100%)	Sodium carbonate	Aqueous
^{82}Br	36 h	γ: 0.55 (70%), 1.32 (27%)	Ammonium bromide	Aqueous
			Dibromobiphenyl	Organic
			Methyl bromide	Gas
^{131}I	8.04 days	γ: 0.36 (80%), 0.64 (9%)	Potassium iodide	Aqueous
			Iodobenzene	Organic
^{99m}Tc	6 h	γ: 0.14 (90%)	Sodium pertechnetate	Aqueous
^{140}La	40 h	γ: 1.16 (95%), 0.92 (10%), 0.82 (27%), 2.54 (4%)	Lanthanum chloride	Solid (adsorbed)
^{46}Sc	84 days	γ: 0.89 (100%), 1.12 (100%)	Scandium oxide	Solid (particle)
^{198}Au	2.7 days	γ: 0.41 (99%)	Chloroauric acid	Solid (adsorbed)
^{197}Hg	2.7 days	γ: 0.077 (19%)	Mercury metal	Mercury
^{79}Kr	35 h	γ: 0.5 (8%)	Krypton	Gas
^{41}Ar	110 min	γ: 1.29 (99%)	Argon	Gas

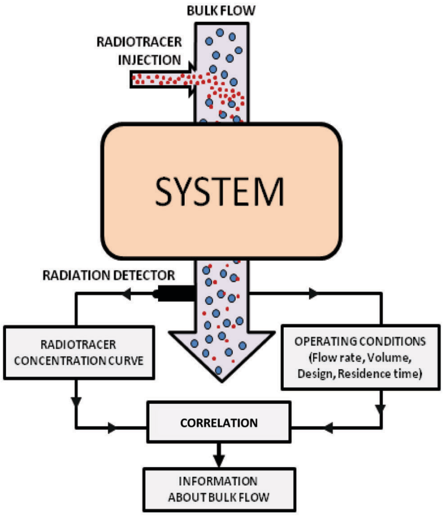

Figure 1. General principle of the radiotracer technique[1].

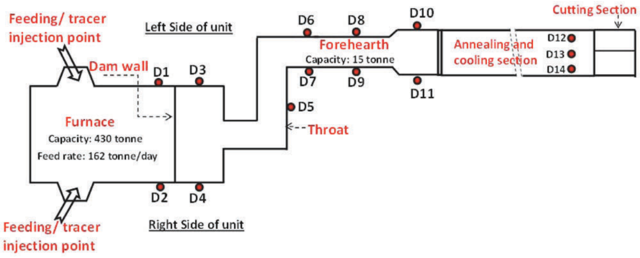

Figure 2. Schematic diagram of the glass production unit showing injection and monitoring locations of the radiotracer.

- Mixing/blending time measurements in batch-type vessels
- Material inventory in process vessels
- Flow rate measurements in pipelines and canals
- Residence time distribution (RTD) measurements in process vessels
- Sediment transport investigations in ports
- Effluent dispersion studies in water bodies
- Wear and corrosion rate measurements in metallic components
- Radiotracer applications in oilfields
- Radioactive particle-tracking technique for flow visualization in process systems

The above-mentioned applications are discussed and reviewed in detail elsewhere[3]. Two applications of the radiotracer technique are briefly discussed below.

RTD measurements in a glass industry

Measurement and analysis of RTD of process materials in industrial systems is an important application of the radiotracer technique. The measurements provide information about various hydrodynamic parameters and flow patterns which are eventually used to investigate the causes of poor quality of the product and reduced process efficacy[1–3].

A glass industry in India had designed and installed a unit for producing glass sheets for use in solar panels. However, it was observed that the quality of the produced sheets was poor and required immediate intervention. At the request of the industry, a radiotracer study was carried out with the objective of measuring the RTD of molten glass in different sections of the unit[4]. Figure 2 shows the schematic diagram of the unit. Lanthanum-140 as lanthanum oxide was selected as a radiotracer. The radiotracer was instantaneously injected at the inlet of the furnace and its movement was monitored at strategically selected locations along the unit using water-cooled and collimated scintillation detectors (D1–D14) connected to a data acquisition system (Figure 2). The radiotracer concentration curves measured as a function of time were treated and modelled to draw information about mixing and flow dynamics of the molten glass. Figure 3 shows a comparison of experimentally measured and model-simulated typical RTD curves at the throat of the furnace.

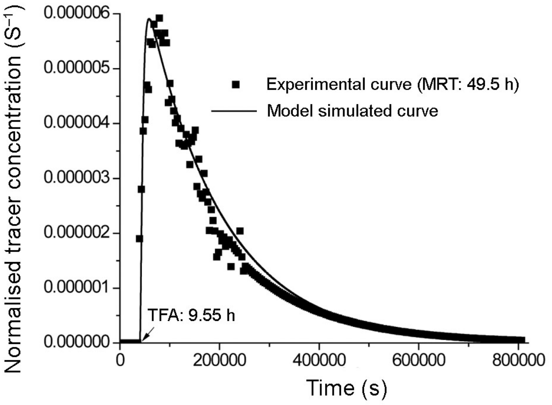

Figure 3. Comparison of experimental and model-simulated RTD curves measured at the furnace outlet.

Various parameters such as time of first arrival (TFA), mean residence time (MRT), dead volume, mixing time and flow pattern of the molten glass within the furnace were determined[4]. The mixing time of the feed within the unit was estimated to be 30 h, which was much longer than the expected value. In addition, several flow abnormalities were identified leading to poor quality (non-uniform composition) of the sheets. Based on the results of the study, a decision was taken to modify the design of the unit. After modifications, the study was repeated and the results showed significant improvement in the flow dynamics of molten glass and quality of the glass sheets. The mixing time of the molten glass had also decreased to about 22 h. The radiotracer study helped in diagnosing the problem and implementing remedial measures leading to significant benefit to the industry.

Sediment transport in ports

In order to maintain the depth of the shipping channels in ports, sediments are dredged and dumped at suitably selected locations. Figure 4 *a* shows a typical dredger used for dredging and dumping sediments in ports. The selected location should be such that the dumped sediments do not find their way back into the shipping channel. The radiotracer technique is often used to examine the suitability of the dumping sites in ports[5]. This involves the preparation of a radioactive particulate tracer having similar physicochemical properties as the bed material, injection of the tracer at the desired location, tracking of the radiotracer on the sea-bed using waterproof scintillation detectors, plotting the iso-activity contours and interpreting the same to evaluate the suitability of the site. Scandium-46 as glass powder having the same density and grain-size distribution as that of the native sediments is used as a radiotracer. About 70 large-scale radiotracer investigations have been carried out by BARC in all major ports in the country. Figure 4 *b* shows a plot illustrating the iso-activity contours monitored in a study carried out in a port[5]. The contours indicate that the selected site is suitable for dumping the dredged material as the radiotracer does not find its way back into the shipping channel.

Sealed source applications

In sealed source applications, a radiation source is encapsulated in a metal capsule that never directly comes in contact with either the process material or the equipment. The penetrating radiations from the source capsule are directed at the desired location in the equipment/material under investigation and the intensity of the transmitted or scattered radiation is measured. The data are analysed to obtain information about the content of the system or physical properties of the material[1,6–10]. The five different areas of applications of sealed sources are listed below and briefly discussed in subsequent sections.

- Radiometry or gamma scanning
- Radiography
- Tomography
- Nucleonic gauges
- Radiation processing applications

Radiometry testing applications

Gamma radiometry technique is used to determine the density of the intervening material between the source and detector, hold-up in multiphase flow systems, shielding integrity of transportation casks, lead blocks, civil structures, scanning of industrial process columns and blockage detection in pipelines in the industry[1]. As shown in Figure 5, the technique involves mounting of a collimated–sealed radiation source and a detector on diametrically opposite sides of the object under investigation and recording the intensity of the transmitted radiation in terms of counts per unit time. Figure 6 shows gamma radiometry investigations being carried out on industrial-scale shielding assemblies prior to their deployment in actual use.

Radiography testing applications

Radiography testing (RT) is a non-destructive technique (NDT) used to examine the integrity and internal structure of materials and assemblies without destroying them or altering their size, shape, physical or chemical properties[6]. It is employed in quality control monitoring in various industries, including nuclear, aerospace and automobile. Figure 7 *a* shows a typical set-up to illustrate the principles of radiography. The technique involves exposing the object to energetic electromagnetic radiations emitted either from a sealed radioisotope source or X-ray machine, and recording the intensity of the transmitted radiations on a recording

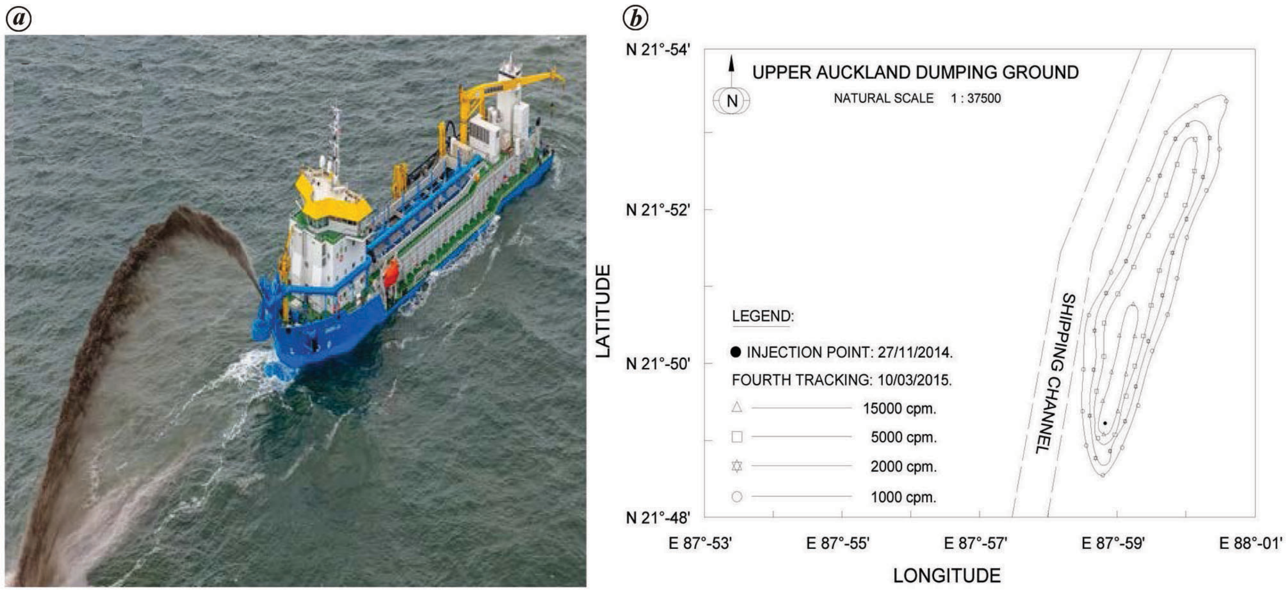

Figure 4. ***a***, A dredger dumping dredged sediments at a selected location. ***b***, Iso-activity contours monitored in a radiotracer study[5].

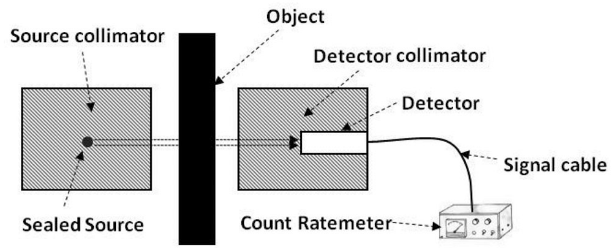

Figure 5. Schematic block diagram of a typical gamma radiometry set-up.

Figure 6. Shielding adequacy tests of typical industrial assemblies using gamma radiometry.

medium like chemical-based film, phosphor imaging plate or a flat panel detector[6]. The distribution of optical density on the recording medium provides information about defects, flaws, voids and internal structure of the object. Figure 7 *b* shows a typical radiograph of a stainless-steel plate weld revealing the lack of penetration (LOP) and spatter around the weld.

Table 2 lists the gamma-emitting sealed radioisotope sources used in RT. BARC has played a pivotal role during the last five decades in developing radiography equipment, production of radioisotope sources for RT and promoting the technique in India. BRIT, DAE supplies radiography equipment and sources to the Indian industry on a regular basis. As on June 2021, there are 3176 RT equipment registered with the Atomic Energy Regulatory Board (AERB), 647 actual licensees for radiography cameras, 740 industrial X-ray devices and similar equipment, 676 entities carrying out commercial activities in the country and 1454 RSOs registered with the AERB. Training courses are regularly carried out by BARC for various levels of radiography personnel such as operators (RT-1), supervisors (RT-2) and managers (RT-3). More than 10,000 personnel have been trained at different levels to carry out radiography testing for quality control of industrial products.

Computed tomography

Computed tomography (CT) is an advanced imaging technique for NDT and process applications. Figure 7 *a* represents a typical set-up for tomography applications, including the basic difference between a radiographic image and a two-dimensional tomographic image plane. CT refers to the reconstruction or recovery of cross-sectional images representing slices through a volumetric object under examination[7]. The cross-sectional images are obtained using a mathematical process called image reconstruction. A complex industrial CT facility can examine specimens in 3D space. CT for process applications requires a different modality.

BARC has been actively involved in research and development (R&D) activities pertaining to advanced industrial applications of X-ray and gamma-ray based industrial imaging for more than two decades. Development programmes

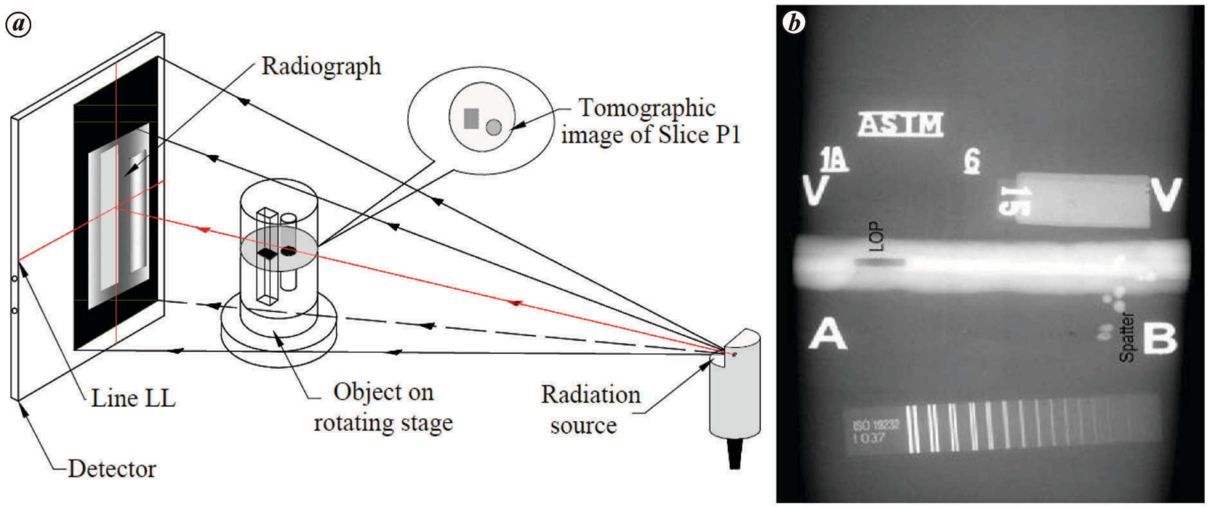

Figure 7. ***a***, Radiographic and tomographic imaging set-up. ***b***, A typical industrial radiograph of a butt-welded plate revealing defects (LOP and spatter).

Table 2. Commonly used radioisotope sources for radiography testing

Radioisotope	Half-life	Gamma-ray energy (MeV)	Activation cross-section (Barn)	Radiation output Rem/h/Ci @ 1 m	Optimum working thickness
Co-60	5.27 yrs	1.17, 1.33	37	1.37	50–200 mm equivalent of steel
Cs-137	30.1 yrs	0.66	–	0.382	50–125 mm equivalent of steel
Ir-192	74.4 days	0.296–0.613	370	0.592	10–60 mm equivalent of steel
Tm-170	129 days	0.052–0.084	130	0.0062	2–10 mm equivalent of steel
Yb-169	32 days	0.063–0.308	11000	0.327	2–12 mm equivalent of steel
Se-75	120 days	0.009–0.400	26	0.859	5–40 mm equivalent of steel
Am-241	432.2 yrs	0.0595	750	0.314	2–18 mm equivalent of aluminium

undertaken earlier resulted in the setting up of an experimental facility for a cone-beam CT system. The system consists of a X-ray generator (40–450 kV) having focal spot sizes of 0.4 and 1.0 mm, a flat panel detector and a multi-axis precision manipulator for positioning source, detector and specimen. It is capable of scanning specimens having maximum dimensions up to 400 mm in any orientation. Components and assemblies for scanning are selected based on their radiation-attenuating capacity and physical shape and size. Figure 8 *a–c* shows photographs of a photomultiplier tube (PMT) assembly, its cut-away view and cross-sectional images. These images clearly exhibit different parts of the assembly such as dynode structure, joints and a stainless-steel cover.

Nucleonic gauges

Nucleonic gauges (NGs) are devices based on ionizing radiations emitted from sealed radiation sources that are used for on-line monitoring of various physical parameters and quality control during production processes in industry[8,9]. A NG consists of one or more radiation sources and a detector system integrated with a data acquisition system. They are arranged in a fixed geometrical configuration depending upon the type of application. The types of radiation sources used in NGs include alpha, beta, gamma, neutron and X-rays. The activity of the sources varies from several kilobecquerel (kBq) to a few gigabecquerel (GBq) and X-rays operating in the energy range 30–160 keV. Table 3 lists the various applications of NGs and typical sources in use[9]. Some of the NGs used in industry are also based on the measurement of natural radiation emitted from the material under study. The applications of NGs are well-established and their socio-economic benefits have been amply demonstrated and recognized. The commonly used applications of NGs include measurement of density, thickness and level of process material in industrial systems, analysis of ores and minerals, and measurement of moisture content in various systems[9].

One of the most important advantages of NGs is the on-line measurement without direct contact between the radiation source and the material being examined. As a consequence NGs are preferred in high-speed production lines and harsh process conditions such as high temperature, pressure and corrosive medium. The measurements are accomplished non-destructively, and without disturbing and changing the properties of the examined material. The penetrating nature of high-energy gamma radiation enables

Table 3. Radiation sources, techniques and applications of nucleonic gauges in industry[9]

Type of gauge	Technique	Radiation sources used	Typical applications
Level and interface	Transmission	Cesium-137, cobalt-60 (gamma)	Level and interface measurements in process vessels in industry
	Backscattering	Americium-241/beryllium (neutron)	Level measurements of hydrogenous materials
Thickness or mass per unit area	Transmission, backscattering	Krypton-85, strontium-90, promethium-147, thulium-170 (beta)	Thickness measurement of paper and plastic sheets
	Transmission, backscattering	Cesium-137, cobalt-60, americium-241 (gamma)	Aluminum and metal sheets in industry, the mass of materials on conveyor belts
Coating thickness	Differential transmission method	Krypton-85, strontium-90 (beta)	Coatings on textiles papers and leather clothes
	Backscattering	Promethium-147, thulium-170 (beta)	Metal coatings on metal sheets and coatings on photographic paper
	X-ray fluorescence	Iron-55, cadmium-109, americium-241 (gamma), etc.	Measurement of thickness coating on metal sheets
Density	Transmission	Krypton-85, strontium-90, promethium-147, thulium-170 (beta)	Cigarettes, fluids and slurries in pipes and tanks, gas and gas-fluidized solids, gas–liquid emulsions, steam-water ratio, etc.
	Transmission	Americium-241, cesium-137, cobalt-60 (gamma)	Fluids and slurries in pipes and process vessels in industry
Bulk density	Transmission, backscattering	Americium-241, cesium-137, cobalt-60 (gamma)	Soil, borehole cores, rocks and ore measurements in boreholes
Moisture	Slowing down of neutron and backscattering	Americium-241/beryllium (neutron)	Soil, rocks and ores, agricultural products
Elemental analyser	Emission of characteristic X-rays and their backscattering	Iron-55, cadmium-109, americium-241 (gamma), characteristic X-rays	Elemental analysis in metals, minerals, petroleum products, etc.
Air quality/dust monitor	Absorption of low-energy beta-radiations	Carbon-14, promethium-147, krypton-85 (beta)	Environmental control

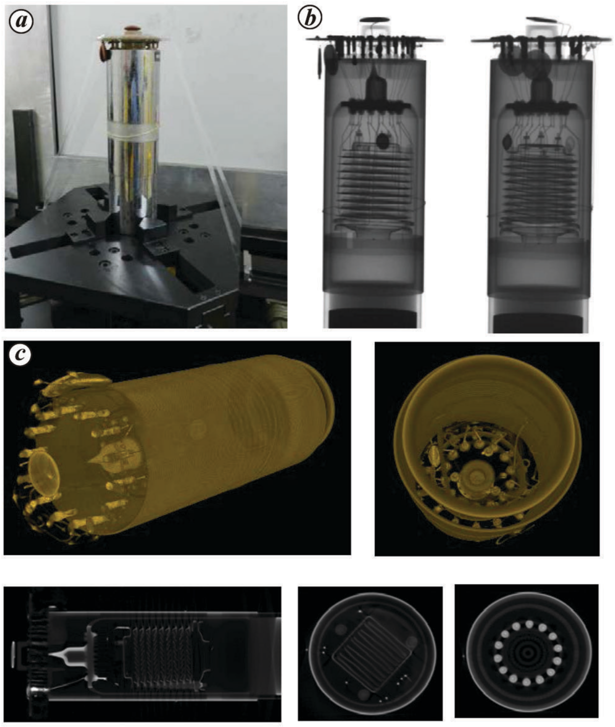

Figure 8. ***a***, Photograph of the PMT assembly. ***b***, Digital radiographic images. ***c***, 3D reconstructed volume, cut-away view and cross-sectional images of the PMT assembly.

measurements to be made through the walls of sealed containers. The sampling volume of most of the NGs is usually larger than that sampled by conventional methods for laboratory analysis.

The Indian industry has been using NGs for over the last five decades. Though majority of the NGs used in the Indian industry are imported, Electronics Corporation of India Ltd (ECIL), Hyderabad, a public sector company of DAE has been indigenously manufacturing and supplying different types of NGs to many Indian industries. BRIT, Mumbai, supplies various sources used in NGs. According to the national inventory, about 7559 NGs have been installed and are in use in about 1119 industrial installations all over India, including a few research institutions.

Radiation processing applications

The ability of high-energy radiations to generate highly reactive free radicals, ionic species or defects in matter in any state and even at sub-zero temperatures has been exploited to bring about changes in materials as soft as elastomers to as hard as diamond. As energy deposition involves electronic levels, the processes are energy-efficient. Reactive monomer radicals/ions which undergo chain reactions to form polymers, high-molecular-weight polymers which undergo significant changes in properties or microorganisms which are deactivated even due to minute changes in their chemical structure are particularly amenable for radiation processing[10]. Gamma as well as electron beam (EB) radiations are two main sources used for industrial radiation processing.

Radiation sterilization of medical products

The present era of disposable materials for medical applications has been possible due to the availability of easily processible materials like polymers and the development of reliable technology for radiation sterilization. The first gamma-radiation sterilization plant, ISOMED, for medical products was set up under a UNDP project by DAE in 1974 (ref. 11). Over four decades of functioning, ISOMED has propelled several entrepreneurs to set up radiation-processing facilities across India. Among noticeable advantages of radiation sterilization are the possibility of sterilization of heat-sensitive materials (as it is a room-temperature process), better and easy control of the process and sterilization in a packed state. Figure 9 shows the process of radiation sterilization.

Radiation-induced crosslinking applications

EB crosslinking is a room-temperature process. Crosslinking results due to the interaction of radicals generated in the polymer matrix on EB irradiation that leads to the formation of a 3D network. The formation of the 3D network enhances mechanical properties and induces a memory effect in the crosslinked matrix.

Electron beam crosslinking of wires and cables: The EB processed wires and cables have several advantages like lower weight, better chemical and abrasion resistance and longer life as compared to un-irradiated wire and cables[12]. BARC in collaboration with M/s NICCO Cables Ltd, Kolkata, developed EB crosslinkable cables and a conceptual design of the EB accelerator for this application. Irradiation of >100 km of cables was demonstrated using an indigenously developed conveyor system. The irradiated cables were found to meet the specifications desired by the end-users. Based on this collaborative work, a trial development order from Chittaranjan Locomotive Works Ltd, Indian Railways, Dist Burdwan (WB) to NICCO Cables for the supply of EB crosslinked cables was successfully executed[13]. Figure 10 shows photographs related to wire and cable crosslinking.

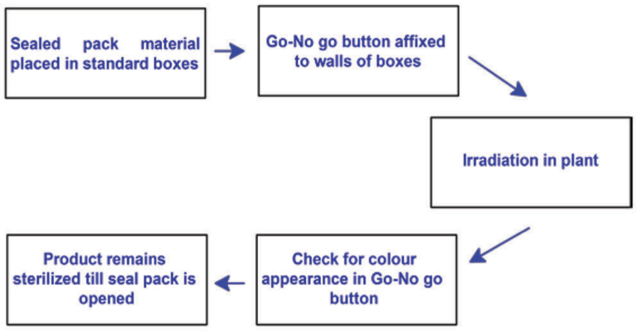

Figure 9. Radiation sterilization process.

Radiation processed heat-shrinkable polymeric matrices: The crosslinking induces a plastic memory effect in the matrix which causes the expanded/stretched crosslinked matrix to shrink back to its original dimensions when heated above a certain temperature. BARC in collaboration with M/s RayChem RPG Pvt Ltd, Mumbai, Maharashtra developed polyolefin-based formulations and an EB irradiation protocol for optimum crosslinking to obtain the desired shrink ratio. The developed heat-shrinkable material finds applications in sealing of high-voltage cable joints as well as vacuum-mouldable insulation sheets[14].

Radiation processed hydrogels

Hydrogels, the cross-linked polymers with the capacity to absorb a significant amount (>20% w/w) of water have drawn a lot of attention for difficult medical problems like the healing of burns. Radiation processed hydrogels have added advantages of additive-free synthesis and the possibility of sterilization during synthesis over conventionally synthesized hydrogels. BARC has developed gamma-radiation processed hydrogels for burn and wound dressing, and the technology has been transferred to four private agencies[15]. These hydrogels also find applications in the treatment of bed sores, diabetic ulcers, leprosy and post-surgical wounds. Figure 11 shows pictures of hydrogel products developed by BARC.

Radiation processed polymer blends and composites

Polymer blends are a combination of two or more polymers obtained by their physical mixing. The aim is to get the best possible homogeneous mixture of two constituents so that a single entity having a set of properties is obtained.

However, most of the polymers are difficult to mix because of unfavourable mixing thermodynamics, high interfacial tension and incompatible morphology. The addition of a compatibilizer (reactive or non-reactive) to overcome mixing constraints is a common practice to obtain a polymer alloy from a blend (blends that are fully compatible). Exposure of polymer blends to high-energy radiation generates radicals randomly on both the polymers, which combine to form any or all of the grafted copolymer, random block copolymer, crosslinked polymer, interpenetrating or semi-interpenetrating networks as shown in Figure 12. The formation of any of these co-polymer structures enhances compatibility and hence affects the properties to a

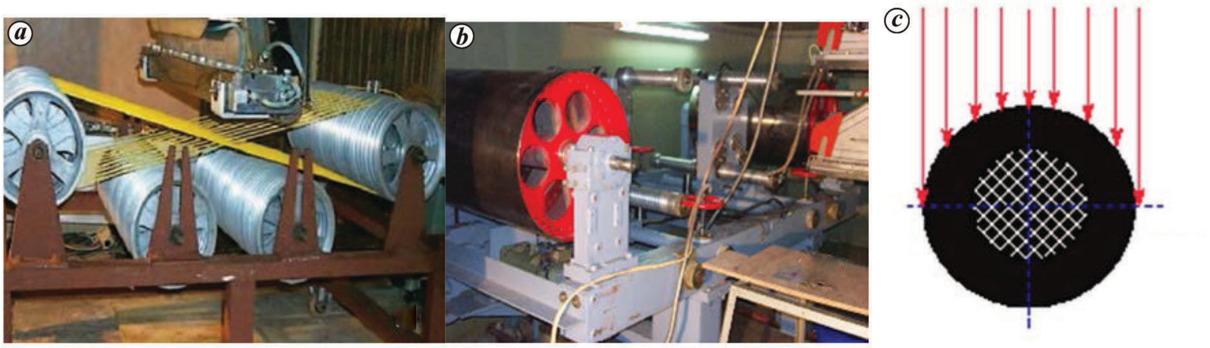

Figure 10. EB crosslinking of cables. ***a***, Continuous eight-shaped conveyor for both sides irradiation. ***b***, Drum conveyor. ***c***, View of one side cable irradiation.

Figure 11. Radiation processed hydrogels. ***a***, Commercial product. ***b***, Non-iodinated and iodinated hydrogels.

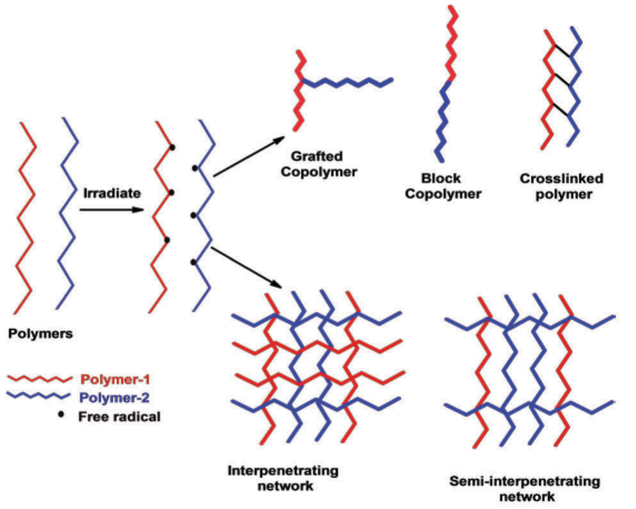

Figure 12. Possible copolymer structure generated on irradiation of two polymer blends.

different extent. Extensive studies carried out at BARC on radiation processing of binary and ternary blends have indicated that high-energy radiation is effective in enhancing property modification of not only elastomer–elastomer[16,17] but also elastomer–plastic blends[18]. Recent studies on shape memory polymer (SMP) blends have proven that at a temperature of 70°C for alpha-olefin (EOC 8440 : EOC 8200 :: 50 : 50)-based blends with an increase in absorbed EB dose, shape fixity value decreases while shape recovery value improves almost linearly up to a dose of 100 kGy (ref. 19). Ethylene vinyl acetate (EVA)-based gamma-radiation crosslinked SMP is being investigated for head and neck immobilization during radiotherapy as shown in Figure 13. SMP shows complete recovery even from 100% elongation.

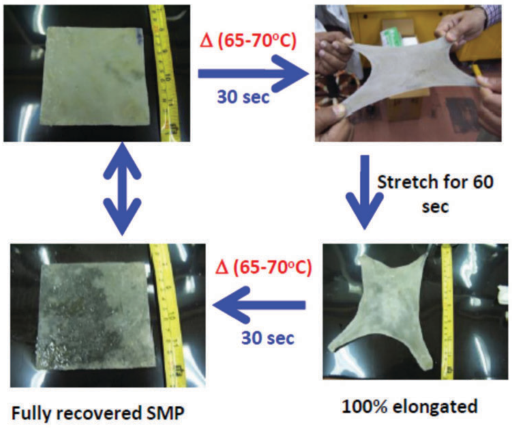

Figure 13. Recovery cycle for an EVA-based SMP.

Polymer composites also consist of two or more chemically and physically distinct materials. One of them is the continuous polymer phase and the other is the dispersed, embedded, discontinuous phase called filler (ceramic, carbon nanotubes (CNT), metal, flake, fibre). The composites are multiphase, multicomponent systems developed with an intention to get a product that has the properties of both the components. Extensive studies have been carried out on radiation processing of composites for contrast imaging[20], synthesis of EPR dosimeter[21], sensing[22], designing flexible shielding[23] and other purposes[24] where radiation has been effectively utilized for uniform crosslinking of matrices and surface modification of composite components for enhancing compatibility among components.

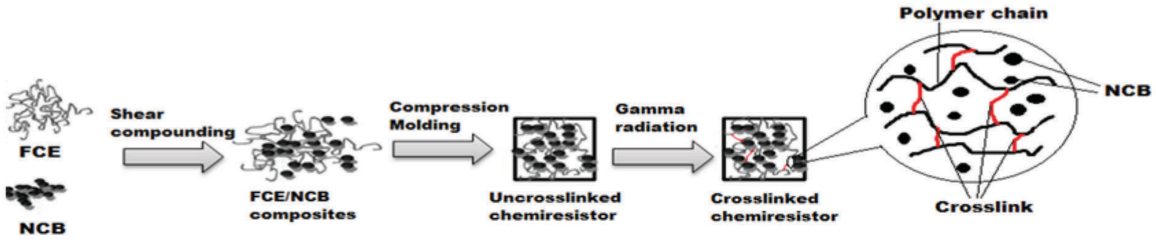

Figure 14. Protocol for synthesis of radiation processed chemiresistive sensor.

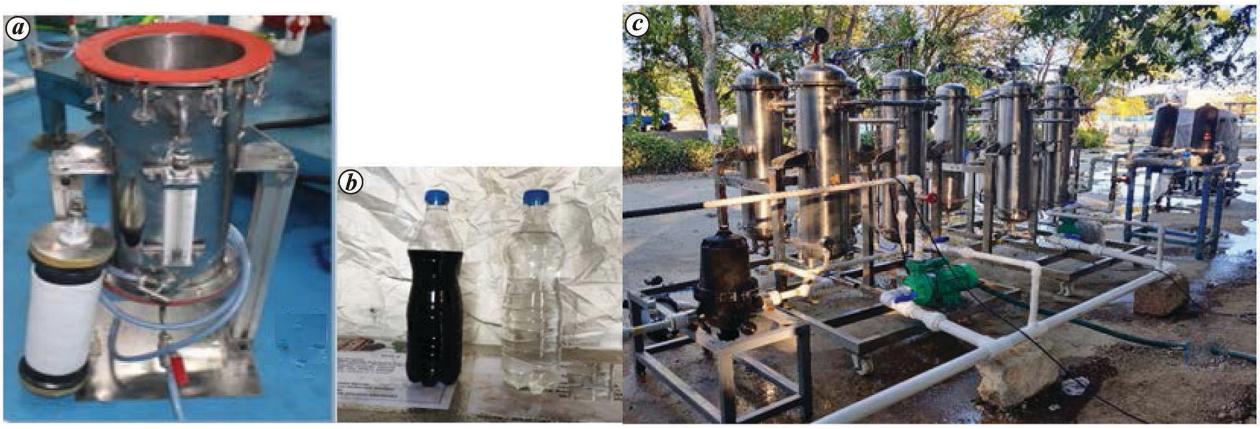

Figure 15. Radiation grafted matrices for treatment of dye effluents. ***a***, Cartridge and casing for dye treatment set-up. ***b***, Pre- and post-treated effluents. ***c***, Pre-pilot-scale set-up for the treatment of industrial dye effluents.

Figure 14 shows a protocol for the synthesis of radiation processed sensors.

Radiation grafted polymeric matrices for separation purposes

Polymer grafting is essentially the process of covalently linking a new polymer of interest to the existing polymer with an aim to synthesize a functional matrix that has properties of both the constituent polymers. Radiation-induced grafting has several advantages over conventional methods like uniform grafting over the whole surface, and better control over the extent of grafting. Being a room-temperature process, even thermosensitive backbones can be grafted[25].

Cellulose backbone-based cation exchange-type grafted matrix was synthesized through one-step gamma-radiation grafting. Initially, the matrix grafted to an optimum extent was rigorously tested under laboratory conditions for its functional requirement in batch and continuous mode for several cycles of adsorption and regeneration with minimal attrition loss[26]. Later, the grafted matrix was given the appropriate shape of a cartridge and employed in a pre-pilot-scale set-up for testing its dye-uptake efficacy from actual industrial effluents. The set-up showed fast adsorption kinetics and treatment capacity of 25,000 l of normal effluents. Figure 15 shows photographs of the dye remediation set-up developed using grafted matrix.

Multifunctional cotton having super-hydrophobic and super-oleophilic properties was developed using the radiation grafting process for efficient separation of organic liquids from organic–water mixtures[27]. The commercially available cotton was soaked in a suitable monomer solution followed by radiation irradiation to an optimum dose. The grafted cotton was dried and used for the desired applications. The grafted long-chain hydrocarbon molecules modify the topography and surface energy of cotton. The modified cotton was tested for its separation efficacy with different organic–water mixtures (water–crude oil, water–kerosene, water–benzene, etc.) and was found to selectively absorb the organic compounds. The absorbed organic compounds could be easily squeezed out and the adsorbent reused for separation. No significant decrease in separation efficacy was observed for 50 cycles of adsorption and removal. The modified cotton was physically and chemically robust, high-temperature resistant and biodegradable. Figure 16 illustrates the properties of the modified cotton and the process. The process has been scaled-up for large-scale production of modified cotton for various applications.

Miscellaneous applications

Hygienization of dry sewage sludge: The ability of high-energy radiation to kill pathogens has been implemented for hygienization of dry sewage sludge through

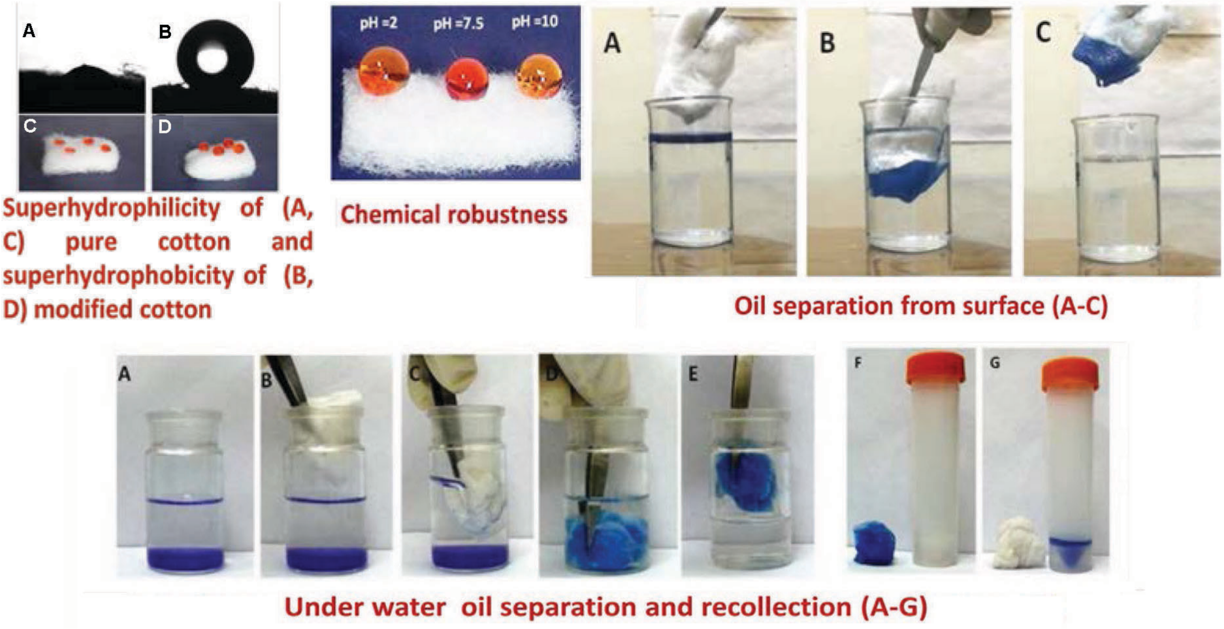

Figure 16. Illustration of properties and separation process of oil–water using modified cotton.

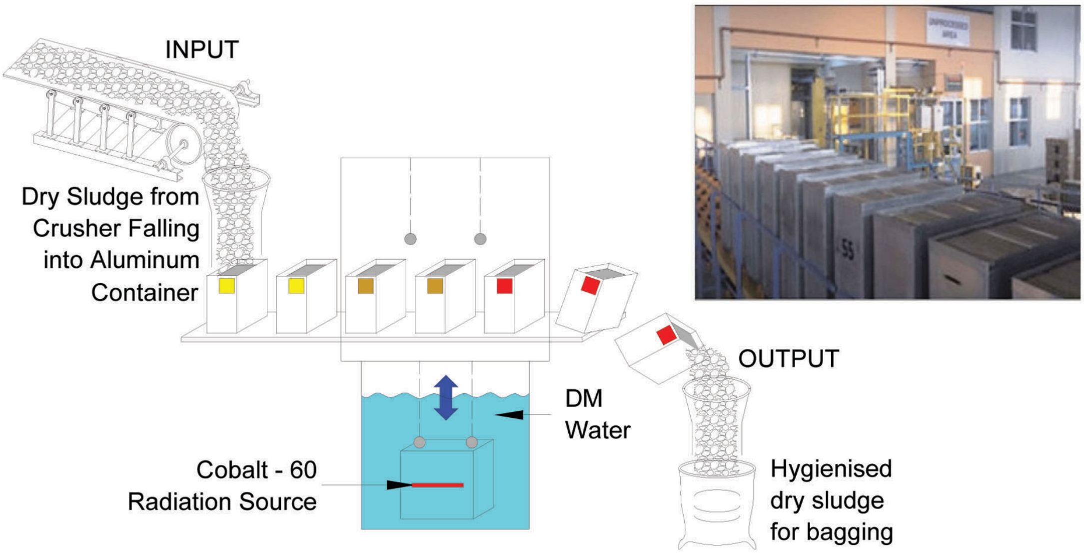

Figure 17. Schematic of radiation hygienization dry sewage sludge.

gamma-irradiation. The hygienized sludge is sprayed with a consortium of beneficial bacteria (Bio-NPK) to make it enriched organic manure.

Based on this technology, the first technology demonstration plant of capacity of ~100 tonnes/day has been designed, constructed and commissioned under an MoU between Ahmedabad Municipal Corporation and BARC. With a cobalt-60 source strength of 300 kCi, the facility is operational since January 2019. A second such plant is coming up at Indore under an MoU with Indore Municipal Corporation. Figure 17 shows the process of hygienization of dry sewage sludge[28].

Colouration of diamonds and precious stones: High-energy radiation is able to penetrate hard matrices like diamond, and create defects and impart/enhance colour depending on the trace element trapped in the diamond. The diamond irradiation services have been provided successfully on a commercial basis for the last two decades[13].

Conclusion

Radioisotope techniques are well established and widely used for troubleshooting and process monitoring in Indian industry leading to significant economic benefits. The applications will continue to expand following substantial developments in supporting technologies and meet the growing needs of the Indian industry. It is generally realized that the level of application of radioisotope techniques in the industry is presently confined to only a few well-informed industries. It is thus essential to explore and plan for a much wider application of these unique techniques to help the Indian industry.

Radiation processing is a clean, reliable, reproducible and easy to upscale technology which enriches the quality of human life in many ways. It finds a spectrum of industrial applications. It is expected that the unique characteristic of high-energy radiation to deposit energy to initiate chemical reactions in any matrix without any significant rise in temperature would be exploited for many more industrial applications in near future. Presently, there are 24 gamma irradiator plants and 18 EB machines operating in India for various radiation processing applications on a commercial basis. These numbers are expected to increase significantly in near future.

---

1. Charlton, J. S., *Radioisotope Tracer Techniques for Problem Solving in Industrial Plants*, Leonard Hill, Glasgow and London, UK, 1986.
2. IAEA, *Guide Book on Radioisotope Tracers in Industry*, Technical Report Series No. 316, International Atomic Energy Agency, Vienna, Austria, 1990, p. 374.
3. Pant, H. J., Applications of the radiotracers in the industry: a review. *Appl. Radiat. Isot.*, 2021; https://doi.org/10.1016/j.apradiso.2021.110076.
4. Pant, H. J., Goswami, S., Biswal, J., Samantaray, J. S. and Sharma, V. K., Radiotracer investigation in a glass production unit. *Appl. Radiat. Isot*., 2016, **116**, 41–50.
5. Sharma, V. K., Pant, H. J., Goswami, S. and Bhar, K. K., Radiotracer investigations in Kolkata Port Trust, India for evaluation of dumping sites for dredged sediments. *Appl. Radiat. Isot*., 2021, **168**, 109524.
6. Raj, B. and Venkataraman, B., *Practical Radiography*, Alpha Science Int Ltd, Narosa Publishing House, New Delhi, 2004.
7. Kak, A. C., Slaney, M. and Wang, Ge, Principles of Computerized Tomographic Imaging, 2002, p. 107.
8. Johansen, G. A. and Jackson, P. (eds), *Radioisotope Gauges for Industrial Process Measurements*, John Wiley, 2004, p. 331.
9. Pant, H. J. and Sen, A., Applications of nucleonic gauges in industry. In *Non-Power Applications of Nuclear Technologies* (eds Tyagi, A. K. and Mohanty, A. K.), SIRD, BARC, pp. 153–164; ISBN: 978-81-954733-2-8.
10. Makuuchi, K. and Cheng, S., In *Radiation Processing of Polymer Materials and its Industrial Applications*, John Wiley, New Jersey, USA, 2012.
11. Madhusoodanan, P., ISOMED – the success story of three decades. *Nuclear India*, 2004, **37**(7–8), 2–5.
12. Vijayabaskar, V., Tikku, V. K. and Bhowmick, A. K., Electron beam modification and crosslinking: influence of nitrile and carboxyl contents and level of unsaturation on structure and properties of nitrile rubber. *Radiat. Phys. Chem*., 2006, **75**, 779–792.
13. Sarma, K. S. S., Rawat, K. P., Benny, P. G. and Khader, S. A., Developments in electron beam processing technology. *BARC Newsl.*, 2011, 323, pp. 38–41.
14. Sarma, K. S. S., A report on the industrial applications carried out since 2001 using ILU-type electron beam accelerator at BRIT-BARC Vashi Complex, Navi Mumbai. *BRIT Bull.*, 2015, pp. 45–52.
15. Varshney, L., Role of natural polysaccharides in radiation formation of PVA–hydrogel wound dressing. *Nucl. Instrum. Methods B*, 2007, **255**(2), 343–349.
16. Dubey, K. A., Bhardwaj, Y. K., Chaudhari, C. V., Virendra Kumar and Sabharwal, S., Evidences of solvent-induced miscibility in polychloroprene-co-ethylene-propene diene terpolymer blends. *J. Appl. Polym. Sci.*, 2009, **111**(4), 1884–1891.
17. Basak, G. C., Bandyopadhyay, A., Bhardwaj, Y. K., Sabharwal, S. and Bhowmick, A. K., Characterization of EPDM vulcanizates modified with gamma irradiation and trichloroisocyanuric acid and their adhesion behavior with natural rubber. *J. Adhes*., 2010, **86**, 306–334.
18. Dubey, K. A., Bhardwaj, Y. K., Chaudhari, C. V., Sarma, K. S. S., Goel, N. G. and Sabharwal, S., Electron beam processing of LDPE/EVA/PCR ternary blends: radiation sensitivity evaluation and physico-mechanical characterization. *J. Polym. Res*., 2011, **18**, 95–103.
19. Chatterjee, T., Wiessner, S., Bhardwaj, Y. K. and Naskar, K., Exploring heat induced shape memory behaviour of alpha olefinic blends having dual network structure. *Mater. Sci. Eng. B*, 2019, **240**, 75–84.
20. Suman, S. K. *et al.*, Development of highly radiopaque flexible polymer composites for X-ray imaging applications and copolymer architecture–morphology–property correlations. *Eur. Polym. J.*, 2017, **95**, 41–55.
21. Suman, S. K., Kadam, R. M., Mondal, R. K., Murali, S., Dubey, K. A., Bhardwaj, Y. K. and Natarajan, V., Melt-compounded composites of ethylene vinyl acetate with magnesium sulfate as flexible EPR dosimeters: mechanical properties, manufacturing process feasibility and dosimetric characteristics. *Appl. Radiat. Isot.*, 2017, **121**, 82–86.
22. Mondal, R. K., Dubey, K. A., Bhanu Prakash, S., Jitendra Kumar, Melo, J. S. and Bhardwaj, Y. K., Copolymer composition tailored carbon nanotube network breakdown and piezoresistivity of ethylene–vinyl acetate electroconductive composites. *Mater. Sci. Eng. B*, 2021, **270**, 115194–115215.
23. Dubey, K. A. *et al.*, Synthesis of flexible polymeric shielding materials for soft gamma rays: physicomechanical and attenuation characteristics of radiation crosslinked polydimethylsiloxane/Bi_2O_3 composites. *Polym. Compos*., 2016, **37**, 756–762.
24. Dubey, K. A., Mondal, R. K., Jitendra Kumar, Melo, J. S. and Bhardwaj, Y. K., Enhanced electromechanics of morphology-immobilized co-continuous polymer blend/carbon nanotube high-range piezoresistive sensor. *Chem. Eng. J.*, 2020, **389**, 124112–127200.
25. Chaudhari, C. V., Guin, J. P., Dubey, K. A., Bhardwaj, Y. K. and Varsheny, L., Radiation induced grafting of glycidyl methacrylate on teflon scrap for synthesis of dual type adsorbent: process parameter standardization. *Environ. Prog. Sustain. Energ.*, 2016, **35**(3), 1367–1373.
26. Misra, N., Rawat, S., Goel, N. K., Shelkar, S. A. and Virendra Kumar, Radiation grafted cellulose fabric as reusable anionic adsorbent: a novel strategy for potential large-scale dye wastewater remediation. *Carbohyd. Polym*., 2020, **249**, 116902–116910.
27. Chowdhury, S. R., Jha, A. and Sarma, K. S. S., Multifunctional superabsorbent cotton and process for preparation thereof. Patent No. 353741, Bhabha Atomic Research Centre, Mumbai, 2020.
28. Naresh Kumar, Bhardwaj, Y. K. and Pujari, P. K., In *Non-Power Applications of Nuclear Technologies* (eds Tyagi, A. K. and Mohanty, A. K.), SIRD, BARC, pp. 105–112, ISBN: 978-81-954733-2-8.

doi: 10.18520/cs/v123/i3/377-387