Radioisotope and Radiation Technology

A. Introduction

1. A large variety of nuclear techniques are available for industrial, environmental, medical and research applications. Radiation and isotopic technology, such as gamma irradiation, electron beam or ion beam, as well as nucleonic gauges, radiotracers and sealed sources, non-destructive testing and nuclear analytical techniques are used for process control, material modifications, to reduce harmful industrial emissions, to reprocess waste streams and for sterilization of medical products and wastewater treatment. Non-destructive evaluation of welds, castings, assembled machinery and ceramics help to make industrial processes safer and more cost-effective. Radiotracers, sealed sources and nucleonic gauges are used for natural resource exploration in the oil industry, in mineral processing and waste water treatment plants. The application of these nuclear techniques has considerable economic and environmental impact as they are introduced in developing countries.

B. Radioisotopes

2. Radioisotopes make important contributions in several sectors of economic significance including medicine, food processing, industry, agriculture, structural safety and research. They are generally produced in research reactors or cyclotrons. More than 150 different radioisotopes in different forms are in use for various applications.

3. It has been observed that the consumption of isotopes in a country depends on the level of its economic development and industrialization: the more advanced, the more the consumption. However, the pattern of use is similar in all countries. The medical field accounts for the majority of the applications, followed by industry and research. The potential for expansion of radioisotope applications is, however, very large.

B.1. Current Status of Radioisotope Production

B.1.1. Radioisotopes for medicine

4. Radioisotopes in medicine are used either in liquid form, called radiopharmaceuticals, for diagnosis and therapy or as a solid sealed source for therapy, mainly for cancer. Radioisotopes also find extensive applications in *in vitro* diagnosis, the most important being in immunoassays.

5. Radiopharmaceuticals are used mainly for diagnostic imaging studies. However, therapeutic applications have shown a substantial growth in the last few years. The radioisotope ^{99m}Tc is used in more than 70% of the diagnostic imaging studies for assessing the dynamic functions of the various organs of the body as well as for the localization of infections. About 20% of medical applications use radioisotopes such as ^{201}Tl, ^{111}In, ^{67}Ga, ^{123}I, ^{81m}Kr, ^{131}I and ^{133}Xe. The use of the cyclotron-produced long-lived isotope 201Tl for cardiac studies is also widespread.

6. The use of radioisotopes for Positron Emission Tomography (PET) studies is showing a faster growth rate. ^{18}F-fluoro deoxy glucose (^{18}FDG) accounts for more than 90% of PET imaging with the

remaining 10% being accounted for by ^{11}C, ^{13}N and ^{15}O based radiopharmaceuticals. Interest in setting up medical cyclotrons and PET facilities has grown in many developing countries in recent years.

7. Radiopharmaceuticals based on ^{131}I have a primary role in the treatment of hyperthyroidism and thyroid cancer. The treatments of certain other cancers, arthritis and palliation of bone pain due to secondary cancer using radioisotopes show a substantial growth. ^{131}I, ^{32}P, ^{153}Sm, ^{90}Y and ^{186}Re are the major isotopes used in therapy. The annual turnover in this area is more than $30 million and is growing at the rate of 10% per annum.

8. Radioactive sealed sources are widely used for teletherapy and brachytherapy of cancer. About 1500 teletherapy machines using the radioisotope ^{60}Co are estimated to be in use worldwide. The main radioisotopes used in brachytherapy are ^{192}Ir, ^{137}Cs, ^{125}I, ^{198}Au, ^{106}Ru and ^{103}Pd. About 3000 brachytherapy centres are estimated to be in operation worldwide. High dose rate sources using ^{192}Ir are becoming increasingly popular. These use high specific activity ^{192}Ir sources, which are encapsulated by precision technology using advanced laser welding machines. The implantation of tiny sources of ^{125}I for ocular and prostate cancer is also being tried. The treatment of prostate cancer using ^{103}Pd has become very successful. The production of these sources requires remote fabrication including encapsulation by remote welding procedures.

B.1.2. Radioisotopes for industry

9. Radioisotopes are used for nucleonic control systems, radiation processing, non-destructive testing (NDT) and in radiotracer studies. Sealed sources of ^{137}Cs, ^{60}Co, ^{241}Am, ^{85}Kr, ^{147}Pm, $^{90}Sr/^{90}Y$, ^{204}Tl, ^{252}Cf, ^{63}Ni, ^{55}Fe, ^{109}Cd, ^{57}Co and ^{241}Am-Be neutron source are used in nucleonic control systems. ^{60}Co in the form of high intensity sources is the main isotope used for radiation processing. ^{192}Ir sources are used in more than 90% of gamma radiography devices. ^{169}Yb and ^{75}Se sources are other radioisotopes used in NDT. A large number of isotopes in various chemical forms are used as tracers in industry.

B.2. Future Trends

10. Radioisotopes will continue to play an important role in national development. With many techniques having an important bearing on either industrial activity or health care, the sustainability of radioisotope supply or “isotope security” continues to be a major cause of concern in view of the decrease in the number of operating research reactors worldwide and the difficulties in transporting radioisotopes worldwide because of security concerns.

11. The radionuclides in demand in regular medical diagnosis will continue to be ^{99m}Tc, ^{131}I, ^{201}Tl, ^{111}In, ^{123}I and ^{18}F. A substantial part of the use of ^{201}Tl for cardiac studies is likely to be carried out with ^{99m}Tc radiopharmaceuticals because of cost advantage and ready availability. The use of ^{99m}Tc generators, the technology of which is well standardized, is expected to increase significantly due to the establishment of an increased number of nuclear medicine centres in both developing and developed countries. Cold kits for the formulation of ^{99m}Tc radiopharmaceuticals for different imaging studies will be expanded, and new ^{99m}Tc radiopharmaceuticals based on peptides and other bio-molecules will be added.

12. The use of ^{18}FDG will increase because of better refined chemistry, starting from the production of the radioisotope through to the preparation of the radiopharmaceuticals and final quality assurance before product delivery. With ready availability of ^{18}F in several centres, further research and development of ^{18}F labelled molecules for various applications is expected to increase. Long-lived PET tracers i.e. ^{124}I and ^{76}Br are under development for studying slow processes such as monitoring gene therapy. ^{123}I production via ^{123}Xe gas target would become more widespread and economical, and

may emerge as another widely used diagnostic isotope. ^{68}Ge-^{68}Ga generators are likely to see an increase in demand for use in PET where cyclotrons are not available.

13. Centralized production and distribution of ^{99m}Tc radiopharmaceuticals and ^{18}FDG are expected to evolve from current, predominantly hospital-based production because of increased regulatory concerns and good manufacturing practice requirements. Even though ^{99}Mo production might continue to be dominated by two or three large producers, widespread use of ^{99m}Tc coupled with the logistics of supplies and the reluctance of airlines to carry radioactive material could generate a need for many small-scale producers of fission ^{99}Mo serving regional needs.

14. There will be considerable interest in therapy using radiopharmaceuticals, and the range of isotopes and their products in regular use are expected to expand significantly. Refined technologies for both ^{90}Y and ^{188}Re generators will be available. Because of the similarity in the chemistry of ^{99m}Tc and ^{188}Re, research is being vigorously pursued into the development of new radiopharmaceuticals, based on peptides, and into other target specific biomolecules labelled with them, for diagnosis followed by therapy. The availability of ^{188}Re in sufficient quantities will be a major problem due to the limited availability of high flux reactors for its production.

15. The use of ^{90}Y radiopharmaceuticals for the treatment of cancer has shown a considerable increase. The use of ^{90}Y is advantageous because the parent radionuclide ^{90}Sr is available in large quantities from nuclear waste in fuel reprocessing programmes. The recovery of ^{90}Sr followed by large-scale centralized separation of ^{90}Y or preparation of ready-to-use radionuclide generators could become a major radiochemistry programme in other countries that have fuel reprocessing facilities. Several ^{90}Y based radiopharmaceuticals for cancer therapy and treatment of arthritis are at present in the clinical trial stage but their widespread application in the near future is envisaged.

16. The use of many beta particle emitting isotopes, including ^{177}Lu, ^{166}Ho, ^{153}Sm, ^{165}Dy and ^{186}Re, for therapy could increase by taking advantage of local reactor production. ^{177}Lu offers a particular advantage, as this isotope can be prepared with very high specific activity and in large quantities, even in reactors having moderate flux. The near future could see large-scale deployment of ^{177}Lu in cancer therapy. ^{124}I and ^{103}Pd from cyclotrons will also be increasingly used for therapy. ^{125}I and ^{103}Pd seed production technology for brachytherapy applications will be in demand in many countries.

C. Radiation Technology for Clean and Safe Industry

C.1. Radiation Processing

17. As well as economic factors, radiation and radioisotope applications have great impact on different aspects of social and industrial development, for example:

- Human health (radiation sterilization of medical products, blood and transplanting grafts irradiation);
- Environment protection (electron beam flue gas and wastewater treatment, gamma rays sludge hygienization);
- Clean and safe industry (radiotracer leakage testing and Non Destructive Testing (NDT) of installations, pipes, tanks);
- Quality system enhancement (nuclear analytical techniques, NDT);
- Process optimization (radiotracers and Nucleonic Control Systems);

- Raw materials exploration and exploitation (on-line processing, borehole logging); and
- Homeland security (cargo inspections, governmental mail irradiation).

18. Radiation and radioisotope applications make a large contribution to economies. The economical scale of industrial applications of radiation and isotopes in the USA and Japan, based on earlier studies, is given in Table 1.

TABLE 1

ITEM	**ECONOMIC SCALE (billions$)**	
	USA	JAPAN
1. Sterilized medical supplies	4.8	2.3
2. Semiconductors	37.2	28.4
3. Radiographic testing (NDT)	0.65	0.26
4. Radiation cured radial tyres	13.5	8.4
Total	56.15	39.36

19. The number of industrial gamma irradiators, working on a service basis or installed on-line worldwide exceeds 160, of which 65 units are operational in developing countries. More than 20% of these gamma irradiators have activities over 1 MCi of ^{60}Co.

20. The total number of electron beam accelerators installed exceeds 13 000, with close to 1200 units being used for radiation processing. New environmental applications demand the development of high power, reliable accelerators. The most powerful radiation processing facility, applying electron accelerators over 1 MW total power, has been constructed for power-plant-emitted flue-gases purification in Poland.

21. The concept of electron beam to X-ray conversion is a new technological approach for constructing powerful X-ray machines, with R&D under way in some pilot units. A breakthrough in the technology is expected after work on a high energy unit (up to 700 kW), which is already under test in Belgium.

22. Chemical or material engineering mostly applies high temperature and/or high pressure processes for material synthesis/modification. Often a catalyst is required to speed up the reaction. Radiation, however, is a unique source of energy that can initiate chemical reactions at any temperature, including ambient, under any pressure and in any phase (gas, liquid or solid) without use of catalysts.

23. Polymers are often irradiated, either for modification or as components of radiation sterilized medical products. Therefore, changes in their structure may be beneficial or undesirable. Polymer R&D is broad and most developments are foreseen in this area.

24. Another possible application is the processing of natural polymers. Cellulose materials for the pharmaceutical and cosmetics industry have already been fabricated.

25. Radiation sterilization is a well-established technique, and multi-technique services employing radiation and heat have emerged recently. A new application of these techniques is decontamination of mail against biological contaminants, such as anthrax.

26. Some radiation processes have promising applications for environment conservation. The plant for liquid sludge hygienization using a ^{60}Co gamma source has been in operation in India since 1991.

27. A pilot plant for dye factory wastewater treatment equipped with an electron accelerator has been constructed in South Korea, and an industrial project aiming to treat 10 000 cubic meters of effluent per day is in progress.

28. Electron beam flue gas treatment plants are operating in coal-fired plants in China and Poland purifying flue gases from 100 MW(e) units). High efficiency of SO_x and NO_x removal has been achieved with a by-product of high quality fertilizer. The other possible application of the technology is Volatile Organic Compound and Polycyclic Hydrocarbon treatment, e.g. in municipal waste incinerator plants and flue gas purification units. The advantage of this technology over conventional ones has been clearly demonstrated, both from a technical and economic point of view.

29. Conservation of archaeological artefacts and art objects by radiation (gamma rays or electron beam) appears to have prospects. Ongoing studies on the application of radiation for consolidation revealed that lacquer, textiles, paper, objects made of wood, stone and gypsum can be considered for conservation purposes.

C.2. Radiotracers and Sealed Source Applications

30. Radioisotopes (^{3}H, ^{82}Br, ^{99m}Tc, ^{140}La, ^{24}Na, ^{131}I) are applied as radiotracers in industry and the environment. Oil fields and refineries, chemical and metallurgical industries and wastewater purification installations are the particular users.

31. Radioisotope techniques (radiotracers, gamma scanning, tomography and single particle tracking) are extensively used to identify and quantify multiphase reactors (phase hold-up distributions, velocity and mixing patterns). Multiphase reactor technology is the basis for petroleum refining, synthesis gas conversion to fuels and chemicals, bulk commodity chemicals production, manufacture of special chemicals and polymers, and the conversion of undesired products into recyclable materials. Quantification of the reactor performance requires a description of: (i) kinetics on a molecular scale; (ii) the effect of transport on kinetics on a single eddy or single catalyst particle scale; and (iii) the phase distribution, flow pattern and mixing in the reactor on the reactor scale. It is critical to understand and predict at what rates each reactant can be supplied to the micro scale and how changes in reactor size or operating conditions affect these rates of supply. While progress has been made in understanding fundamental reaction mechanisms and in computing from first principles the effect of mass transfer on the reaction rate locally, the description of the reactor scale flow pattern and mixing is in general primitive and rests on the assumption of ideal flow patterns. Radioisotope techniques help optimizing multiphase reactors saving hundreds of million of US dollars annually worldwide.

32. Information gained from interwell use of tracers in oil fields is indispensable for the evaluation and optimization of oil field performance. It is possible to make qualitative or semi-quantitative evaluations, as was the case of a reservoir in Colombia, which is naturally heavily compartmentalized. Information about fluid flow across faults, and therefore the effect of water injection could only be studied by the use of tracers. Several wells were uniquely labelled, and the exercise showed that there was an unexpectedly good communication across a fault that originally was a suspected barrier.

D. Nuclear Analytical Techniques

33. Nuclear analytical techniques play an important role in the certification of element content in a variety of materials. Particularly in international trade, for example in food, legal limits have to be observed and analytical results need to be based on mutual recognition, which is obtained if laboratories work according to internationally accepted quality standards such as the ISO 17025. National accreditation following the installation of a concise quality system assures nuclear analytical laboratories' superior performance compared to conventional analysis.

34. New trends in nuclear applications can be seen in the development of robust, automated and portable instruments, which can be used under laboratory as well as under field conditions. Flexible X-Ray fluorescence instruments have been used for non-destructive analysis of art objects. Portable neutron sources of variable strength are developed for field applications of prompt gamma neutron activation analysis enabling fast and non-destructive element screening of, e.g., unknown packages suspected of illicit trafficking of nuclear materials. There are different nuclear analytical techniques applied for package inspection depending on the size and content of the packages. Dual energy X-ray absorption analysers are most familiar in their use as on-line security devices screening baggage at airports.

35. Long lived radionuclides and stable isotopes are increasingly used to study metabolic effects of essential and toxic elements in plants, animals and the human body. Monte Carlo simulations of neutrons and gamma rays enable the design of new irradiation and counting devices optimized for a particular application.

36. Nuclear techniques also serve in preserving human cultural heritage. Neutron Activation Analysis is very sensitive multi-elemental analysis that allows identification of art objects. Coins and other metallic artefacts, stones, pottery and ceramics have all been subjected to trace element fingerprinting to distinguish originals from fakes. Neutron activation analysis has been successfully demonstrated as a technique to add valuable information to the interpretation of archaeological problems.

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