INDIAN ASSOCIATION OF NUCLEAR CHEMISTS
AND ALLIED SCIENTISTS

Industrial Applications of Radioisotopes

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Editorial

Serendipity, sharp judgment and investigative spirit were the key factors for the success of genii like Roentgen, Becqurel, Curies, Rutherford, Hevesy and many more pioneers who contributed to the understanding and development of nuclear sciences. They succeeded in demanding and at times, adverse situations. George de Hevesy, the father of isotope applications could not separate RaD (^{210}Pb) from lead. Being a genius, he concluded that RaD could be used to label lead and utilized it as an indicator in some interesting experiments. Thus the applications of radioisotopes began in 1913. Discoveries of neutron, artificial radioactivity, demonstration of nuclear chain reaction and construction of accelerators and reactors paved the way for production of a large number of radioisotopes. Radioisotopes are used in a myriad of ways for the benefit of mankind. One of the major areas is Industrial applications. This thematic bulletin on "Industrial Applications of Radioisotopes" is aimed at reviewing the status and presenting a gist of the Indian contribution to this area. IANCAS is fortunate to have an expert like Shri Gursharan Singh, Head, Isotope Applications Division, BARC as the Guest Editor. He has chosen meticulously topics and authors and I thank him for his efforts. My special thanks are due to all authors for providing their articles and Dr. H.J. Pant for editorial assistance in bringing out this bulletin.

The highlight of this issue is a stimulating interview with Dr. Anil Kakodkar, Chairman, Atomic Energy Commission and Secretary, Govt. of India wherein he gave his views and ideas on the various facets of the Atomic Energy Programme, focus being the Applications of Radioisotopes. I am grateful to Dr. Anil Kakodkar for sparing his valuable time for the interview.

A.V.R. Reddy

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Radioisotope Sealed Source Applications in Industry

__Shri Gursharan Singh__ joined Bhabta Atomic Research Centre in 1973 through 16th batch of BARC training School. Since his joining, he is working in the field of industrial applications of radioisotopes. His field of expertise includes applications of sealed sources and tracer technology for industrial troubleshooting and process optimisation, non-destructive testing and hot cell operations. He has served as an IAEA expert in several countries and trained over 6000 persons in NDT. Shri Singh is presently heading Isotope Applications Division of BARC.

Introduction

The petroleum industry was one of the first to develop an interest in the use of large scale sources of radiation. The industry has utilized radioactive materials more than any other industry, and has developed and used a wide range of tracer applications. For example, radionuclides have been extensively used in a variety of ways in oil exploration and recovery operations, since they provide the only convenient means of locating and evaluating underground flow patterns. They have also been extensively used in above ground flow measurements which are important to the processing and pipeline transportation of petroleum crudes and refined products. The oil industry also uses radionuclides in wear studies to determine the lubricating properties of various petroleum products.

Radiographic techniques are used in inspecting petroleum and gas pipeline welding, and this one application alone has been the basis for the founding of a number of service companies. The petroleum industry has also made use of radioactive gauges, primarily the density and liquid level type.

In oil well logging in a borehole, characteristics of rock formations can be automatically recorded by traversing a radioactive materials measurement device. This procedure permits the measurement of density, porosity and chemical elements, and establishment of the lithology. Hydrogen containing strata, when water or oil are present, can be identified by the strong absorption of neutrons. Information on the minerals surrounding a borehole may be obtained by means of a logging method, where the lowered source emits neutrons of various energies and the detector registers the radiation emitted in nuclear reactions as well as from inelastic neutron scattering in the surrounding material.

As a consequence of an early realisation of the importance of isotopes and radiation technology and production of radioisotopes in the research reactors from late fifties, India has today a fairly advanced base for applications of isotopes and radiation technology in medicine, industry and in agriculture. Board of Radiation and Isotope Technology (BRIT), Department of Atomic Energy supplies radioisotopes and radiation equipment. The Bhabha Atomic Research Centre, Mumbai offers professional service to meet the country's demand in various fields of applications and undertakes R&D programmes for advanced applications.

Radioisotopes, as sealed sources of ionising radiation and as tracers supplement each other. An important feature of their application is their unique ability in investigating problems, without disrupting the process. In particular, shutdown times could be avoided or reduced to minimum. Thus these applications have proved to be the most useful in terms of economic benefits, realized either due to savings or improved production efficiency. Most of these applications do not have any competing alternatives.

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Sealed Source Applications

In sealed source applications, the radioactive radioisotope makes no contact either with the plant or the process material. Radiation from the source is directed at the item of interest and by analysing the modified (due to transmission or scattering) radiation pattern, it is possible to draw conclusions about the internals of the process vessel. Due to their greater penetrating power, gamma and neutron sources are most useful. The applications can broadly be divided into 4 categories;

- Industrial radiography / radiometry testing
- Industrial computed tomography
- Gamma scanning of industrial process columns
- Nucleonic control systems

Industrial Radiography / Radiometry Testing

Isotope radiography is one of the earliest applications of isotopes in industry and it has steadily grown as the isotope sources have many advantages over X-ray machines such as portability, freedom from electric power requirement and possibility of use of tiny isotope sources in otherwise inaccessible areas of an industrial system.

Conventional penetrating radiation based non-destructive testing methods use X and gamma ray sources as radiation sources with industrial X-ray film as detector. By choosing a variety of source - film combinations, varying degrees of flaw detection, in different materials can be achieved. However, the existing techniques have their inherent limitations in flaw detection sensitivity for examination of thicker and thinner sections of materials. Present techniques are suitable for examination of steel equivalent thickness between 15 - 175 mm. Testing of thick concrete and composite materials made up of concrete, lead and steel, high energy X-ray emitting sources like linear accelerators and betatrons are needed.

Recent trends in penetrating radiation based NDT techniques include;

- Applications of high energy radiation sources like linear accelerators and betatrons for examination of thick welded and cast steel structures, civil engineering concrete structures, rocket propellants, explosives and special materials.
- Use of microfocus X-ray systems for examination of thin sections for high resolution radiography and for geometric enlargement projection radiography.
- The newer trends in the use of flash X-ray systems for examination of dynamic systems in petrochemical industries, ballistics, detonation phenomenon, biomedical applications and nuclear technology.
- Use of new sources like ^{169}Yb, ^{75}Se and ^{241}Am for testing of thin sections of light metals and composites.
- Gamma ray scattering NDE techniques for inspection of assemblies with one side access.
- Applications of neutron sources for NDT of explosives, turbine blades, electronic devices, assemblies and their use in metallurgy and nuclear industry.
- Special radiography methods for inspection of radioactive objects and use of robotised X-ray systems.
- Use of instant cycle radiographic paper in place of X-ray film for recording of radiographic image for a few applications.

Flash Radiography

This is a unique radiography technique used to produce a single stop motion image or a series of sequential images of a high speed phenomenon.

- Milli second for vibration studies
- Micro second for ballistic or shock wave studies
- Sub-nano seconds for extremely short duration events like nuclear fuel pellet implosion.
- In real time event's motion should be slow ~30-60 frames/sec.

Applications

- X-ray imaging of process fluid dynamics for improved knowledge of flow patterns of solids, liquids or gases inside reactors or transfer pipes operating under realistic process conditions i.e. pressure upto 100 bar and temperature upto 1,000°C. This helps in improved plant design, process troubleshooting and optimisation.

- Ballistics for study of dynamic and flight characteristics of projectiles (μs)
- Detonation phenomenon (μs)
- Metal casting processed during test pouring of multiple cavity shell mould.
- Study of organ displacement under impact (e.g brain displacement under lateral head impact)
- Flash X-ray diffraction for materials under very high dynamic stress.

Industrial Computed Tomography

Although still only at an early stage of development, Industrial computed tomography (ICT) systems clearly represent a breakthrough in industrial radioisotope and radiation applications since they provide a range of cross-sectional views through materials, components and assemblies which would otherwise be opaque. CT imaging is an established technique in medical diagnostic radiology. Based on the same principle, but significantly different in operating parameters, a prototype Computed Industrial Tomography Imaging System (CITIS) has been indigenously developed using 7 curies of ^{137}Cs source in the BARC. The gamma-ray based prototype unit is capable of scanning specimens of small diameters (upto 100 mm) and of varying densities. It has wider applications in the fields of nuclear, space and allied fields. A modified, X-ray based industrial CT system with PIN photo diode detectors is presently being developed. Details are given in a separate article in this issue.

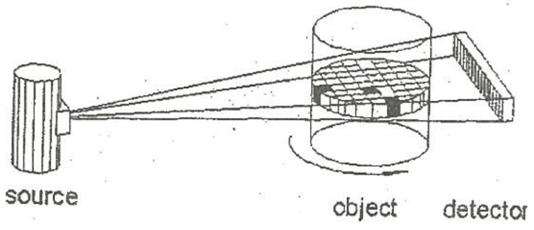


Fig. 1 Principle of 2D CT imaging with line detector.

Digital Industrial Radiography

The development of high resolution digitization system allows the electronic handling of radiographic films in Non-Destructive Testing. Film digitisation is useful to gather the high image quality of radiographic films (optical density range and spacial resolution) in the digital image. Digitisation yields several new possibilities for conventional radiographic testing; digital archiving, quantitative evaluation, image processing, automatic image evaluation, remote image transfer and production of reference catalogues for flaw evaluation.

Recent advances in X-ray detection technology has made available a number of fast, accurate and sensitive detectors that far exceed in performance and reliability. For online radiographic inspection systems, image intensifiers have long been used as the radiation detection medium. The limited dynamic range of such systems restricted their use in imaging dense objects. Among the latest detectors for on line radiographic imaging systems are linear diode arrays, high resolution two dimensional detector arrays and for a wide energy range, amorphous silicon flat panel detectors.

Gamma Scanning of Industrial Process Columns

In chemical, petro-chemical and petroleum refining industries, proper working of process columns such as distillation, extraction, stripper and others is very important as it affects the production efficiency and product quality. To determine why a column is not performing up to the desired design expectations is challenging. This is because many problems in the column can produce similar symptoms. The conventional techniques used to identify troubles in the column are;

- On-line tests like pressure drop, density and viscosity measurements.
- Simulation studies based on mathematical models and hydraulic correlations.

These studies are useful to identify the areas of problem but cannot pin point the exact location of the problem.

Gamma scanning is a non-invasive technique used frequently for troubleshooting of distillation columns. This technique is also employed for debottlenecking studies of processes involving multiphase systems. The technique is effective for predictive maintenance of column hardware. This technique uses absorption of gamma ray emitting from radioisotopes by process fluids consisting of vapour and liquid. The technique is gradually being used to solve more and more complex problems like maldistribution in packed bed and entrainment from tray columns. In the international scenario this technique is exploited on a routine basis and offered as specialised service. Gamma scanning technique has also emerged as a reliable research tool to generate valuable performance data.

BARC has developed this technique in collaboration with Engineers India Limited to a high degree of precision and adaptability. We have jointly carried out inspections of about 100 various types of columns in last 5 years, which were losing huge revenue per day due to production losses. Gamma scanning can provide information about the following column processes;

- Location and extent of flooding
- Presence or absence of trays and other internals
- Liquid level on trays and packed column liquid distributors
- Location and severity of entrainment
- Liquid level in down comers
- Presence of liquid weeping
- Location and density characteristics of foaming
- Position of packed beds.
- Integrity of mist eliminators.
- Liquid level in reboilers, reflux drums, etc.
- Extent of liquid maldistribution in packed beds.

Gamma scanning can also be utilised for column optimisation, extending run-time of the column, predictive maintenance and scheduling shutdown. Scanning results in conjunction with simulation studies can be used to diagnose most of the column troubles and improve the design of the columns. Gross abnormalities could be:

- Missing trays
- Collapsed trays
- Flooding of tray or down comers
- Collapsed packed bed

Malfunctions of the column could be due to:

- Entrainment from trays
- Weeping from trays
- Missing valves from valve tray
- Maloperation of liquid distribution

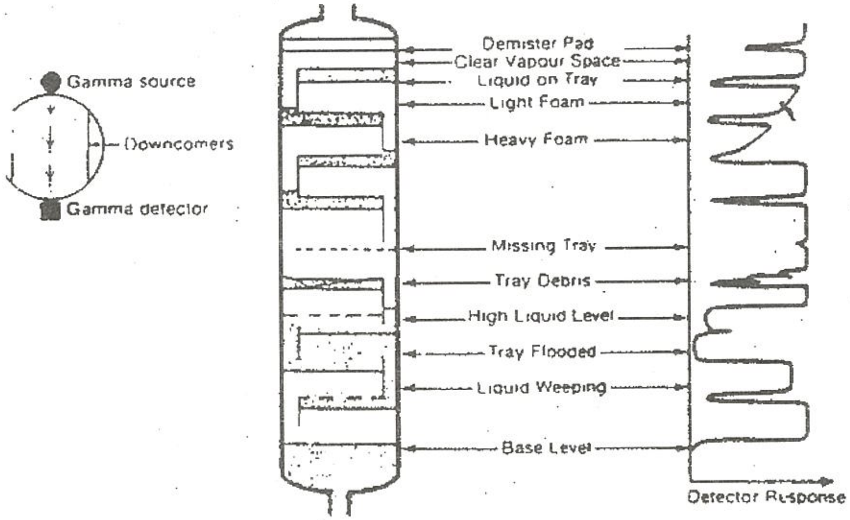


Fig. 2 Gamma scan of a tray type process column

- Maldistribution in packed bed.

A typical process column and its gamma scan is shown in Fig. 2. As an example of gamma scan showing the effect of addition of antifoaming agent to reduce foaming inside a column is shown here. Current trend is to have signature scan of columns operating satisfactorily. The idea is to generate a set of scan profile when the column is operating satisfactorily. During trouble-shooting additional scan could be taken and compared with signature scan.

Nucleonic Control Systems

As sealed sources, radioisotopes are used in a variety of equipment for different applications. A range of level gauges, alarms and density gauges are used worldwide in refineries, chemical plants, oil platforms and terminals, in mining and mineral extraction industries. There are about 5,000 nucleonic control systems in operation in India today. These systems are sub-divided into 2 classes;

- Based on radiation transmission through the object
- Based on radiation scattered from the specimen.

Applications based on Gamma Ray /Beta Ray Radiation Transmission

- As installed thickness gauges to measure thickness of deposits in pipes and vessels.
- Detection and measurement of corrosion.
- Detection of voids
- Level measurements
- Detection of water in hydrogen transmission line
- Detection of liquid interfaces.

Interface Measurements

In the sea, oil and gas are transported together by pipeline to onshore terminals. There, the gas is separated from the oil fractions and is recompressed for onwards distribution. In this process, fluctuations in the foam level occur unpredictably. These fluctuations cause carry over of oil droplets in the gas stream with serious consequences for the downstream compressor. Density profile measurements can be carried out using portable gamma ray scanning equipment and these can show the interface between the oil and the foam and variations in the density of the foam layer.

The variation in the foam height, foam density and position of the oil/ foam interface render conventional methods of control impossible. However, using a nucleonic proportional level gauge to measure the oil/foam interface and a high level nucleonic alarm to give warning of excessive upward excursions of the foam, it is possible to provide a system which eliminates the carryover problem and protects the gas compressor.

A typical density profile is shown in Fig. 3 to detect the interface in a pipe line.

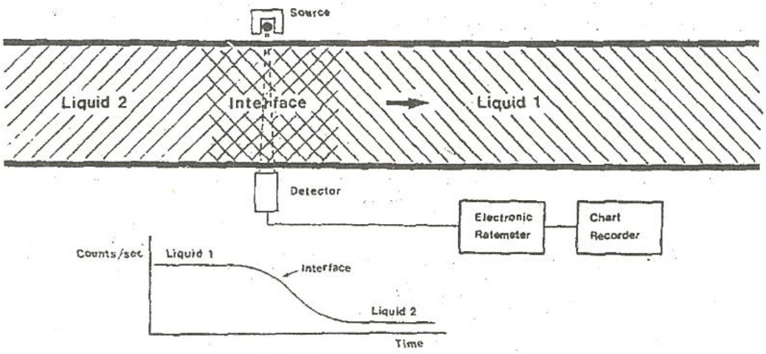


Fig. 3 Interface detection in a pipeline by density gauging.

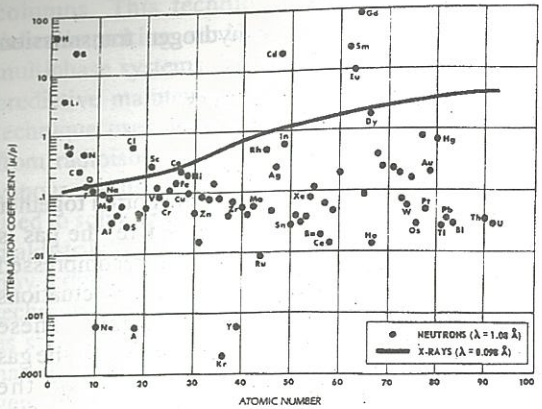


Fig. 4 Mass attenuation coefficient as a function of atomic number. ● For thermal neutron and ▬ for X-ray (125 kV).

Applications based on Gamma Ray /Beta Ray Radiation Scattering

These applications are generally used when either the size of the vessels is very large, or only one side is accessible for inspection. These techniques are useful for;

- Portable level gauges
- Viodage determination and thickness measurement.
- Well logging.
- XRF for elemental analysis.
- Analysis of mixers, based on beta ray back scatter

Techniques based on Neutron Sources

These applications are based upon neutron moderation, absorption and activation of the test samples. For most of the elements, the mass attenuation is distinct as it depends on cross-section that is isotopic. A comparison of mass attenuation coefficient for thermal neutrons and X-rays (125 kV) are given in Fig. 4. Neutron sources are used in portable gauges rather than in installed instruments. Apart from detecting the position of oil water interfaces, the neutron back scatter technique has been applied to;

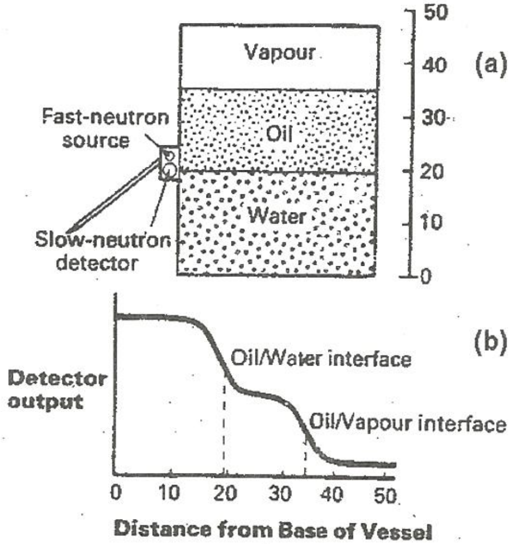


Fig. 5 Measurement of levels and interfeces using a neutron moderation technique.

(a) Locate a pig packer in pipelines prior to cutting the line to install emergency shut-down valves.

(b) To check for the presence of brine in oil pipelines.

(c) To identify water ingress into platform tubular members above the waterline.

Some other applications are;

- Neutron moisture gauge
- Level and interface measurement between process fluids in plant vessels.
- For elemental analysis.
- For detection of hydrogenous blockages in pipes
- For neutron radiography.

A detector assembly based on neutron moderation and density for locating the oil / vapour interface and oil / water interface is given in Fig. 5a. The correspondence between the interfaces and the actual distances is clearly brought out in the profile given in Fig. 5b.

Gap meter for Oil Storage Tanks

A unique technique for surveying the foundation shape of oil-storage tanks has been

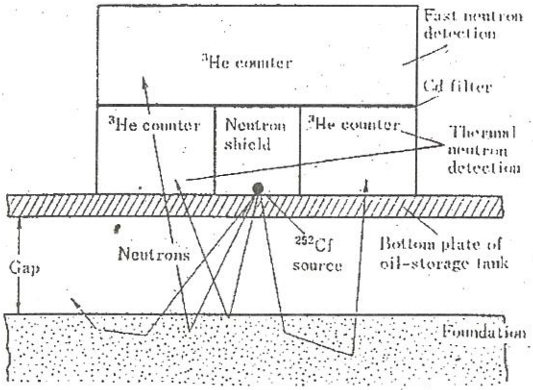


Fig. 6 Principle of gap measurement by neutron scattering.

developed in Japan. Since a number of oil storage tanks are placed on the soft ground near seashore, problems often occur for uneven sinking of the tank and repair of the foundation is made by material injection. Before and after the repair, it is necessary to find the gap, if any, over the whole area of the bottom plate. The technique utilizes back scattering of fast neutrons from ^{252}Cf source about 3.7 MBq. Measurement is made by placing the apparatus at predetermined positions on the bottom successively, at the time when the tank is made empty for various kinds of inspections. ^{3}He counters covered with cadmium filter and moderator are used to detect fast neutrons scattered from the foundation (Fig. 6). The count corresponds to the distance between the bottom plate and the foundation, namely the gap. The other ^{3}He counters without cadmium filter measure the quantity of water or oil existing at the gap, correcting the gap measured. By combining this gap measurement with ordinary surveying of the height above the sea of each measuring point, the abnormality in shape of the foundation can be found. A typical contour diagram obtained by this technique is shown in Fig. 7a and the gap formation is reflected in the dip as shown in Fig. 7b. The gap measuring technique has been applied to a large number of oil-storage tanks for more than 20 years, and the periodical measurement at the time of legal inspection is being continued up to now.

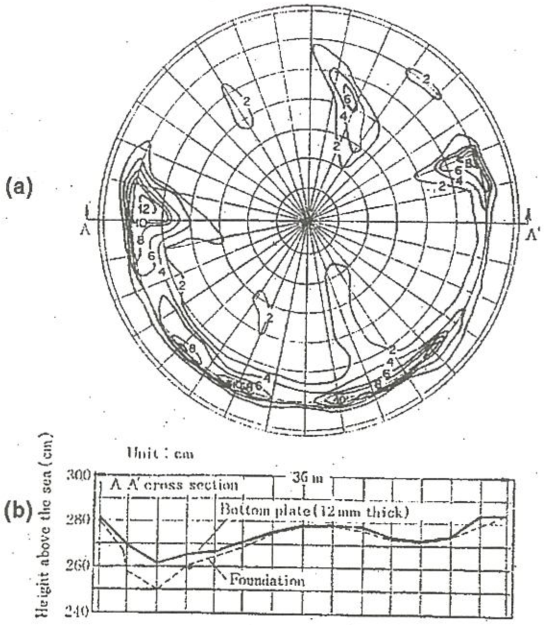


Fig. 7 Contour diagram obtained by gap measurement technique in oil storage tank.

Deposits in Onshore and Topsides Vessels/Pipelines

The gamma ray absorption technique is used to determine the extent and magnitude of scale build up in oil pipelines. A portable system is used to survey sections of the line to determine the overall density of the material inside it. Provided that the line is running full (or completely empty) and the oil density is known, the additional attenuation of the transmitted radiation due to scale thickness may be estimated. Scale thickness can generally be measured to within a few millimeters.

Lines which contain deposits and partially full of oil or water can sometimes be studied using the gamma ray absorption technique in combination with neutron back scatter technique. The neutron back scatter technique is used to determine the level of the hydrogenous liquid and from this information, together with the results of a number of diametric gamma ray transmission scans made around the

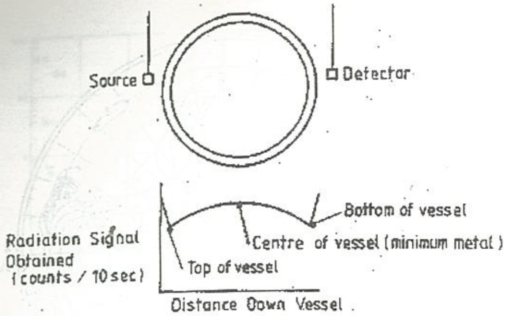


Fig. 8 *Gamma ray scans of separations: through an empty horizontal vessel.*

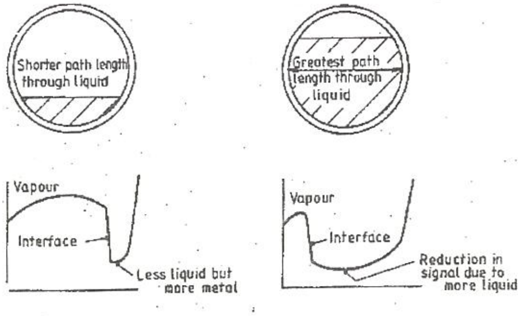


Fig. 9 *Gamma ray scans of separations: through an partially filled horizontal vessel.*

pipe, the radial distribution of the deposits could be inferred.

Study of Foaming

The gamma ray absorption technique is also used to study foaming in separators. Foaming is generally combated by the addition of an antifoaming agent. However, antifoams are expensive; the correct anti foam must be selected and it must be used at the correct concentration. The gamma ray absorption technique provides a means of directly studying the effect of antifoam addition. The principle of the measurement is illustrated in Figs. 8 and 9 which show typical results obtained from scans on horizontal vessels. The presence of foam above the liquid level modifies the transmission profile. By studying the effects of the antifoam directly and without any disruption to the process is clearly advantageous and can result in significant economic benefits by reducing antifoam usage and optimizing the operation of the separator.

Sub-Sea Applications

The technology is also used below the sea with the design of the equipment is modified in a manner appropriate to the marine environment. A portable gamma ray absorption gauge, mounted on a Remotely Operated Vehicle (ROV) is used routinely to examine sub- sea structures to detect flooded members. The source and detector, mounted on a yoke, are positioned on either side of the tubular using the ROV. The signal from the detector is fed to the surface to an electronic system, which records the level of transmitted radiation. Water inside the sub-sea section will result in a decrease in the transmitted signal, which is identifiable. The measurement is rapid (less than two minutes) and requires no prior cleaning of the tubular. It is unambiguous and fail- safe. Any failure of the equipment will indicate that the member is flooded. The ROV is controlled from topsides; no divers are required and measurements can be carried out for extended periods. For these reasons, this is becoming the standard method of inspecting the platform tubulars in the North Sea.

Under Water Pig Detection

Recently developed “Gammatrac” system for monitoring the progress of pigs through sub- sea pipelines is another application. A gamma-emitting radioisotope is fitted into a pocket in the pig on the launch platform and the pig is launched. As the pig passes each detector station, the LED display turns from white to red. Visual inspection of the detector by a diver confirms that the pig has passed down the line. Should the pig become stuck, the section of line in which this has occurred, can be identified. Thus by strategically deploying the detectors, the free movement of the pig through critical sections of line such as through newly installed valves can be checked. Further development is in progress.

New Developments in on-line Measurements

Radioisotope instrumentation maintain a lead role in the paper, plastics and steel industries; and for density gauges particularly in the chemical and mineral processing industries, due to the use of new materials, the introduction of highly stable solid state electronics and fast data processing. Ionization chambers which were air-filled at near atmospheric pressure and included a single collector electrode were relatively insensitive and had only poor temperature stability. Currently available ionization chamber includes a titanium window so that the gas volume is virtually invariant. Also present day ionization chambers are normally filled with argon or krypton at 5 to 7 bar pressure and this results in a significantly higher current gain and allows sources of smaller activity to be used whilst still achieving a higher overall sensitivity. In 1960, a typical source would be 200 mCi ^{204}Tl ($E_{bmax} = 0.77$ MeV, $t_{1/2} = 3.9$y) which is now replaced by a 50 mCi ^{85}Kr source ($E_{bmax} = 0.67$ MeV, $t_{1/2} = 10.6$y). The result is that ionization currents have typically increased from $\cong 10^{-12}$ A to between 10^{-9} and 10^{-8} A with almost no leakage current. The intrinsic response time of the ionization chamber is 10^{-2} ms and the external time constant of the system is between about 50 and 200 ms. Apart from a significant improvement in the stability of the ionization chamber, the temperature stability of the chamber load resistor is good and temperature control of this component is no longer required.

Another significant changes in recent years is the introduction of on-line data processing and display. A large amount of operational information can now be collected and displayed on demand. Included in these data are lateral profiles of thickness variations, longitudinal variations, short term trends and overall averages. The gauge is the heart of the automatic system controlling the speed of the product line and the inclination of the rollers, which can be adjusted automatically. Typically, variations in both directions can be held to within 0.3 mm.

In addition to on-line control equipment for sheet material, the steel industry also uses various other types of radioisotope systems. The measurement of the moisture content of coke supplied to blast furnaces is made in order to control the proportions of coke and iron fed to the furnace and the monitoring of coke breeze is carried out in iron ore sinter plants. The preferred method uses a combination of fast-neutron and γ ray transmission techniques.

Coal and Mineral Industries

The coal and mineral industries all around the world have been undergoing profound changes in recent years with the introduction of new technology to meet economic, environmental and governmental demands to improve production efficiency, reduce waste and environmental degradation, and conserve natural resources. Analysing, sensing and measuring instruments based on nuclear radiation techniques have formed a significant part of the new technology to meet these demands. These instruments assist in process control, optimisation and automation in coal and mineral processing plants for the efficient and economic production of materials of a predetermined quality.

Iron Ore Analysis

Development of on-stream analysis techniques and instruments for the iron ore industry mainly as a result of the demand from large iron ore mining companies which export high grade iron ore at tight tolerance. The most successful of these on-stream analysers have been the pair production analyser for monitoring the iron content and the natural gamma analyser for monitoring the alumina, manganese and potassium contents of the ore.

Pair Production analyser

The pair production analyser is one of the most accurate on-stream iron ore analyser commercially available at present. As in the case of coal, high-grade iron ore can be regarded as a binary type material composed of Fe, a high-Z element in a low-Z matrix of silicon, alumina, oxygen, etc. Consequently, the intensity of the 511 keV gamma radiation is determined by the iron content. However, problems can arise if significant concentrations of other high atomic number elements such as manganese are present. The iron content of the ore is determined by combining the intensities of the 511 keV gamma rays and the Compton scattered gamma rays. The main components of the analyser assembly are a 3.9 GBq ^{226}Ra gamma-ray source and a 150x100 mm NaI(Tl) gamma-ray detector in a lead housing. Signals from the gamma-ray detector are fed into a multichannel analyser equipped with a microprocessor which analyses the gamma-ray spectrum and calculates the iron content using a calibration equation derived from measurements of ore samples of known Fe contents.

Extensive field trials in Australian iron ore mines have shown that the analyser can monitor the Fe content of ores with an accuracy of better than 0.5% Fe. However, the depth of ore on the conveyor belt must exceed 10 cm and the gap between the analyser and the conveyor belt must be minimised to achieve this accuracy. Variations in the free moisture content of the ore also affect the accuracy, e.g. 1 wt% change in moisture resulting in an error of about 0.7% Fe in the predicted iron content. Consequently, an instrument to measure the free moisture content of the ore is required to correct for moisture variation if high accuracy is required.

Natural Gamma-Ray Iron Ore analyser

The minor constituents in iron ores cause a range of quality control problems. In some mines alumina is the problem element to control, while in others silica, manganese or potassium may be the major problem. Gamma-ray activity due to the presence of naturally radioactive elements in iron ore can be used as a reliable means to monitor alumina, manganese and potassium content. The naturally radioactive elements, as in the case of coal, are uranium and thorium, together with their daughter products, as well as potassium. These elements are present in trace quantities ranging from fractions of a ppm to a few ppm, although potassium content of some iron ores can be 3% or more. In addition, it is possible to determine the manganese content of iron ore from the potassium gamma-ray activity with an accuracy of 0.35% Mn. In the cases where potassium content is high, it can range up to unacceptably high levels. In this case, potassium content can be measured directly from the ^{40}K gamma-ray activity. Laboratory measurements have shown that the potassium content can be measured with an accuracy of 100 ppm K_2O. The natural gamma-ray iron ore analysers can operate under primary ore conveyors (-200 mm particle size) as well as product conveyors which carry thousands of tonnes of ore per hour.

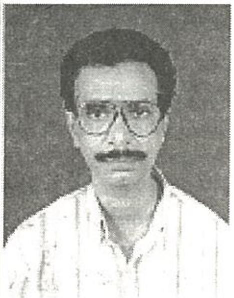
Conclusion

The applications of sealed sources as mentioned are now well established and practiced by the industry. Recent years have seen the development and commercial availability of a variety of nuclear radiation based instruments for on-stream and bulk analysis of coal and minerals. Improvements in the performance of these instruments have been mainly due to the development of new or improved techniques using deeply penetrating neutrons and gamma rays for the interrogation of the material, the development of fast and stable electronics and the availability of inexpensive microprocessors and computers. These applications will continue to expand in manufacturing industry.

Status of Industrial Radiography in India

Shri ***Gursharan Singh*** *joined Bhabta Atomic Research Centre in 1973 through 16th batch of BARC training School. Since his joining, he is working in the field of industrial applications of radioisotopes. His field of expertise includes applications of sealed sources and tracer technology for industrial troubleshooting and process optimisation, non-destructive testing and hot cell operations. He has served as an IAEA expert in several countries and trained over 6000 persons in NDT. Shri Singh is presently heading Isotope Applications Division of BARC.*

Shri ***P. Sree Ramakrishnan*** *is a senior scientific officer in the Isotope Applications Division of Bhabha Atomic Research Centre, Mumbai. After graduating in physics from University of Calicut, he joined Bhabha Atomic Research Centre in 1974. He was associated with the development of radioisotope based instruments for industrial applications. Presently he is working on industrial applications sealed sources for troubleshooting and process optimisation. He has undergone advanced training course in the field of radiography testing. He is actively involved in the training and certification programme of Radiography Testing, Level 1 and 2 personnel.*



Introduction

In a wide range of industrial applications of sealed sources, ranging from laboratory investigations to routine applications of economic significance, radiography testing enjoys a unique position. It is perhaps the most widely practised non-destructive evaluation technique for routine inspection and quality assurance programme. The range of application of the technique includes inspection of materials, components and assemblies ranging from nuclear reactors, boilers, pressure vessels and piping to common industrial products reaching the consumer.

It is now extensively used as mandatory requirement in the manufacture of pressure vessels, turbines, space vehicles, aircrafts, ships, bridges, offshore rigs and platforms, transport pipe lines and a host of other industrial areas. There has been a phenomenal growth in the number of radiography testing installations in India. Today there are over 1050 gamma radiography cameras, 350 industrial X-ray machines and 750 radiography sites in about 450 institutions.

The Department of Atomic Energy was the first in India to employ Isotope radiography technique on a large scale for the inspection of welds and assemblies during construction of the CIRUS reactor early in 1957. All the equipment, accessories and radiation sources required for inspection were then imported from Canada. An integrated approach for technology development was taken up by the then Isotope Division in 1959. Production of radiography sources were started in 1959 on a limited scale in the APSARA reactor. By 1962, large scale production of radiography sources of ^{192}Ir and ^{60}Co sources was commenced in the 40 MW CIRUS reactor.

Presently, Bhabha Atomic Research Centre (BARC), and Board of Radiation & Isotope Technology (BRIT), have an integrated programme of development, production and supply of a range of gamma radiographic equipment along with the production of radiography sources useful to inspect

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specimen from 10-200 mm steel equivalent thickness.

Development of Radiography Equipment

Design and development of gamma radiography equipment is linked with the radiation safety programme of application of radioisotopes for non-destructive testing. Radiography cameras both for ^{192}Ir and ^{60}Co sources have been designed, developed, produced and tested to qualify type approval and supplied to a large cross-section of engineering industries under indigenous development programme.

Standard Specifications and Regulatory Aspects

The Atomic Energy Regulatory Board (AERB) of India specifies that the design and construction of industrial gamma radiography exposure devices and source changers should meet the AERB/SS-1 (ISO 3999 1977 E) standard requirements. The design also should meet AERB Safety Regulations on Transport of Radioactive Materials AERB/SC/TR-1(IAEA)

Radiological Safety Aspects of Radiography Equipment

These include

- Performance checks of radiography cameras,
- Management of off-normal situations in the operation of these cameras,
- Calibration of radiation monitors, maintenance of accessories and tools used in industrial radiography and
- Familiarization with recent radiation protection standards.

Indian Atomic Energy Act 1962 is the basis for legislative control of use of radiation in India. The radiation surveillance procedures for industrial radiography installations were specified by notification by the competent authority in July 1980, under the title, "the Industrial Radiography (Radiation Surveillance) Procedures". The notification specifies the requirements relating to;

- radiography equipment
- approval of radiography installations
- staff requirements
- personnel and area monitoring
- safe work practices and
- licensee's responsibilities

Test Procedures

Prototype radiography cameras are developed and tested to qualify the standard design specifications for type approval from the competent authority. Radiography cameras and their driving units/control units and source holders are subjected to the following recommended tests given in Tables 1A and 1B .

TABLE 1A. Tests for radiographic exposure devices

AERB/SS-1 (ISO-3999)	Class		
	Portable P	Mobile M	Fixed F
Shielding efficiency	X	X	X
Vibration	X	X	-
Horizontal shock	X	X	-
Vertical shock	X	X	-
Endurance	X	X	X
Kinking[a]	X	X	X
Crushing[a]	X	X	-
Tensile[b]	X	X	X
Accidental drop 1&2	X	X	-

[a]Tests for control unit; [b]Test for source holders

TABLE 1B. AERB/SC/TR-1 (IAEA safety regulations)

Type-A	Type-B
Heat	Free Drop
Cold	Puncture
Water spray	Thermal
Compression	Water immersion
Vibration	
Free Drop	
Penetration	

Shielding Efficiency Test

Maximum permissible radiation leakage levels for radiography cameras and source changers are given in Table 2. Shielding efficiency test is

TABLE 2. Maximum permissible radiation leakage levels

Type	At source mGy/h	At 5 cm mGy/h	At 1 meter mGy/h
Portable (P)	2	0.5	0.02
Mobile (M)	2	1	0.05
Fixed (F)	2	1	0.1

mandatory to check the permissible radiation leakage levels during the regular use of radiography cameras.

Radiography Equipment in India

About 350 industrial X-ray machines, both Indian and foreign make, have been licensed for industrial use. 160 kV to 300KV X-ray machines are most commonly used in India. A brief description of the gamma ray equipment being used in India is given in Table 3. Use of high energy X-ray is also increasing. The present status of such accelerators in India is given in Table 4

Human Resource Development in Radiography Testing

Training and certification of NDT Personnel is vital in the country's industrialisation programme since 'Quality' is the key word in its growth and prosperity. The reliability and success of NDT application greatly depends upon the technical skill and ability of the practitioners, as the data generated during these tests have to be analysed and interpreted to arrive at a correlation with the soundness of the material under test. The industrially advanced countries have developed training and certification schemes about 30 years back. These are specialised training courses and the curriculum is not taught at college or university level. Industries employ only those personnel who are successful and certified in these programmes. Majority of these schemes have adopted a 3 tier system.

- Level-1 - For operators or technical assistant
- Level-2 - For technicians (Supervisors)
- Level-3 - For Engineers or Technologists

Different countries have established schemes tailored to suit one's own educational pattern and to

TABLE 3. Remotely operated Radiography Cameras (AERB Approved) in India

Camera	Isotope	Capacity curies	Shielding	Weight kg
Amertest660/ Tech/Ops660 (U.K.)	^{192}Ir	100	Depleted Uranium	20
Amertest 680 Tech/Ops680 (U.K.)	^{60}Co	100	Depleted Uranium	184
Amertest 684 TecH/Ops684 (U.K.)	^{60}Co	10	Depleted Uranium	102
Amertest 741 Tech/Ops741 (U.K.)	^{60}Co	30	Depleted Uranium	136
Amertest 676 Tech/Ops676 (U.K.)	^{60}Co	300	Depleted Uranium	210
Gamma century S.A (U.S.A.)	^{192}Ir	100	Depleted Uranium	18
Teletron SU-50 (W.Germany)	^{192}Ir	50	Depleted Uranium	18
Teletron SU-50 (W.Germany)	^{192}Ir	100	Depleted Uranium	20
Spect-2T (U.S.A.)	^{192}Ir	140	Depleted Uranium	20
Gammamat TI (W.Germany)	^{192}Ir	40	Depleted Uranium	12
Gammamat TIF (W.Germany)	^{192}Ir	100	Depleted Uranium	18
Gammamat TK 30 (W.Germany)	^{60}Co	30	Depleted Uranium	120
Gammamat TK 100 (W.Germany)	^{60}Co	100	Depleted Uranium	140
Gammrid 192 (USSR)	^{192}Ir	100	Depleted Uranium	20
ROLI-1 (India)	^{192}Ir	35	Lead	40
CRC-2A (India)	^{60}Co	10	Lead	450

TABLE 4. Status of high energy X-ray accelerators used for NDT in India

Sl. No.	Accelerator type	Make	Location
1.	4 MeV linac	USA	BHEL, Trichy
2.	8 MeV linac	USA	BHEL, Trichy
3.	12 MeV linac	USA	ISRO, SHAR
4.	4 MeV linac	India	ERDL, Pune
5.	4 MeV linac	USA	Ord. Factory
6.	12 MeV linac	Japan	L&T, Hazira
7.	6 MeV Betatron	UK	CERI, Karaikudi
8.	4 MeV linac	USA	VSSC, Trivandrum

BHEL - Bharate Heavy Electricals Ltd.; ISRO - Indian Space Research Organisation; ERDL - Explosives Research Development Ltd.; L&T - Larsen & Tuobro Ltd.; CERI - Central Electrochemical Research Institute; VSSC - Vikram Sarabhai Space Centre

meet the prescribed regulations and are thus not universal. To harmonise the adaptability, a 3 level International Certification Scheme has been prepared by the International Standards Organisation (ISO) with active support of International Committee on NDT (ICNDT) and International Atomic Energy Agency (IAEA). This scheme is accepted by over 80 countries.

Certification courses on Radiography Testing in India were started in 1978. Till 1993, BARC has been conducting following two types of courses for personnel practising Industrial Radiography (RT), for supervisors and operators;

Site-in-Charge course (30 days IRG-1 course) equivalent to levels between 2 and 3 of American Society for Non-Destructive Testing (ASNT)

10 days Radiographer's course equivalent to Level-1 of ASNT.

Licensing procedures for RT Personnel in the country, make it mandatory to have completed the relevant certification course. From January 1994, these courses are conducted based on ISO 9712 scheme with a three level system (Table 5). The major portion of the course content is as per Bureau of Indian Standards document IS 13805, 1993 "General Standard for Qualification and Certification of NDT Personnel", based on the guidelines of ISO - 9712. To meet large demand, these courses are held regularly at different centres in the country in collaboration with various centres. More than 6000 personnel have been trained so far.

Details of the various Radiography Testing courses conducted by BARC are given in Tables 6, 7 and 8.

TABLE 5. Radiography testing courses conducted thus far

Courses	Conducted by	Approx. persons trained
Radiography Testing, Level-1	Radiological Physics and Advisory Division, BARC	2000
Radiography Testing, Level-2	Isotope Applications Division, BARC	4000
Radiography Testing, Level-3	Isotope Applications Division, BARC	135

Conclusion

Indigenously produced radiography equipment and trained NDT personnel are available to Indian industry. These equipment have been developed with the intension of minimizing radiation exposures to operators and to avoid radiation accidents. Availability of the indigenous low cost radiography cameras and trained man power have helped to popularise this technology in India towards achieving the self reliance in this important branch of non-destructive testing.

TABLE 6. Training Course on Radiography Testing Level-1

1.	Objective	This course has been tailored to meet the professional needs in industrial radiography and to provide the instructions on proper use of radiation sources. An individual certified to Radiography Testing Level-1, will be able to; • Carry out Radiography Testing • carry out correct exposure procedure • Set up and calibrate equipment This course is conducted as per the guidelines of ISO-9712, IAEA TECDOC 628 and IS-13805. This course is mandatory in India for those who would like to work as radiographers in radiography companies.
2.	Eligibility	• 12 th standard with Physics and Mathematics
3.	Selection Procedure	The selection is based on the Radiographic Testing practical experience.
4.	Duration	15 Working days
5.	Frequency	3-4 courses in a year in different institutions in the country.

TABLE 7. Training Course on Radiography Testing Level-2

1.	Objective	This course has been designed to meet the professional needs in industrial radiography and to provide instructions on proper use of radiation sources. An individual certified to Radiography Testing Level-2, will be able to; • Choose the proper test technique • Set up and calibrate equipment • Interpret and evaluate results according to applicable codes, standards and specifications. • Train Level - 1 persons in Radiography Testing This course is conducted as per the guidelines of ISO-9712, IAEA TECDOC 628 and IS-13805. This course is mandatory in India for those who would like to obtain radiography sources on their names to set up radiography testing facilities and to act as site-in-charges in radiography installations.
2.	Eligibility	• Diploma/Degree in Engineering • Degree in science with Physics and Mathematics
3.	Selection Procedure	The selection is based on the Radiographic Testing practical experience.
4.	Duration	22 Working days (132 hours)
5.	Frequency	3-4 courses in a year in different institutions in the country.

TABLE 8. Training Course on Radiography Testing Level-3

1.	Objective	This course can meet the professional needs in industrial radiography. An individual certified to Radiography Testing Level – 3, will be able to; • Have general familiarity with other NDT methods • Acquire familiarity with material fabrication and processing technology. • Establish new techniques and procedures. • Interpret codes, standards, specifications and procedures and take / accept / reject decisions. • Train Level-1 and Level-2 person in Radiography Testing This course is conducted as per the guidelines of ISO-9712, IAEA TECDOC 628 and IS-13805.
2.	Eligibility	• Diploma/Degree in Engineering with a minimum of 3 years practical experience after passing RT-2 course. • Degree in science with Physics and Mathematics with a minimum of 3 years practical experience after passing RT-2 course.
3.	Selection Procedure	The selection is based on the Radiographic Testing practical experience.
4.	Duration	19 Working days (114 hours)
5.	Frequency	1 course in a year in different institutions in the country depending on demand.

Nuclear Instrumentation for Industrial Application of Radioisotopes

__Shri A. S. Pendharkar__ is currently Head, Isotope Instrumentation Section of Isotope Applications Division of BARC. He joined the 14th batch of BARC training school after obtaining M.Sc. degree in Physics from University of Mumbai in 1970. He is involved in the application of radiotracers in industry and hydrology. His area of interest includes development of instrumentation and software for radiotracer applications. Presently he is working on Computed Industrial Tomographic Imaging System. He has visited several countries as an IAEA expert.

__Shri G.S. Ramakrishna__, Senior Scientific Officer, obtained B.Sc. (Science / Maths) from Bangalore University and B.E. (Electronics and Communication) from Indian Institute of Science, Bangalore. After under going one year training in BARC Training School of 13^{th} Batch, he joined Isotope Applications Division in 1970. Since then he is working in the field of Nuclear Electronics, Nucleonic Gauges, Control System and Instrumentation for Industrial applications of Radioisotopes. Currently he is working on the development of Computed Industrial Tomographic Imaging Systems with radioisotope and X-ray sources for Non-destructive testing applications. He has about 20 publications to his credit.

Introduction

As a part of peaceful uses of atomic energy, radioisotope applications have gained importance in the fields of science, engineering, medicine, agriculture and industry. Radioisotopes and ionising radiations like α- rays, β-rays, γ-rays, X-rays and neutrons are extensively employed in industries. In order to facilitate development of nuclear instruments, a variety of radiation detectors and associated instrumentation are needed.

Principle

For detection it is necessary to convert the nuclear radiations which are non electrical in nature into an electrical quantity like charge, current or voltage. This is achieved in nuclear radiation detector by the process of interaction of radiation with matter in the detector medium. Radiation while passing through the matter may interact with matter. Radiations like α and β undergo coulombic interaction and produces ionisation and excitation in the matter being traversed. On the other hand, radiations like γ, X and n may be absorbed and produce electrons and charged particles respectively, which act as the representatives of γ and X, and neutrons. In this case energy transfer may be complete or partial. The ionisation / excitation is used for the detection of radiation. In some cases, depending on the thickness of the object (matter), the radiation intensity is reduced after passing through it and the extent of the reduction depends on the atomic number and the density of the matter. The characteristics of the incident radiation and emergent radiation uniquely define certain specific properties and characterstics of the material under investigation. These principles are used in nuclear instrumentation for a variety of applications in industries like nondestructive testing, radiotracer analysis, radiometric process coloumn scanning, leak detection, process parameter measurement, nucleonic gauging and automation in addition to its application in other branches of science and engineering. Depending on the application and the

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type of radiation, the detector material has to be carefully chosen.

In order to be compatible with the type of radiation and the desired parameter of measurement the characteristics of the detector such as energy response, energy resolution, effeciency, counting rate, signal decay time, sensitivity, noise and temperature coeffecient (drift) are of significance. The amount of charge produced depends on the amount of energy deposited in the detector volume.

Types of Detectors

There are a variety of detectors available, e.g. gas filled detectors, scintillation detectors and semiconductor detectors. The gas filled types are e.g. ionizatiuon chamber, proportional counter and Geiger Muller Counter. In these detectors, ionisation produced due to interaction of radiation with the fill gas is measured with or without further multiplication. On an average about 30 to 35 eV of energy is required to produce an ion pair. NaI(TI), CsI(TI), $CdWO_4$, BGO ($Bi_4Ge_3O_4$, ZnS), Anthracene($C_{10}H_{12}$) and Stilbene (C_8H_{10}) are a few examples of scintillation detectors. These detectors produce scintillation or short duration light pulses. Liquid scintillators like Diphenyl Oxazole (POP) which are commonly used in industrial applications.

Semiconductor detectors like germanium or silicon have extensive applications in some specialized field of radiation measurement and analysis.

For neutron detection, the detector medium is so chosen to have high cross-section for reactions like (n,α) and (n,p). The charge particles produced will undergo coulombic interaction to cause ionisation and excitation. Gaseous detector with Borontrifloride (BF_3) or Helium (He-3) gas are used for these. Solid medium type of detectors like plastic scintillator using a dopant Gadollium (Gd) having very high cross section for thermal neutron can also be used.

Some Important Characteristics of Detectors

Resolution and efficiency, suitability of the detector for timing experiments, and cost are important criteria for selection of detectors. The efficiency of a detector is a measure of how many pulses are produced for a given number of radiations i.e. the ratio of the number of pulses produced by the detector to the number of gamma rays incident on the detector. To be useful, the detector must be capable of absorbing a large fraction of the gamma ray energy. Detector resolution is the full width at half maximum at a specific energy, the capability to distinguish between two nearby radiation energies. It is either expressed in keV or as a percentage of the energy at that point,

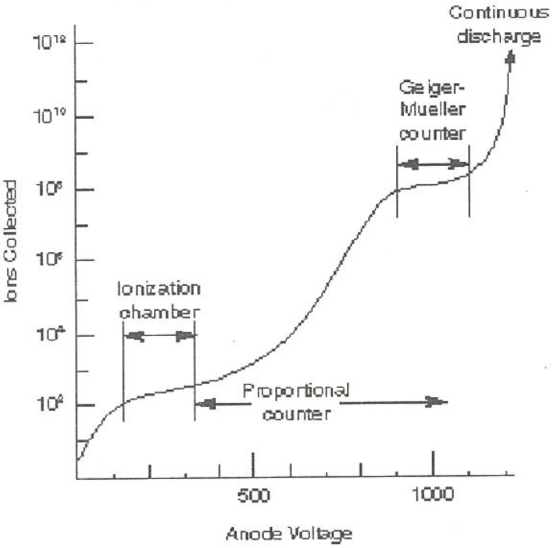

Fig. 1 Gas Detector Output vs. Anode Voltage

Gas-Filled Detector

A gas-filled detector consists of a metal chamber filled with gas and containing a positively biased anode wire. Radiation passing through the gas produces free electrons and positive ions. The electrons are attracted to the anode wire and collected to produce an electric pulse.

At low anode voltages, the electrons may recombine with the ions. Recombination may also occur at high density of ions. At a sufficiently high voltage nearly all electrons are collected, and the detector is known as an ionization chamber (Fig. 1). At higher voltages the electrons are accelerated towards the anode at energies high enough to ionize other atoms, thus creating a larger number of electrons. This results in multiplication of ionisation. The multiplication factor, in the range of 10^4 to 10^6, is proportional to the applied voltage. Detectors operated in this voltage region are known as proportional counters. At higher voltages the electron multiplication is even greater, and the number of electrons collected is independent of the initial ionization. This region is known as Geiger-Müller region, in which the large output pulse is the same for all radiations. At still higher voltages continuous discharge occurs and is useless for detection.

The different voltage regions are indicated schematically in Fig. 1. The actual operating voltages can vary widely from one detector to the other, depending upon the detector geometry, gas type and pressure.

Ionization Chamber

The very low signal output for the ionization chamber makes this detector difficult to use for detecting individual gamma rays. It finds use in high radiation fluxes in which the total current produced can be very large. Many radiation monitoring instruments use ionization chambers. Absolute ionization measurements can be made, using an electrometer for recording the output.

Proportional Counter

Proportional counters are frequently used for X-ray measurements where moderate energy resolution is required. Operating voltages depend upon the fill gas as well as the geometry. For X-rays, noble gases like xenon, krypton, neon and argon are used. Xenon and krypton are selected for higher energy x rays or to get higher efficiencies, while Neon is selected when it is desired to detect low energy x rays in the presence of unwanted higher energy x rays. Sometimes gas mixtures are used, such as P-10 gas, which is a mixture of 90% argon and 10% methane

Geiger-Müller Counter

The Geiger-Müller counter produces a large voltage pulse that is counted without further amplification. No energy measurements are possible since the output pulse height is independent of initial ionization.

While one pulse is being processed the detector is not available for processing another pulse i.e. detector is dead. The pulses that arrive when the detector is dead are lost. This dead time can be hundreds of microseconds long, which limits the counter to low count rate applications. The voltage drop across a large resistor between the anode and bias supply will serve to quench the discharge since the operating voltage will be reduced below the plateau. Often the ionisation produced by a process like deexcitation followed by photo ionisation which is not related to primary ionisation may lead to enhancing the signal by causing further ionisation. Such signal has to be quenched. This is accomplished by using a fill gas that contains a small amount of halogen in addition to a noble gas.

Scintillation Detector

A gamma ray interacting with a scintillator produces a pulse of light, which is converted to an electric pulse by a photomultiplier tube. The photomultiplier consists of a photocathode, a focusing electrode and 10 or more dynodes that multiply the number of electrons striking them several times each. The anode and dynodes are biased by a chain of resistors typically located in a plug-on tube base assembly. Complete assemblies including scintillator and photomultiplier tube are commercially available.

The properties of scintillation material required for good detectors are transparency, availability in large size, and large light output proportional to gamma ray energy. Relatively a few materials have good properties for detectors, and no single material has all the properties. Thallium activated NaI and CsI crystals are commonly used, as well as a wide variety of plastics. NaI is the preferred material for gamma detection because it provides good gamma ray resolution and is economical. However, plastics have much faster pulse light decay and find use in timing applications, even though they often offer little or no energy resolution.

Semiconductor Detector

A semiconductor is a material having a band gap intermediate to an insulator and a conductor. In electronics the term "solid state" is often used interchangeably with semiconductor. Semiconductor detectors are fabricated from either elemental or compound single crystal materials having a band gap in the range of 1 eV. The group IV elements silicon and germanium are by far the most widely-used semiconductors, although some compound semiconductor materials like BGO are finding use in special applications.

Semiconductor detectors have a P-I-N diode structure in which the intrinsic (I) region is created by depletion of charge carriers when a reverse bias is applied across the diode. When photons interact within the depletion region, charge carriers (holes and electrons) are produced and are swept to their respective collecting electrode by the electric field. The resultant charge is integrated by a charge sensitive preamplifier and converted to a voltage pulse whose amplitude is proportional to the original photon energy.

Both Ge and Si photon detectors must be cooled while in use in order to reduce the thermal charge carrier generation. The most common medium for detector cooling is liquid nitrogen. However, recent advances in electrical cooling systems have made electrically refrigerated cryostats a viable alternative for many detector applications.

Detector Signal

In general the basic operation of the detector can be in current mode or pulse mode. In current mode the signal generated is proportional to the average quantity of charge generated per unit time. This corresponds to the average amount of energy deposited in the detector volume. Integration of this charge over a period of time may be used to obtain the total energy deposited. The instantaneous charge per unit time provides the dose rate information and the total integrated charge over a period of time gives the dose information.

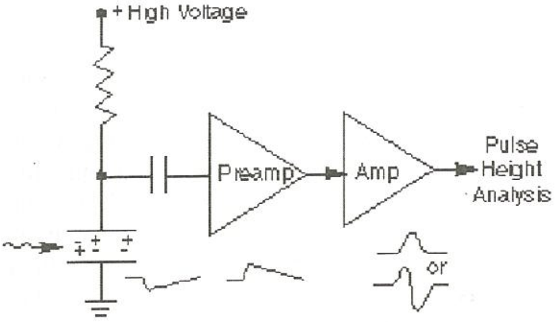

Fig. 2 Basic Detector and Amplification

In the pulse mode the amplitude of the pulse is related to the energy and the repetition rate or the number of pulses per unit time is related to the dose rate. Thus by counting these pulses for the desired time, dose information can be obtained. The width including the pulse rise time and decay time is the characteristic of the detector. This seriously limits the maximum counting rate of the detector without significant loss of count rate. The quantity measured by the radiation detector can be processed to obtain the desired information such as activity in becquerrel (curie), dose in gray (rad)/Sievert (rem) or dose rate in rad/hr or rem/hr.

Detector Performance

Semiconductor detectors provide greatly improved energy resolution over other types of radiation detectors. Energy required to produce a charge carrier is low and the consequent "output signal" is large relative to other detector types for the same incident photon energy. At 3 eV/e-h pair (see Table 1.1) the number of charge carriers produced (N) in Ge is about one and two orders of magnitude higher than in gas and scintillation detectors respectively. This large number reflects in better energy resolution as one of the main contributions to the resolution is the statistics of charge carrier production which is equal to $\sqrt{N}$.

Basic Counting Systems

Pulse Electronics

The nuclear electronics industry in addition to specific designs has also standardized the signal definitions, power supply voltages and physical dimensions of basic nuclear instrumentation modules (NIM). The standardization provides users with the option of interchanging modules, and the flexibility to reconfigure or expand nuclear counting systems, to suit the counting applications.

Preamplifier and Amplifier

Most detectors can be represented as a capacitor into which a charge is deposited. By applying detector bias, an electric field is created which causes the charge carriers to migrate and be collected. During the charge collection a small current flows, and the voltage drop across the bias resistor is the pulse voltage.

The preamplifier is isolated from the high voltage by a capacitor. Charge-sensitive preamplifiers are commonly used for most solid state detectors. To maximize performance, the preamplifier should be located at the detector to reduce capacitance of the leads, which can degrade the rise time as well as lower the effective signal size. Additionally, the preamplifier also serves to provide a match between the high impedance of the detector and the low impedance of coaxial cables to the amplifier, which may be located at great distances from the preamplifier.

In the amplifier the pulse is shaped and amplified. The long delay time of the preamplifier pulse may not be returned to zero voltage before another pulse occurs. Thus, it is important to shorten it and only preserve the detector information in the pulse rise time. By standard pulse processing techniques near-Gaussian pulse shape is produced, yielding optimum signal-to-noise characteristics and count rate performance.

Pulse Height Analysis and Counting Techniques

Pulse Height Analysis may consist of a simple that can be set above noise level and which produces a standard logic pulse for use in a pulse counter or as gating signal. However, most of the data consists of a range of pulse heights of which only a small portion is of interest. One can employ either Single Channel Analyzer and Counter or Multichannel Analyzer. The single channel analyzer (SCA) has lower and upper level discriminators, and produces an output logic pulse whenever an input pulse in between the discriminator levels. This helps to select and count all voltage pulses in a specific range.

Full energy spectrum is obtained by setting the SCA's discriminators to a narrow range (i.e. window) and then entire range of voltages is scanned. However, the preferred method of collecting a full energy spectrum is with a multichannel analyzer which basically consists of an analog-to-digital converter (ADC), control logic, memory and display. The multichannel analyzer collects pulses in the entire voltage range which can be recorded and displayed. It is a major improvement over SCA spectrum analysis.

Counter and Ratemeter

Counters and ratemeters are used to record the number of logic pulses, either on an individual basis as in a counter, or as an average count rate as in a ratemeter. Counters and ratemeters are built with very high count rate capabilities so that dead times are minimized. Counters are used in combination with a timer (either built-in, or external), so that the number of pulses per unit time are recorded. Ratemeters feature a built-in timer, so that the count rate per unit time is automatically displayed. Typically, most counters are designed with 8-decade count capacity and offer an optional external control/output interface, while ratemeters are designed with linear or log count rate scales, recorder outputs and optional alarm level presets/outputs.

Semiconductor Detector with Multichannel Analyzer

A typical semiconductor detector based gamma spectroscopy system consists of a HPGe or silicon detector, high voltage power supply, preamplifier, amplifier, analog to digital converter and multichannel analyzer. For higher count rate applications, it is necessary to use an additional circuit to reject pileup pulses that distorts the spectrum. Pileup Rejection/Live Time Correction inspects both the leading edge and the trailing edge of the pulse and can discriminate between two events separated by less than 0.5 microseconds. Since these pileup pulses are rejected, the ADC live time must be lengthened to properly compensate for the period the system was unable to process pulses. Virtually all current ADCs and MCAs provide signal paths for pulse Pileup Rejection/Live Time Correction.

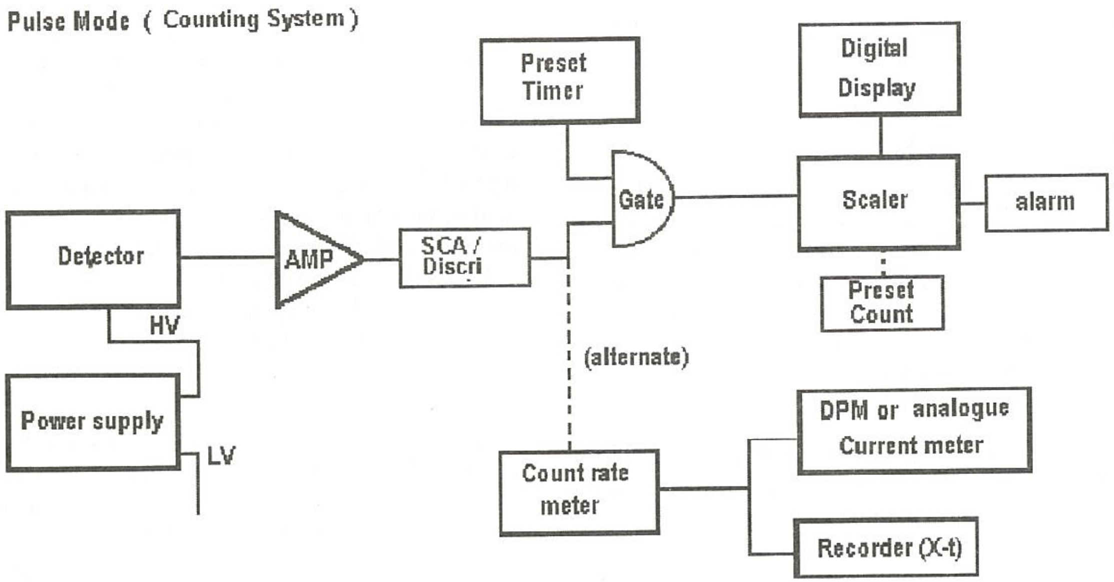

Fig. 3 Block diagram of a pulse mode counting system

Digital Signal Processor

Historically, analog devices have been employed to perform the function of the amplifier in Pulse Height Analysis systems in addition to processing of the pulse. The detector signal is processed, shaped, and filtered by the amplifier and then digitized by the ADC at the end of the processing chain. The output pulse shape and its associated time constants are selected to maximize the signal-to-noise ratio for optimized resolution and reduced sensitivity to transients, while providing the maximum throughput consistent with the resolution requirements of the application. With advances in high speed digital hardware, it is now possible to design and implement digital pulse processors to perform the operations previously only performed by an analog amplifier. In Digital Pulse Processing system, the detector/preamplifier signal is digitized much earlier in the signal processing chain. Subsequent processing, filtering, baseline restoration, and pileup rejection are performed digitally, and the results are transferred directly to the MCA histogram memory for viewing and analysis. This system, has been shown to provide resolution and throughput performance well in excess of commercially available analog systems, as well as increased precision and repeatability.

System Electronics

The main function of the nuclear instrumentation is to acquire the detected signal, process and display it, in suitable form. In addition, in some cases, output for recording or energising some annuciators such as alarms flashing light etc. may be provided. The basic requirement of nuclear electronics can be generalised based on the nature of detection and mode of operation.

Figure 3 shows a block diagram of the commonly employed nuclear radiation detector system for industrial applications. Some important nuclear instrument, the detectors used, radiation measured and the applications intended for are given in Table 1.

Quality Control and Quality Assurance

Quality Control (QC) and Quality Assurance (QA) is an important aspect of nuclear instrumentation. This is required to give an assurance that under the specified conditions the instrument will perform the desired task within the

Table 1. Important nuclear instruments

Sr. No.	Instrument	Radiation	Detector	Application
1	Survey Meter	β, γ	GM	Monitoring
2	Area Monitor	γ, X	GM	Preset level alarm
3	Teletector	γ, X	GM	Wide range dose rate measurement
4	Wide range Survey meter	γ, X	Ionization	Dose, dose rate & activity measurement
5	Level Gauge	γ, neutron	GM	Level control continuous and fixed
6	Thickness Gauge	α, β, γ	GM, Ionization	Paper, steel control etc.
7	Density Gauge	γ	GM	Density measurement online/offline
8	Blockage Monitor	γ	Scintillation GM	Pipeline blockage monitoring/detection
9	Spectrum Analyser	γ, X	Ge(Li), HPGe	Spectrum analysis, activiation analysis, source calibration
10	Bore-well Logger	γ, neutron	He3, BF-3, Scintillation	Mineral analysis, Rock sample analysis
11	X-ray fluorescence Analyser	γ, X	Scintillation, Ge(Li), HPGe	Activation analysis, Mineral analysis, XRF elemental analysis
12	Gamma Scintilation Monitor	γ	Scintillation	Low level radiation monitoring, nucleonic gauges
13	Back-scatter gauge	γ, neutron	Scintillator, He3, BF-3	Density, thickness etc. measurement in industry. Moisture measurement. Mineral exploration.
14	Contamination Monitor	α, β β, γ	Scintillator (ZnS) GM	Radioactive contamination in nuclear installation & laboratories.

limits of operation. Also, in the event of any deviation in the operational conditions, such as power supply fluctuations, operating temperature, radiation parameters like energy, dose and dose rate, the instrument behaviour should be predictable and suitable alarm/indication should be enabled.

Also, when the instrument is operated within the limits of operation, it should provide measurement value within the specified limits of precision and accuracy. The instrument should serve as a measuring or monitoring unit as intended over a specified period of time within the counting and statistical limits there by establishing the expected life of the instrument, particularly in industrial environment where hostile conditions of weather and working conditions can be expected, the instrument should assure the guaranteed performance. In the event of the failure of the system, specified component or connection, appropriate warning should be provided to prevent the operator from recording false measurements and also diagnostic message(s) or indications should provide to facilitate rectification of the malfunction. In general, if not all, a few representative samples of the instruments should be subjected to QC & QA test to establish the reliability of its operation under the specified conditions.

Preventive maintenance comprises the daily care, providing a conducive environment for the proper functioning of the equipment and the periodic testing of system functions to identify in advance the faulty or inaccurate system components. It is aimed at minimizing equipment breakdown possibility by forewarning the user of the deteriorating situation. The preventive maintenance must include (a) the periodic inspection of the equipment to discover the conditions which may cause the equipment failure or degradation and (b) necessary maintenance to alleviate such conditions before they reach major proportions. At regular intervals preventive maintenance should be reviewed in close detail to detect any faulty trends or deficiencies which may have developed during say the current year.

Conclusion

Nuclear radiation detectors and instrumentation play vital role in the growth of the industry. This directly benefits in improving the quality of life and prosperity of the nation. To perform variety of tasks, wide range of nuclear instruments are commercially available. Technology and progress achieved in India has enabled to develop various and equipment and control systems for nuclear applications in the field of industry, agriculture, medicine, water resources management etc.

Tomographic Imaging Systems for Industrial NDT

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Introduction

Computed Tomography (CT) or Computer Assisted Tomography (CAT) as is widely known, is now an established medical diagnostic methodology. Industrial computed tomographic imaging systems (ICT) are very similar in principle to the medical CT scanners, and only a very few and expensive systems are available commercially. It is one of the latest techniques in the field of non-destructive testing and examination of industrial specimen including defect localization, dimensional measurement and density distribution mapping. ICT systems differ from the conventional imaging techniques e.g. gamma and X-ray radiography in which the imaging beam path is perpendicular to the surface being imaged. Industrial tomography is an imaging technique to build up transverse sectional views by numerical processing of the transmission data through a test object. A first generation ICT system based on radioisotopes can be designed and developed at a very low cost though at the lower scale of operational capabilities. Recent developments in semiconductor based radiation detectors and detector arrays for online imaging as well as availability of high stability X-ray generators have elevated industrial tomography to new heights. Use of amorphous silicon flat panel imaging arrays with high dynamic range and multi-axis precision manipulators is becoming common. Some of the costly systems include three dimensional volume visualization and measurement capabilities. Most of such systems are custom designed based on specific requirements.

A prototype unit called Computed Industrial Tomographic Imaging System (CITIS) developed in BARC based on monochromatic gamma rays is described and some of the tomographic images obtained with this system are shown.

Principle

The attenuation of a mono-energetic collimated beam of gamma rays as it passes through a uniform slab of material is given by

$$I = I_0 \, e^{-\mu l} \qquad (1)$$

where, I is the intensity after passing the material; I_0 is the initial intensity of the gamma beam; μ is the linear attenuation coefficient of the material and l is the path length of the material.

Rewriting equation (1), equation (2) is obtained

$$\ln (I_0 / I) = \mu l \qquad (2)$$

If the ray passes through a non-homogenous material and the path can be considered to consist of a number of elements of width w with attenuation coefficients $\mu_1, \mu_2, \mu_3, \ldots m_n$ then the equation (2) becomes

$$\ln (I_0 / I) = \mu_1.w + \mu_2.w + \mu_3.w + \ldots \mu_n.w \qquad (3)$$

In computed tomography, the quantity $\ln (I_0/I)$ is normally called ray sum. As a single ray sum cannot by itself give any information of the

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distribution of the attenuation coefficients inside the specimen, one obtains a set of ray sums at different angles about the object being examined. A mathematical algorithm is then used to reconstruct the unique distribution of the attenuation coefficients (μ) within the object that gave rise to the experimentally measured ray sum.

Design Creteria

The design is based on the concept that a slice of the specimen is intercepted in a thin beam of gamma radiation which is attenuated as it passes through the specimen. The fraction of the radiation beam that is attenuated is directly related to the density and thickness of the material, to the composition of the material and the energy of the gamma ray beam. The reconstruction routine quantitatively determines the point by point mapping of the relative attenuation coefficients from the set of one dimensional radiation measurements taken at different scanning angles.

Experimental Implimentation

In its simplest form a tomographic scanner is designed to obtain sets of parallel ray sums from a single plane corresponding to many directions around the object. The system consists of collimated source of gamma radiation from a ^{137}Cs source, a single 3" x 3" NaI(Tl) – PMT integral assembly in a thick shielding enclosure with a removable detector collimator head and a three-axes stepper motor controlled mechanical manipulator. Energy threshold discrimination of the output of the detector is achieved through the use of single channel analyzer and gamma rays within a narrow window around the photo peak are recorded as the transmission data. A single PC/AT controls the mechanical system and data acquisition system for a full scanning sequence.

Reconstruction Algorithm

It is a set of sequential steps for solving a mathematical problem by a series of operations following a defined procedure. In computed tomography the mathematical process is used to convert the digitized transmission measurements into cross sectional images. There are two commonly used computation methods for image reconstruction from projection data. The Fourier transform method or filtered back projection method (FBP) normally operates in spatial frequency domain whereas a simplified version called Convolution Back Projection method (CBP) operates in special domain and is quite easy to implement. CBP method has been employed for the development of image reconstruction software in CITIS. The reconstructed image is processed and analysed by separate image processing software.

System Description

CITIS (Fig.1) comprises of mainly three major sub-systems : (1) beam generator containing 220 GBq of ^{137}Cs radioisotope equipped with an ON/OFF mechanical assembly and a source collimator; (2) a single 3" x 3" (dia) NaI(Tl) – PMT integral assembly in a thick shielding enclosure with a removable detector collimator head and (3) a three-axes stepper motor controlled mechanical manipulator. Fig. 2 shows another experimental setup which utilizes an industrial constant potential X-ray generator as the radiation source and CsI(Tl) – PIN photodiode detectors, output of which is fed to the PC based data acquisition system. Data acquisition and control software running on a personal computer is used for overall control of the mechanical system and data acquisition for a full scanning sequence. The entire software for mechanical manipulator, data acquisition, image reconstruction and interactive image display has been developed which includes

(a) Integrated motion control and data acquisition system routine,

(b) Simulation software,

(c) Image reconstruction software with interactive image and graphical profiles display and

(d) 3D volume visualization and oblique plane ICT image display.

Typical Industrial CT Images

Figures 3-8 show typical computed tomographic images as well as 3D visualization of CT data obtained on the ^{137}Cs based system described above.

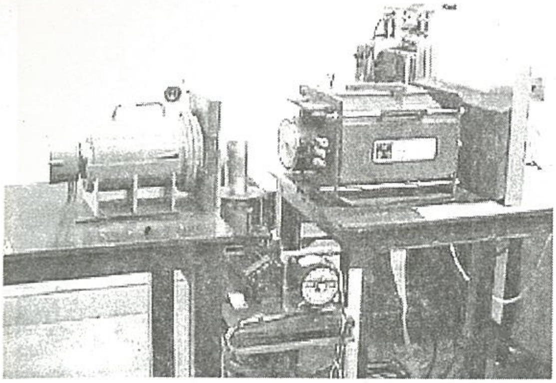

Fig. 1 *^{137}Cs radioisotope source based industrial CT system.*

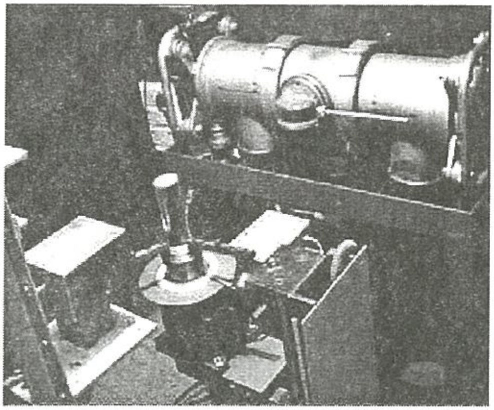

Fig. 2 *X-rays based industrial CT system.*

X-ray Based Tomography

Due to high beam intensity and variable energy range, X-ray equipment specifically manufactured for tomographic imaging purposes are preferred to isotopic gamma sources. However, polychromatic nature of the X-ray emission from constant potential industrial tubes gives rise to some artefacts in the tomographic images.

Applications of Industrial Computed Tomographic Imaging Systems

The very fact that a computed tomographic system has the ability to present a density or linear absorption coefficient map across a slice through a specimen allows the visualization of many types of structures and flaws. Different applications of industrial computed tomography can be grouped as follows:

Solid Specimen

Voids and inclusions are readily detectable in high-contrast objects. Targets smaller than the resolution of the system can also be seen, but it will have less contrast from the background material. Porosity and micro shrink reduce the density of the material and are usually visible if distributed over a large area. Disbonds and delaminations are detectable if separated.

Castings and Forgings

ICT systems are used for the production inspection of small complex precision castings and forgings especially turbine blades used in aircraft engines. ICT is also used to analyze wall thickness of certain used blades to evaluate if sufficient material remains for refurbishing the component.

Assembled Structures

If the resolution and contrast sensitivity of the system is suitable, ICT will produce remarkable cross-sectional images. In this way, ICT can also be used to verify proper assembly or help evaluate damage or distortion caused by the fabrication process. The major limitation of ICT systems is low throughput as compared to film radiography or online radiographic systems.

Process Industry

Gamma scanning of process columns especially in chemical engineering is an established technique for industrial troubleshooting.. Though this technique does not call for intensive computational data analysis, it is highly operator-dependent and requires manual interpretation. A different implementation of industrial computed tomographic imaging system where the object (process column) is stationary and the source-detector assembly moves for acquiring the transmission data can be adapted for process tomography using penetrating radiation. Process tomography may be defined as imaging process parameters in space and time. A number of sensors are installed around a cross-section of the object that is to be imaged. The type of sensor chosen determines the parameter or characteristic to be

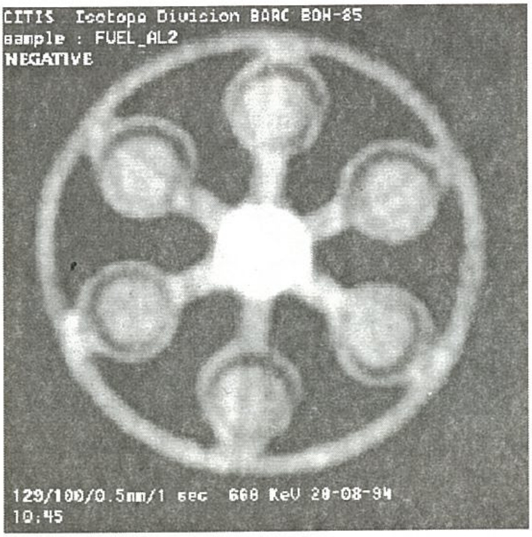

Fig. 3 *A cross-section of an experimental fuel pin assembly (end cap)*

imaged. Capacitance sensors, for example, are sensitive to the dielectric constant of the object, while gamma rays and X-rays are sensitive to density. The sensor signals are amplified, possibly also filtered and multiplexed, and digitized and read into a computer in which a cross-section of the measured parameter is reconstructed. Computed tomographic imaging system based on monochromatic gamma radiation sources has been used to obtain quantitative information on local time-averaged void distributions within fluidized beds in process industry.

Petroleum Industry

Use of computed tomography for geological analysis and for fluid dynamics research studies are known. Rock core samples are obtained from drilling sites to evaluate oil production capabilities of a well. ICT imaging can be used to evaluate these core samples with regard to heterogeneity or contamination by the drilling process. CSIRO, Division of Petroleum Resources, in Australia uses computed tomography imaging for core analysis applications such as core characterization, fracture analysis and others.

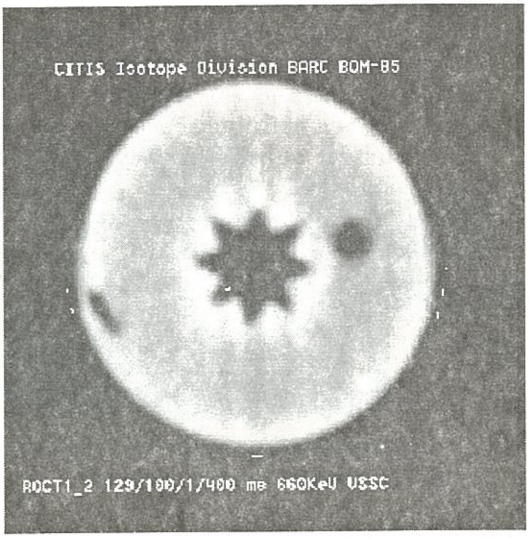

Fig. 4 *Typical cross-sectional view of a simulated rocket propellant grain*

ASTM Standards for Computed Tomography Imaging

ASTM (American Society for Testing and Materials) guidelines for industrial computed tomography system design, operation and system selection are listed below:

(i) Computed Tomography (CT) Imaging : Designation E1441-00

(ii) Computed Tomography (CT) Examination : Designation E1570-00

(iii) Computed Tomography (CT) System selection: Designation E1672-95

(iv) Computed Tomography (CT) Standard Test Method : Designation E1695-95

(v) Computed Tomography (CT) Standard Practice for Examination of Castings : Designation E1814-96

(vi) Standard Test Method for Calibrating and Measuring CT Density : E1935-97

Each one of these guidelines are very broad in description and the documentation, especially Designation E1441-00 deals with the subject of Computed Tomography (industrial applications) in an introductory way.

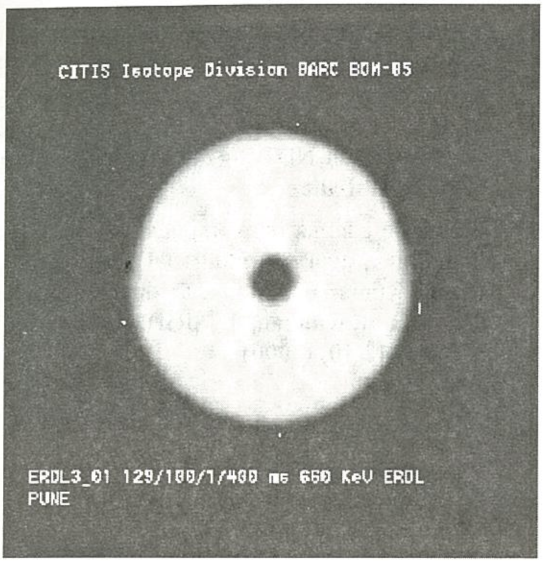

Fig. 5 *CT scan of live propellant grain*

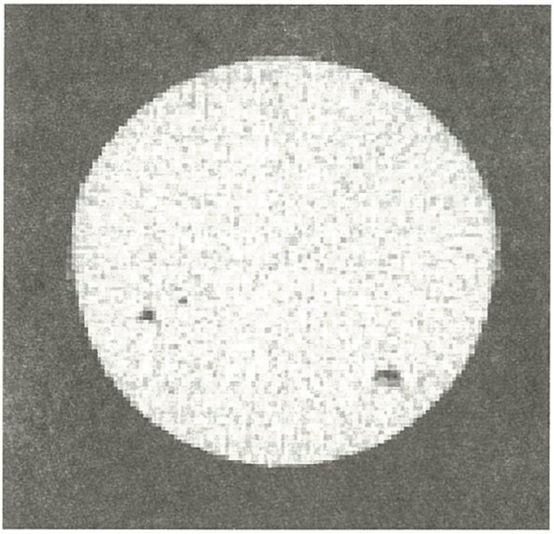

Fig. 6 *Another scan of a propellant grain showing defect locations*

For Further Reading

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2. Application of gamma-ray tomography to gas fluidized beds, N. MacCuaig, J.P.K. Seville, W.B. Gilboy and R. Clift, Applied Optics Vol. 24 No. 23 Dec. 95 pp 4083-4085.

3. Design and Implementation of a portable computerised axial tomography system for field use, Willium H. MILLER, NIM in Phys. Res. A270 (1988) 590-597.

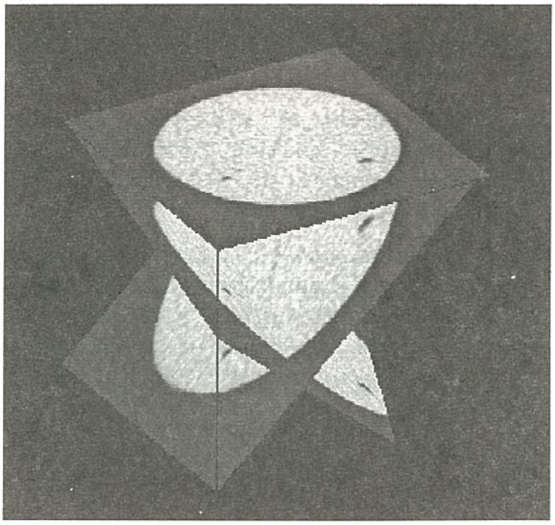

Fig. 7 *CT images through different oblique planes of the same sample as shown in fig. 6*

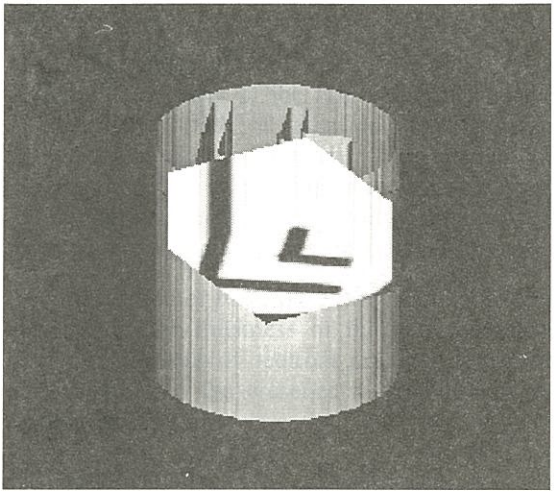

Fig. 8 *Typical three-dimensional surface rendered image from 2-D CT data of an aluminium sample.*

4. Metals Handbook, Ninth edition, Vol. 17, Nondestructive Evaluation and Quality Control, pp 359-383 (1989).

5. Development of Industrial Isotopic Tomographic Imaging System (CITIS-I), Umesh Kumar et al., BARC Report No. BARC/1993/E/019, 1993.

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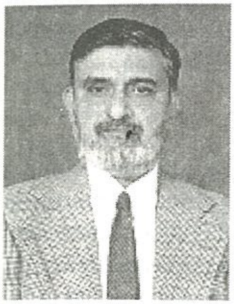
Nucleonic Control Systems In Industry



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Introduction

The increasing awareness among the consumers of industrial products has resulted in industries adopting modern quality control techniques. Depending upon the nature of industrial application, process control is achieved through the *effects of materials on radiation.* Nucleonic control systems are used as advanced monitoring, controlling and automation tools for technological processes. In a measuring system using a radiation source, the directed radiation from the source penetrates the sample under process where it will be partially absorbed and partly scattered by the sample. Industrial nucleonic control systems are characterized by non-destructive sensing. The principal elements of such a system are radiation, interaction and detectors. Scientific literature abounds in useful information on the various techniques of nucleonic control systems [1-3] Some of the most common techniques used in industrial nucleonic control systems are discussed here.

In industry a number of parameters are used to characterize the product properties in processes. However, usually, only a few physical material parameters like level height, bulk density, thickness, moisture and quantity are determined by isotope techniques because in many other cases, conventional measurements e.g. temperature measurement are preferred.

Principle

Nucleonic gauging uses principle of (a) transmission of radiation and (2) scattering of radiation.

The extent of radiation transmitted by a medium is an index of the magnitude of absorber present in the path of radiation. This physical parameter is used to determine the level of the process fluid / slurry or the quantity of the material on the conveyor belt or the density of the process material or the thickness of the product.

Reflection or back-scattering of radiation is a measure of the thickness of the material under process. Scattering of neutrons provides a measure of the extent of the presence of moisture in the medium under study.

Radiation Sources

The radiation sources which are most commonly used in nucleonic control systems are α emitters like ^{210}Po and ^{241}Am, β emitters like ^{85}Kr, ^{90}Sr, ^{147}Pm and ^{204}Tl, γ emitters like ^{60}Co, ^{137}Cs and ^{241}Am and neutron radiation sources like ^{241}Am-Be.

Level Height Determination

Level height is an important feature in material storing or transportation systems. Level gauging can

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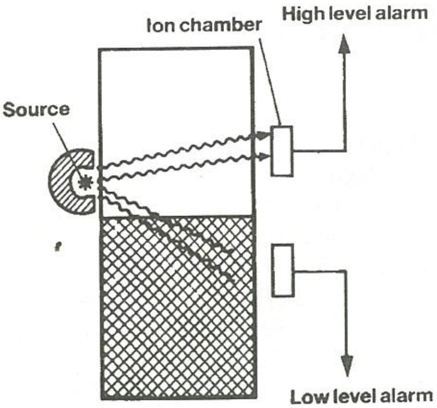

Fig. 1 Storage hopper level control

be vital for process control and for quantity monitoring. The level indicator is suitable for sensing and remotely indicating a specified extreme value, a schematic of which is given in Fig. 1. The level measuring device can be applied through continuous level height telemetering. The advantage of a level switch is that the indication depends only on relative absorption variations caused by material level changes. The absorption of radiation by the process vessel walls in its path can be corrected for by increasing the radiation source activity or preferably, increasing the sensitivity of the radiation detector. The type and activity of radiation sources are determined by the measurement function. Commonly used sources for this purpose are 40 MBq to 4 GBq of ^{60}Co and ^{137}Cs. For measurement of small bulk density substances (like foams) or with a small quantity of material available for measurement (as in the case of dental paste quantity indication in the tube) the use of β sources like ^{90}Sr (40 to 400 MBq) is recommended. The detector is generally GM type. However, use of very sensitive scintillation detectors are becoming more common. The filling level of beverages (e.g. soft drinks, beer, etc.) are controlled by passing an array of filled cans between a gamma emitter and a sensitive detector.

Density Measurement

The density of substances is a significant factor in numerous chemical engineering processes, in raw material processing technology, in the building industry, in hydraulic material systems, etc. The purpose of automation is to carry out continuous, accurate and contactless density measurements. Nucleonic density gauging is based on the absorption of radiation in matter. The intensity of radiation passing through the material is attenuated by an extent depending on the composition, thickness and density of the substance in the radiation path, according to the equation

$$I = I_0 \exp(-\mu l) \qquad (1)$$

Where I_0 is the dose rate of the incoming radiation in mR/h, μ is the linear absorption coefficient in m^{-1}, and l is the material thickness in m. Using the concept of mass absorption coefficient $\mu_m = \mu/\rho$, where ρ is the density of the material in kg/m^3, we have,

$$I = I_0 \exp(-\mu \rho l) \qquad (2)$$

The degree of radiation absorption is determined for a uniform material composition by the product of thickness and density. Using a suitably arranged measuring station, one can ensure a constant absorption length of radiation in the substance so that the measured radiation intensity decreases exponentially with increasing density of the material. The problem is usually to continuously record the density of a substance flowing in a pipe. Any of the following detectors: ionization chamber, GM Counter and scintillation detector, can be used for isotope density gauges. Generally, GM counters are preferred for moderate accuracy density monitoring (sensitive to density variation of 1-2%); ionization chambers and scintillation counters are suitable for high accuracy density measurements (sensitive to density variation as low as 0.05-0.1%). High accuracy density measurements have found wide application in the petroleum industry. In the pipe lines between the oil refinery or, considering sea transport, between the port and the distribution plant, petroleum batches of more or less different densities are forwarded successively or alternately which, should be stored at the receiving station separately. To eliminate interference by air pockets and air bubbles moving in the pipe, the radiation beam should be horizontal at the measurement place. For oil density measuring in pipes of large diameter 800 to 1000 mm, the combination of ^{60}Co and scintillation detector is suitable. Moderate density measurement is used mainly for density and solid content monitoring of slurries, for example, in dredgers. The accuracy required for slurry bulk density monitors is an order of magnitude lower than that for petroleum product monitoring. Gamma ray absorption density gauges can be applied effectively for process measuring purposes in chemical engineering, the building materials industry, etc. For density measuring of material transported by conveyor belts, reflection density gauges with ^{137}Cs radiation sources and scintillator detectors are recommended (Fig. 2). For reflection measurements on conveyor belts either a radiation source for which the layer thickness is infinite or a layer thickness kept constant is needed. Portable density gauges can be used for soil density and soil compactness testing. The most extensive use of beta ray absorption density measurement is for the continuous monitoring of packing density in cigarette manufacturing machines.

Quantity Measurement

A frequently occurring problem is that of measuring material flow in transportation systems. The problem can be solved by using nucleonic gauges for solid material transportation by conveyor belts or other means. The measurement is based on the radiation absorption dependence on the $\rho \times l$ product, which is equal to the mass of material per unit surface area in the radiation path. The belt weigher used for quantity measurement at belt transporters consists of a linear radiation source with its length equal to the belt width and a detector array of the same length. The ^{60}Co or ^{137}Cs source is placed underneath the belt and the detector is positioned above it. The radiation emitted by the source is partly absorbed by the substance transported on the belt. An empty belt absorbs approximately 5 to 10 % of the radiation and the variation in radiation attenuation by the transported material depends on the instantaneous thickness (or, sometimes, density) of the layer at the measurement point. Therefore, the detected radiation intensity can be used as a measure of instantaneous thickness or, the quantity of the material passing though the measurement lines. The bulk weight analyzer finds extensive use in coal mines and coal-fired thermal power stations to measure the quantity of produced / consumed fuel. In pneumatic pipe-line transportation systems, the solid quantity flowing in the air carrier can also be determined by radiation absorption techniques. The instantaneously flowing masses are determined by the instruments based on β-ray absorption for low mass material transportation and γ-ray absorption for high-mass material transportation. Another common application of weigh belt analyzer is the continuous monitoring of crude powder quantity in cement manufacturing heat exchangers. The density measured by the nucleonic gauge is proportional to the quantity of the material reaching the heat exchanger. In coal mines the quantity of coal produced is measured by nucleonic gauging (Fig. 3).

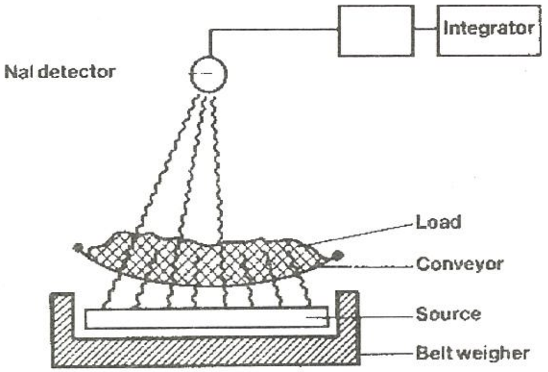

Fig. 2 Density gauge based on gamma transmission

Thickness Measurement

Strict quality control norms demand that the surface mass thickness of the output of certain industrial products be monitored continuously. This also saves raw material. Two types of nucleonic gauges are in use for thickness measurement, viz., absorption gauges and reflection gauges. In thickness measurement by radiation absorption, the source and the detector are placed on opposite sides of the material being tested. In thickness measurement by reflection, the source and the detector are on the same side of the material. Provided the density and the elemental composition of a substance are the same (which is a requirement for all rolled products, like metal sheets), and for those produced by other processes like casting or material deposition by spreading, the degree of absorption depends on the thickness of material alone. For some substances, e.g. paper, instead of its thickness in mm units, the surface mass expressed in g/m^2 units, is the significant term because the

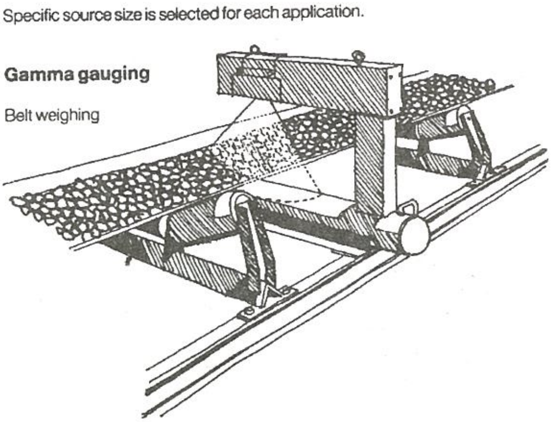

Fig. 3 Gama gauging belt weighing

products are specified commercially by this value ($\Delta l=\rho d$).

The reflection arrangement, is favoured in frequent practical situations when access to both sides is impossible. A crucial point in the solution of thickness measurement problems is the correct choice of the source. The available options are limited by short half-life are further reduced by the specified measurement accuracy. Alpha radiation sources (e.g. ^{210}Po) can be used for the thickness measurement of very thin samples in the thickness range of 5 to 50 g/m^2. Thickness gauges with β sources (^{85}Kr, ^{90}Sr, ^{147}Pm, ^{204}Tl) can be used for the thickness range of 50 to 10,000 g/m^2. Thicknesses of 10^4 to 10^5 g/m^2 can be covered by the absorption of γ rays from ^{60}Co, ^{137}Cs and ^{241}Am or of β ray-induced bremsstrahlung. Ionization chambers, scintillation counters and proportional counters are used as detectors for thickness gauges (Figs. 4 & 5).

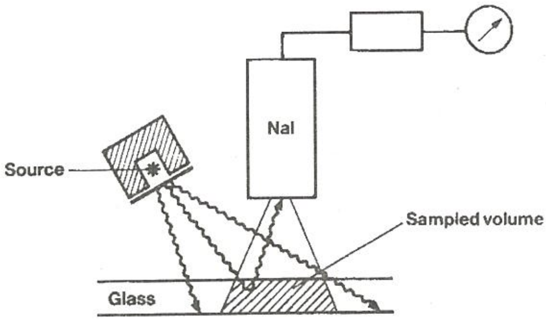

Fig. 4 Gamma back scatter thickness gauge.

Thickness gauges are used mainly for paper manufacture, for metal sheet and foil rolling and for machines manufacturing rubber foil and plastic foil, plate glass, textile and fibre slab production. To measure metal sheet and foil thicknesses in cold rolling nills, mostly β-ray monitors are used up to 5000 g/m^2. Recently, the use of ^{241}Am source has grown rapidly, because γ ray emission energy is most suitable for this application. Radiation sources of activity 10 to 40 GBq are used for these measurements. Because the working conditions at steel plate hot rolling plants are extremely hard, γ ray thickness monitors are preferred. High temperature protection of the measuring components is accomplished by utilizing the source and the detector at suitable distances. Radiation sources of activity 300 to 600 GBq are located usually beneath the sheets tested while the detector above them in an independent mechanical structure to avoid vibration and shock effects by rolling mills. The thickness of plate glass can be measured by the γ rays from ^{241}Am (Fig. 4). The thickness measurement of plate glass presents difficulties similar to those of hot-rolled iron plate measurements. In sheet metal industries, paper and PVC film manufacturing industries, the need for ensuring the required uniform thickness is achieved by means of nucleonic thickness gauges. Protective coating thickness of *a few microns* can be controlled accurately by nucleonic thickness gauges.

Coating Thickness Measurement

Coating thicknesses can be determined by destructive or nondestructive techniques. Film thicknesses can be determined with radioisotopes in many ways (e.g. XRF, activation, scattering). The principle of thickness gauging by back-scattering technique using β radiation is that the intensity of scattered particles for homogeneous material composition is proportional to the thickness, up to a saturation material thickness. Depending upon the energy of the β radiation and the material tested, the saturation thickness of solids is a few mm (500 to 1500 g/m^2). The intensity variation of the scattered radiation will depend on the atomic numbers of the substrate and coating substance. Coating thicknesses up to 50 μm can be measured using β backscatter gauges. For thin coating, low energy β sources are

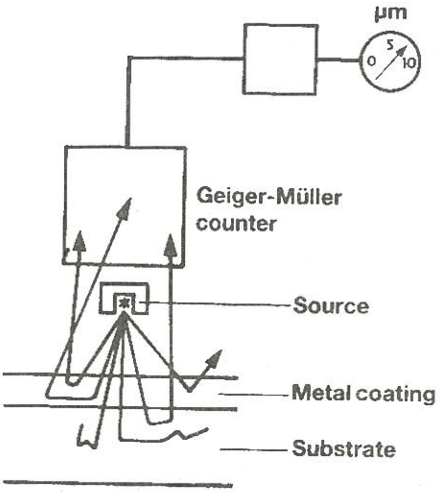

Fig. 5 Beta backscatter thickness gauging

needed. The common β sources used for coating thickness measurements are ^{14}C, ^{147}Pm, ^{204}Tl and ^{90}Sr in the activity range of 100 kBq to 0.4 GBq. End window GM counters and scintillation detectors are commonly used. In the case of continuous processes, the ionization chamber is preferred using an uncoated sample as reference and comparing it with the coated samples. β-ray backscatter gauges are used for copper, gold, silver, tin and plastic coating thickness measurements, provided the difference in the atomic numbers of the coating material and that of the substrate is at least 2.

Moisture Content Measurement

In certain industries processing moist or wetted substances, the problems associated with control requirements and quality improvement, warrant a knowledge, within well-defined limits, of the moisture content in the processing stuffs or in mixtures. This problem can be solved only by continuous measurement systems with possible interconnection capabilities to control equipment. For continuous moisture determination during technological processes, nucleonic gauging techniques based on neutron scattering are valuable.

Neutron scattering and moderation can be used for determination of moisture content. The most commonly used neutron source is ^{241}Am-Be of activity 4 to 10 GBq. This source emits fast neutrons which interact with the medium. If the medium contains moisture, the fast neutrons would be thermalised and scatterred. The moisture gauge in a BF_3 counter for neutron counting. The amount of α detected is a measure of the neutron scattered into the BF_3 counter. Higher the thermal neutron count, higher is the moisture content. The moisture content determination in a given volume may be affected if the mass filled in the volume is not constant. Hence, determination of moisture content for a given density only will yield meaningful results. Hence, often the moisture gauge is used in conjunction with a density gauge, usually incorporating ^{137}Cs of activity 0.4 to 1 GBq. Neutron moisture gauges are used during concrete fabrication, ore dressing, blending of ceramic materials, glass manufacture and foundry sand conditioning processes, determination of structure compactness, damming work, road construction and also during the production of building materials. The best known application of moisture gauge is oil well logging.

Bright Future

Nucleonic gauging is a growing technology. This technology offers accurate results, assures the best possible quality at a reasonable cost. The radiological safety requirements are minimal since the main attraction of these gauges is their design safety. The radiation levels around the gauges are, generally, so low that, except in the case of well logging, there is no need for personal monitoring. It is enough if the users are familiar with basic radiological safety and use the common radiation survey meters. Thus this technology has wide scope in any economy that depends on technology. It also offers a bright future for industrial growth.

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Radiotracer Applications in Industry

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Introduction

Radiotracer Technique

The first practical application of radioactive substance as a "tracer" was made by George de Hevesy. The use of radiotracers for troubleshooting and to investigate flow phenomena in chemical process equipment has specific advantages over conventional tracers. The main advantages of radiotracers are physico-chemical compatibility, high detection sensitivity, in-situ detection, availability of a number of radiotracers for different phases, stability in harsh industrial environment and their limited memory effects.

In radiotracer technique, the radioactive material in a suitable physico-chemical form similar to the process material is injected into the system at the inlet and its passage is monitored along the system at strategically selected locations using radiation detectors. The presence of tracer or profile of tracer concentration as a function of time at detection location(s) are used to obtain information about occurrence of malfunctions, if any, and hydrodynamic behaviour of the process equipment. The general principle of tracer technique is shown in Fig. 1. Most commonly used radiotracers in industry are listed in Table 1.

Selection Criteria

The physico-chemical form, half-life, specific activity, type and energy of radiation and radiotoxicity are main characteristics considered for the selection of a radiotracer. If chemical properties such as reaction kinetics, solubility, vapour pressure and molecular diffusion are to be studied then both physical and chemical properties of the tracer have to be identical to that of the material being traced and the tracer is referred to as chemical radioactive tracer. For example, ^{24}Na as NaOH is an ideal tracer for tracing NaOH in a chemical reaction. If the hydrodynamic behaviour of the process material is to be investigated, as in the case of most of the industrial systems, then only the physical properties of the tracer are considered for the selection and the tracer is referred as physical radioactive tracer. For example, para- dibromobenzene is used to investigate the hydrodynamic behaviour of petroleum and petro-chemical products in industrial systems.

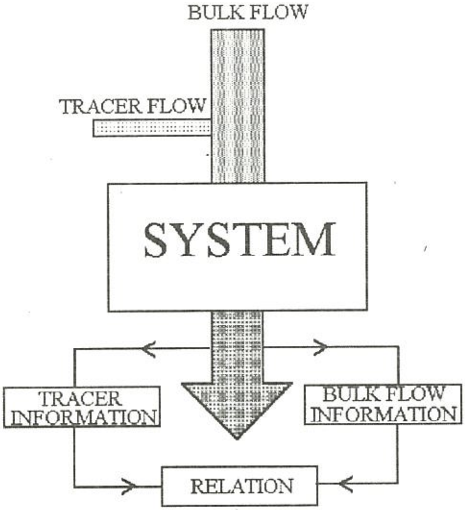

Fig. 1 General principle of tracer method

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TABLE 1. Most Commonly used Radiotracers in Industry

Isotope	Half-life	Radiation type, energy in MeV and abundance	Chemical form	Tracing of phase
Tritium (^{3}H)	12.6 y	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, p-Dibromo benzene, Dibrobiphenyl, Methyl bromide	Aqueous Organic Organic Gas
^{140}La	40 h	γ : 1.16 (95%) 0.92 (10%) 0.82 (27%) 2.54 (4%)	Lanthanum Chloride	Solid (Adsorbed)
^{198}Au	2.7 d	γ : 0.41 (99%)	Chloroauric acid	Solid (Adsorbed)
^{197}Hg	2.7 d	γ : 0.077 (19%)	Mercury metal	Mercury
^{203}Hg	46.6 d	γ : 0.28 (86%)	Mercury metal	Mercury
^{131}I	8.04 d	γ : 0.36 (80%) 0.64 (9%)	Potassium or sodium iodide, iodobenzene.	Aqueous Organic
^{99m}Tc	6 h	γ : 0.14 (90%)	Sodium pertechnatate	Aqueous
^{46}Sc	84 d	γ : 0.89 (100%) 1.84 (100%)	Glass	Solid (particles)
^{85}Kr	10.6 y	γ : 0.51 (0.7%)	Krypton	Gas
^{79}Kr	35 h	γ : 0.51 (15%)	Krypton	Gas
^{41}Ar	110 min	γ : 1.29 (99%)	Argon	Gas

Half-life of the radiotracer should be comparable to the duration of the study. Most of the radiotracers commonly used in industrial tracer experiments are gamma emitting tracers with the exception of tritium. The energy of the gamma radiation should be sufficiently high to penetrate through the wall of the system for '*in situ*' detection. Lower energy gamma emitting tracers are, on the other hand, easier to transport in view of their modest shielding requirement.

Industrial Applications

Some of the common applications of radiotracer techniques in industry are briefly discussed below.

Blockage Detection and Location

In pipelines blockage occurs because of inadvertent introduction of foreign materials during construction and due to scaling on walls during the operation. In tracer method, a small sealed source (3.7 MBq to 37 MBq) of ^{60}Co or ^{192}Ir or ^{137}Cs is loaded into a "pig" introduced into the pipeline and is pushed along by air or water pressure. The movement of the pig in the pipeline is monitored by radiation detectors located at suitable trenches along the pipeline. Non-arrival of the pig at any point indicates a blockage upstream of that point. The technique has been routinely used for blockage location in buried process pipelines in oil and gas, petroleum, petro-chemical and chemical industries all over the world for the last three decades. The same procedure using a spherical rubber pig loaded with a tiny ^{60}Co source could be used to locate the interface between different fluids in pipelines. Some of the examples of blockage detection in pipelines and industrial systems are reported by Charlton [1] and Rao [2].

Leak Detection and Location

Any undesirable interconnection between isolated parts of a system or between two systems is a leak. By injecting the radioactive tracer into the part suspected to be leaking and monitoring for the tracer in the contaminated part, leak, if any, is unambiguously detected. Location of actual leak position is a little more complicated as the monitoring procedure needs to be designed to suit each specific application. This is probably the most widespread use of radiotracers in industrial trouble shooting with highest benefit to cost ratio. Some of the applications of radiotracer technique for leak detection in buried pipelines and industrial systems are reported by Charlton et al. [1] and Pant et al.[3].

Flow Rate Measurement

Detailed knowledge of flow rates in different systems of a plant is essential to operate the plant at an optimum efficiency. The knowledge of the flow rates in a system is required for one or more than one of the following purposes: to calibrate the installed flow meters, to measure the flow rate in parts of the plant which do not possess installed flow meters, to measure the distribution of flow in a network, to provide data for consumption of mass balance across a plant, to detect and quantify leaks, to measure the efficiency of pumps and turbines, to diagnose faults in plant operation and for environmental control.

Pulse velocity and dilution methods employing radiotracersare used to measure flow rates of different phases in industrial process systems. The principles of the methods and their various applications are discussed in the IAEA guide book [4] and references therein.

Residence Time Distribution Measurement

Residence time distribution (RTD) of process material in a system is a characteristic parameter of continuous process systems which provides information about hydrodynamic behaviour of the systems and has significant bearing on the product quality and process efficiency. Therefore, the knowledge of RTD is essential to investigate the hydrodynamic behaviour of a system and assessment of its performance. Radiotracer techniques are widely used to measure RTD of process material in industrial process systems.

The molecules of a fluid entering the system at a certain moment of time t=0 will generally not stay in the system for exactly the same period and thus there will be a distribution of residence times. Fig. 2 represents the frequency distribution function often used in statistics and called the E curve in RTD description. The shaded area E dt represents the fraction of fluid molecules that entered the system at t=0 and leaves the reactor between t and t+dt. The E curve thus defined has an area equal to unity and is given by:

$$\int_0^\infty E(t)dt = 1 \qquad (1)$$

where, E(t) is residence time distribution function which is non-negative over (0,∞).

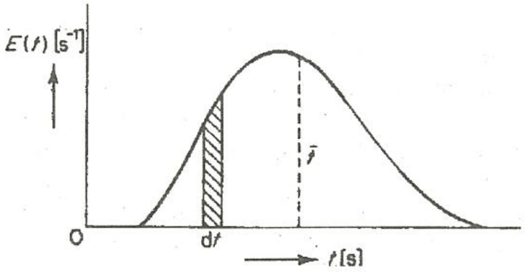

Fig. 2 Residence time distribution or E-curve

The RTD has following applications: (a) identification of malfunctions like leak, scaling/fouling and dead/stagnant volume, bypassing, parallel flow paths or chanelling, internal or external recirculation, radial distribution, holdup and axial dispersion in packed beds and modeling of control systems; (b) investigation of hydrodynamic bevaviour of industrial process systems and (c) development and verification of mathematical models.

Material/Volume Measurement

Mass balance approach using radiotracers is routinely used for material and volume measurement in chemical industry. The isotope dilution method and measurement of mean residence time form the basis of such measurements.

The extent of dilution of a known amount of tracer in a batch system provides a measure of volume material of the system. If an aliquot of known mass of tracer m_a with known specific concentration C_a is introduced into a system and a sample of known mass m_s is taken for tracer concentration (C_s) measurement after complete mixing (homogenisation), then mass (m_s) is given by:

$$m_s = m_a\left(\frac{C_a}{C_s} - 1\right) \tag{2}$$

Similarly in the case of volume measurement, Vs is given by:

$$V_s = V_s\left(\frac{C_a}{C_s} - 1\right) \tag{3}$$

Since count rates of samples measured under identical detection geometry are proportional to their concentrations, eqn (2) can be re-written as:

$$m_s = F\, m_a\left(\frac{N_a}{N_s}\right) \tag{4}$$

where, N_a and N_s are net count rates in an aliquot of the injected solution after dilution with trace material and sample after homogenisation respectively.

A common application of the technique is inventory of mercury in caustic soda plants. Radioactive elemental mercury (^{197}Hg and ^{203}Hg) is injected into the operating cell. The tracer concentration allowing it to mix thoroughly over a period of a day [5]. Standards prepared from samples of injected mercury are also counted along with the cell samples. The accuracy obtainable is 1-1.5%. The technique is employed on a regular basis by many caustic soda plants in India and elsewhere.

The determination of slag and metal in furnaces in metallurgical industry is another common example of material inventory using isotope dilution method. A few examples of applications are described in IAEA guide book [4]. The technique is especially useful for volume measurement in containers of irregular shape or liquid with foam above liquid layer in various industries. Stimulus-Response Method is another technique used for material inventory [4].

Effluent Dispersion

The untreated effluents produced in chemical, petro-chemical, fertilizer industries and domestic sewage generated in big cities is usually disposed off into a river, creek or sea available nearby and may pollute water bodies. Dilution and dispersion of the effluent in such water bodies depends upon wind force, tidal current and other hydraulic conditions as well as the temperature and salinity gradients. Dispersion measurements are required to investigate the physical dilution of pollutants and demarcate the area of contamination with an objective to verify the suitability of a site used for a proposed new outfall. Radiotracer techniques provide the required data under field conditions either by using existing outfall or by simulating the outfall in a physical model.

A suitable radiotracer is injected either instantaneously or continuously into the simulated effluent/sewage and the tracer concentration is strategically measured across different transactions at a specified depth using water proof scintillation detectors to obtain isocount contours. From the isocount contours, the maximum lateral and longitudinal distances are determined and the area of contamination is demarcated. Ratio of the concentration of the tracer at the discharge point to the concentration of tracer at a particular position gives dilution factors at that position. Further, suitable mathematical models are used to simulate the tracer data and model parameters such as dispersion coefficient are estimated by Kumar et al.[6].

Mixing /Blending Time Measurement

Radiotracer techniques are widely used to measure the mixing times in pilot scale as well as in large scale batch systems in different industries. The technique involves the introduction of a suitable tracer into the system along with one of the components of the mix and monitor the concentration of the tracer either continuously using radiation detectors placed at one or more than one locations or samples taken from a single location at regular intervals. Another approach is to take a large number of samples from different locations, possibly at less frequent intervals, which is statistically representative of the process. In this case the average concentration of a given group of samples is determined and the standard deviation (σ) is calculated. Adequate mixing is deemed to have been achieved when σ becomes constant. The standard deviation is calculated as:

$$\sigma = \sqrt{\frac{\sum (C - C_{av})^2}{n-1}} \tag{5}$$

where, C and C_{av} are sample tracer concentration and mean tracer concentration of a given group of n samples. Some of the studies on measurement of blending/mixing time have been reported by Charlton [1] and Hoffman [7].

Liquid Entrainment or Carry Over

Liquid droplets entrained in gas streams from process vessels can cause severe problems in chemical plants. For example, liquid caught up in the gas stream from a separator in an oil fractionation chain can cause severe damage to a downstream gas compressor. Similarly in distillation processes generally non-volatile compounds carried over in the overhead stream from a column can act as catalyst poison in catalytic cracking units. Radiotracer techniques are sometimes used to detect carryover of the liquid. In the technique, a suitable radiotracer is injected into the liquid stream at a strategically selected point and its presence is monitored in the gas stream. If the amount of carryover can be estimated and correlated with controllable process parameters such as feed rate or reflux rate to a distillation column, it is possible to improve the process and stop the carryover. The gross carryover can be usually investigated using sealed source gamma-ray absorption technique. However, slight but persistent carryover is best investigated using radiotracer technique. Some of the applications of the radiotracer technique in carryover studies are reported by Otto et al. [8].

The technique is also used to examine the quality of throttle and extraction steam of steam turbines operating predominately within the moisture region with steam supply in nuclear power plants. The moisture in the steam leaving the steam generator is the result of water carryover. A radiotracer present in the steam generator water will also be found in the steam leaving the generator. Sodium-24 as sodium carbonate is injected into the feed water to the steam generator and monitored in the steam after it condensation. The wetness (W) or the fraction of the moisture is estimated as:

$$W = \frac{C_{cw}}{C_{fw}} \tag{6}$$

where, C_{cw} and C_{fw} are tracer concentration in condensate and feed water respectively.

Sediment Transport Studies

Understanding of the movement of sediment either on sea bed or river bed or in suspension is essential to harbour development programme. Radiotracer techniques are in use to evaluate parameters such as direction of movement, velocity and quantity of of bedload transport in many countries for over three decades. The procedure involves preparation of a radioactive particulate tracer having similar physicochemical properties as the bed material, injection of the tracer at the desired point, tracking of the tracer with underwater nuclear detectors and interpretation of isocount contours to evaluate the parameters mentioned above. Two kinds of tracer preparations are in common use. In first method, the tracer is prepared by incorporating an active element like scandium or irridium in glass, ground the glass and mix the different grain size fractions to have the grain size distribution as the bed material of interest and activate the powder in a nuclear reactor to produce the radiotracer (incorporating ^{46}Sc or ^{192}Ir). In the second method, normally used in short duration studies, careful treatment of the surfaces of the grains is needed to obtain good labelling of radioactive material.

Most of the radiotracer investigations are amied at:

- Examining the suitability of the existing dumping ground for dreadged silt.
- Selection of a suitable dumping ground for new projects
- Examining the suitability of alignments of proposed navigation channels
- Pollution studies in coastal areas

In India about more than 50 large radiotracer investigations have been carried out in all major ports over the last three decades.

Economical Benefits

A number of industries, particularly chemical industry, have been considerably benefited from various radiotracer applications. Some of the factors considered for estimating the cost to benefit ratios are as follows:

- direct cost comparison with alternative techniques
- savings due to increased production efficiency
- savings due to improved product quality
- savings due to reduction in down time of the plant

On the basis of above considerations IAEA [9] proposed a formula often referred as "Agency's Formula" to estimate the economical benefits accrued due to the applications of radiotracer techniques in various industries. The cost of the tracer investigation is clearly defined whereas it is difficult to estimate the actual direct or indirect benefits. The cost to benefit ratios of industial applications of radiotracer carried out all over the world ranges from 1:3 to 1:5000.

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Applications of Radiotracer Techniques in Designing of Industrial Process Systems

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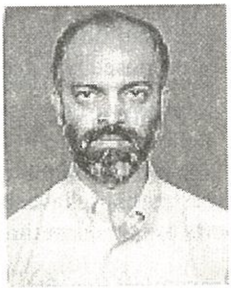

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Introduction

Radiotracer technology is being used in many diverse scientific disciplines to gain a better understanding of the dynamic processes. Medicine, biology, agriculture, chemistry and chemical engineering are examples that all have a wealth of applications. Some of the important aspects to consider as regards the use of tracer technology are;

- a wide range of suitable radiotracers are available
- availability of modern nucleonic detection equipment that is highly reliable, sensitive and relatively cheap
- radiotracers have limited half lives. As the radioisotopes decay at known rates, they offer considerable advantages in a wide range of investigations requiring consecutive experiments. A suitable radioisotope will effectively decay away before the next injection thus avoiding problems of residual tracer concentration or tracer build-up in the system.
- radiotracers can be introduced into most of the systems for investigation without affecting the flow and material balance.

On technical grounds, radiotracers can be clearly seen to provide not only characteristics unavailable in other tracer materials but also the potential for clear cost effective justification for their use.

The typical applications of radioactive tracers include process design of reactors, various unit operations such as mixing, drying, crystallization and calcination, environmental pollution control and process control. In the following sections, a few of the important applications are described.

Reactor Design

A reactor can be considered as the heart of the process plant where either chemical reactions such

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as oxidation, nitration and hydrogenation or physical operations such as blending, emulsification, gas transfer and separation occur. All the above operations and the efficiency of the process depend on the effectiveness of the design of the reactors. The basic design strategy is to supply and/or to remove energy from the reactor and efficient use of the same for the desired process application. The parameters which are of crucial importance in the design procedure are mean residence time, residence time distribution and the non-ideal behaviour for the different phases present in the reactor (Gas-Liquid-Solid) and the phase-phase interaction. Proper estimation of these parameters is important and radiotracer can potentially be applied for the measurement of these parameters. Tracers can be used for every phase and practically for every parameter assessment. The important design considerations where the use of radiotracers is being practised in the process and other industries are as follows:

- Flow rate measurement with precision
- Qualitative assessment of the flow patterns, examining the validity of the plug flow or complete backmixing assumptions and estimation of dispersion coefficients for all the phases
- Impulse response evaluation (i.e. transfer function identification)
- Quantification of the flow patterns, mean velocities of dispersed and continuous phases and settling velocity in the case of fluidised beds
- Measurement of line average hold-up of the dispersed phase, interfacial area available for contacting
- Estimation of mixing efficiencies which can lead to optimum homogenous mixing time
- Measurement of residence time distribution in reactors and identification of active volume, dead volume, channelling, by-pass etc.

The details of the mathematical treatment to interpret the tracer response curves can be obtained from Foggler [1] and Levenspiel [2].

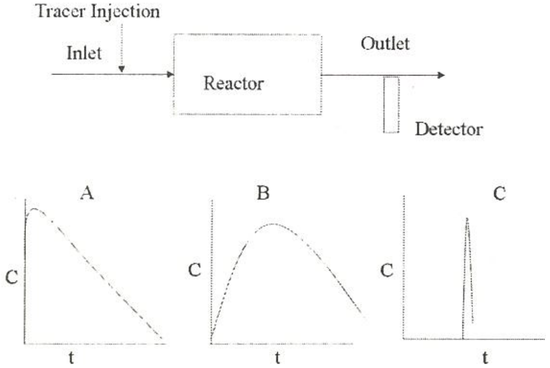

Fig. 1 Concentration of the tracer against time at the outlet; A - complete mixing, B - intermediate mixing and C - plug flow

The residence time distribution studies are very important in the design of chemical reactors. Usually the tracer is injected at the inlet and the concentration is monitored at the outlet with the help of suitable radiation detector. The tracer response depends on the type of the reactor, mixing characteristics and the flow patterns existing in the same. The typical responses for the three conditions have been shown Fig. 1. The two ideal conditions are the plug flow (all the molecules spent exactly identical time in the reactor) and complete backmixing (input is instantaneously mixed within the reactor). However, in practice an intermediate response is usually observed.

It is very important to analyze the data obtained by introducing the radioactive tracer in the reactor. Mean residence time (τ) is defined as the first moment of the concentration time distribution curve (A, B and C in the Fig. 1) and is compared with the theoretical mean residence time obtained by dividing the system volume by the flow rate ($\tau = V/Q$). Any deviation between the two is an indication of the dead volume within the system. Variance (σ^2) is another important characteristic which describes the spread of the distribution and is equal to the second moment of c-t curve. There are two simple flow models : i.e. axial dispersion model and tank-in-series model, used to characterize the flow process in terms of the deviation from the ideal plug or completely mixed flow conditions.

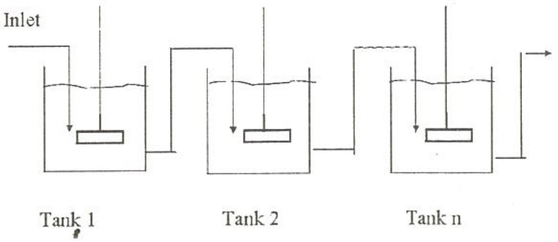

Fig. 2 Tanks-in-series model.

Axial Dispersion Model

The dispersion model is used to describe the non-ideality of the tubular reactors. In this model, there is an axial dispersion of the material, which is governed by an analogy to Fick's law of diffusion, superimposed on the flow. The model equation in terms of the dimensionless numbers can be given as:

$$\frac{1}{Pe}\frac{\partial^2\psi}{\partial\lambda^2}-\frac{\partial\psi}{\partial\lambda}=\frac{\partial\psi}{\partial\theta} \qquad (1)$$

where, ψ is the non-dimensional concentration ($c(t)/c(0)$), λ is non-dimensional distance (z/L), L is distance between two measuring points and z is distance along x-axis, θ is the non-dimensional time ($\theta=t/\bar{t}$), $\bar{t}$ is mean residence time, Pe is Peclet number ($Pe=uL/D$), D is axial dispersion coefficient, u is mean velocity, C(t) is tracer concentration at time t, Co is initial tracer concentration. The left hand side of the equation represents the flow of the tracer due to convection and dispersion and hence the change of concentration with respect to distance. Thus the concentration varies with time and also with distance from the starting point. The dimensionless number which characterizes the flow by this model is the Peclet number. In practice, the c-t response is simulated with assumption of different values of Pe and matched with the experimental tracer response. The numerical value of Pe for the best fitting simulation represents the degree of deviation from either of the ideal conditions. Very high Pe value indicates a tendency to plug flow and very low Pe values indicates well mixed flow.

Tank-in-Series Model

In this case the fluid is assumed to be passing through a series of closely placed and perfectly mixed tanks of equal volumes (Fig. 2). It is easier to simulate the c-t curves with this model since it is independent of boundary conditions.

The theoretical equation for tank-in-series model which gives residence time distribution (RTD) for n CSTRs in series, E(t) is given as:

$$E(t)=\frac{n^n t^{n-1} e^{-nt/\bar{t}}}{\bar{t}^n (n-1)!} \qquad (2)$$

where n is the number of tanks in series, is the adjustable parameter and $\bar{t}$ is the mean residence time. E(t) is defined as the exit age distribution of the tracer and is given mathematically as:

$$E(t)=\frac{C(t)}{\int_0^t C(t)dt} \qquad (3)$$

The integral in the denominator gives the area under the c curve.

The number of tanks can be obtained by calculating the dimensionless variance from the tracer experiment or model simulation of experimental RTD curve. It can be easily shown that for a very large number of the tanks, the solution represents the plug flow. When 'n' is equal to one, it is equal to the situation of completely mixed stirred tank. The numerical value of 'n' obtained for the best fit curve using the model (similar to the best fit Pe number for the earlier model) represents the degree of deviation of the process from either of the two ideal conditions. For details about the measurements of RTD and the further analysis, readers are requested to refer Curl and Mcmillin [3], Hill [4] and Smith [5]. A list of the different radioactive tracers that can be used for the parameter estimation for different phases [6] is given in the article by Pant in this volume.

Process Control

Process control is very important for the efficient operation of any process plant. The parameters that need to be controlled are temperature, pressure, flow rate, residence time concentration etc. Any parameter before control needs to be measured precisely and the radioactive tracers have been used for the measurement of flow rate, residence time and concentration, though not for temperature and pressure. The function of the tracer can be stated as, to trace the fluid flow / path without any slip and emit radiations which can be detected. The intensity of signal is measured in terms of counts per unit time. Radiotracer technique used for measurement of above mentioned parameters will require a suitable tracer (in terms of miscibility, half life and activity), an efficient detection system and also well established mathematical models to quantify the degree of mixing (e.g. Axial dispersion model, Tank in series model).

Flow Rate Measurement

In process plants, radiotracer methods are used to measure product flow rates more accurately than those obtained by installed flow instruments and check the calibration of conventional flow meters installed in the lines. As the radiotracer methods require only addition of a small amount of a substance to the main flow stream, there is no interference with the process plant operation and therefore no interruption to production either. Depending on the actual plant situation, the available length of measuring distances between the two detectors and the stability of flow in the line during the time of measurements, it is possible to achieve accuracy of smaller than 1 % with the radiotracer methods. The two types of techniques used for flow measurement are (a) The pulse velocity method and (b) The dilution method.

In the first method the measurement is based on the injection of suitable tracer into a pipe line and the subsequent timing of the tracer pulse between the two detectors situated downstream from the injection time. The mixing length required for high accuracy is of the order of 150 pipe diameters of the pipe while lower mixing length will be sufficient depending upon the extent of additional turbulence due to presence of valves, orifice etc. The flow velocity is calculated from the distance between the detectors and the pulse transit time, and the volumetric flow rate can then be calculated from the product of the velocity and the cross sectional area of the pipe.

The dilution method is based on the injection of a suitable tracer at a known constant rate into the flow line and the subsequent sampling of the product downstream from the injection point. The method can be used for the measurement of liquid, gas and steam flow. From the mass balance of the tracer, the unknown flow rate (Q) can be calculated as;

$$Q = q\,(Ci - Cs) / (Cs - Co) \qquad (4)$$

where, q is the injection flow rate, Ci is the concentration of the tracer in the injection solution, Cs is the concentration of the tracer in the downstream product and Co is the background concentration of the tracer in the line. Since only concentration of the tracer is required at the sampling point, samples can even be taken from the branch line in the cases where main line is unaccessible. The most important requirement of the method is that sufficient distance be allowed between the injection and the sampling point to ensure complete mixing of the tracer throughout the cross-section of the conduit to ensure representative sampling. As the measurements depend on dilution only, it is independent of the linear velocity of the fluid or the dimensions of the conduit. Hence if the mixing requirements are satisfied, this method can be used for flow measurements in irregular containment, i.e. in open channels or rivers.

Mixing Time Measurement

While designing a mixing unit it is important to establish the degree of homogeneity and the time required for the same. The degree of homogeneity can be tested with the help of the radioactive tracers. A radiotracer such as ^{140}La labelled kaolin can be mixed in the stock solution before mixing operation starts. The homogeneity of the solution can be assessed by measuring tracer concentration using either monitored by immersed scintillation detector into the mixture or samples withdrawn at multiple positions. The obtained data are analyzed for estimating the mixing time depending on the required degree of homogeneity.

The residence time distribution and hence the mean residence time can also be obtained by injecting radioactive tracer at the inlet and analyzing the concentration of the same at the outlet of the reactor. Such an analysis also gives an indication of the dead volumes existing in the mixer.

Designing Oil Recovery Units

In petroleum industry, oil is recovered from reservoirs under their own pressures till the production rates fall below a certain level. This is known as primary recovery phase. After this, in the secondary recovery stage, water or gas can be injected into the layer for the oil recovery. However, before undertaking secondary recovery operation it is necessary to ensure that the investment for such an undertaking is economically feasible and to locate the production wells for optimum production. Radioactive tracers can be used to investigate the interconnections between the injection and the production wells and identify the characteristics of layer formation from the tracer break through curves.

Conclusions

The radiotracer technology can be utilized at every stage of the operation: (1) For design of plant components, based on the pilot plant studies giving confidence in scale-up, (2) For optimization of the reactor performance parameters, (3) For efficient running of the plant i.e. in terms of controlled operating conditions and (4) As a diagnostic tool, to establish the deviation of the operating parameters from the design parameters so that the corrective action can be taken. This, being a non-intrusive measurement technique, experiments can be carried out without disturbing the plant operation.

The interpretation of the radiotracer data requires physical understanding of the process and operation. Mathematical models coupled with radiotracer response are likely to be the key to the success of this technique of design/optimization/ control and correction of the chemical process plants.

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Application of Tracers in Effluent Dispersion Studies at Bombay Coast

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Introduction

It is a common practice to dispose off the treated industrial effluent and domestic wastewater into nearby perennial water body. In doing so, the assimilative capacity of the system has to be considered for sustainable development and conservation of environment. However, in the wake of intense human pressures, it is recognized that the traditional practice of releasing waste into water bodies requires careful control and better pre-release treatment.

The ocean being a vast natural sink, has large assimilative capacity. Wastewater discharge in the ocean is a preferred management option world wide, for all the coastal cities. However, the problem occurs when anthropogenic activities create huge and concentrated wastewater discharge in a limited area instead of dispersing them over large areas and at longer distances away from the coasts of the city. Of 25 megacities in the world, 17 are coastal cities with 25% of world's population which use ocean for waste disposal.

For a metro city like Mumbai, generating about 2225 million liters per day of sewage from seven drainage zones, the problem of disposal can be complex [1]. Five drainage zones directly or indirectly discharge wastewater on the west coast. Under the Bombay Sewage Disposal Project (BSDP) scheme, at Worli and Bandra sewage will be disposed on west coast through 3.4 km long outfall with diffuser section at the end after preliminary treatment in the form of screening and degritting.

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The outfall at Worli has been commissioned in June 1999.

Diffusers offer an attractive engineering solution to the problem of managing wastewater discharges in an environmentally sound way. The mixing behaviour of any wastewater discharge through diffusers and marine outfall is governed by the interplay of ambient conditions in the receiving water body and by the discharge characteristics. Therefore while using ocean as sink, proper designs of wastewater treatment and disposal plan are required to avoid significant adverse impact on the flora and fauna.

Tracer investigations provide a valuable tool to obtain information on several pertinent parameters of waters that receive wastewater. For the study of dispersion in receiving water, dilution and the residence time of the discharged wastewater are the two fundamental physical parameters with reference to the biological and bacterial consequences of discharges.

Globally different radiotracers are commonly used in environmental field. These are available in different forms viz. gaseous tracers like ^{76}As, ^{82}Br, ^{85}Kr, ^{133}Xe and ^{35}S, organic material tracers like ^{24}Na, ^{82}Br, ^{140}La, ^{64}Cu and ^{60}Co, water tracers like ^{113m}In, ^{99m}Tc, ^{82}Br, ^{198}Au and ^{137m}Ba, sand tracers like ^{140}La, ^{198}Au, ^{52}Mn, ^{147}Nd and ^{192}Br and fine particle tracers like ^{113m}In, ^{99m}Tc, ^{198}Au, ^{51}Cr and $^{175+181}$Hf.

In environmental studies, the tracers are used in finding out dispersion of wastewater into the river and coastal region, blockage detection in underground pipe lines, sediments transport studies in estuaries, hydrodynamic behaviour of fluidized bed reactor in a treatment system etc. These tracers are used in industrial applications for identifying troubleshooting factors and process control.

This paper presents the findings of investigations carried out on dilution and dispersion patterns of wastewater released into the ocean through marine outfall by tracer techniques.

Objectives

The primary objectives of the tracer studies carried around Mumbai coast were :

- Monitor the dispersion of the plume in three dimensions as a function of distance from the diffuser heads.
- Measure the near and far field dilution factors for marine outfall
- Compare the data from the isotope and dye tracers to obtain quality assurance on both the techniques.
- Estimate approximate transit times from the effluent channel to the diffuser under normal operating conditions.

Estimation of three parameters were considered during this study to evaluate the pollutional status viz. radiotracer, fluorescent dye (Rhodamine WT) and Bio-chemical Oxygen Demand (BOD). The data was used to find out actual initial dilution and compared with mathematical modelling results.

Study Area

Experiments were conducted at new 3.4 km long sewage outfall commissioned in September 1999 at worli (Fig. 1). The discharge of wastewater from the outfall was between 350 to 400 mld.

Methodology

During the first experiment a controlled wastewater discharge was maintained at 2.4 m^3/s and in second experiment the normal operation of discharging 7.2 m^3/s of wastewater was followed. The parallel injection of two different tracers viz. ^{82}Br and fluorescent tracer (Rhodamine-WT) was employed to determine the dilution and the dispersion of the wastewater discharged on the west coast. Rhodamine WT dye tracer was used for the experiment because of its stable nature and solubility in the natural waters. Samples were collected at various intervals and locations and brought to laboratory for analysis on spectroflourometer (Shimadzu - RF 5000). Radiotracer concentrations were measured in-situ by scintillation detectors.

Tracer Injection

Radioisotope ^{82}Br ($t_{1/2}$ = 36 h) in the form of aqueous solution of ammonium bromide was used as a radiotracer for the experiment in view of its excellent property to trace the sewage discharges.

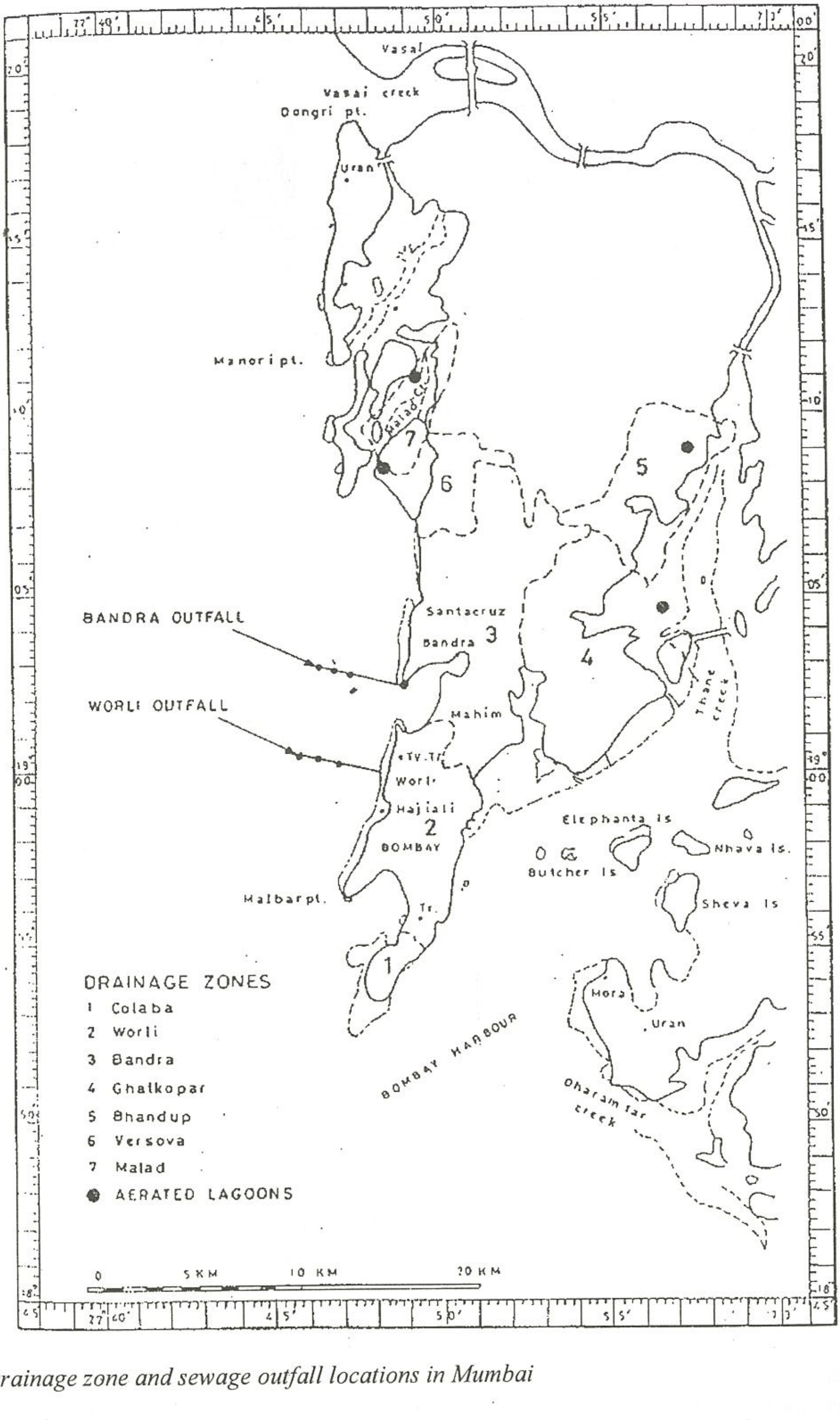

Fig. 1 Drainage zone and sewage outfall locations in Mumbai

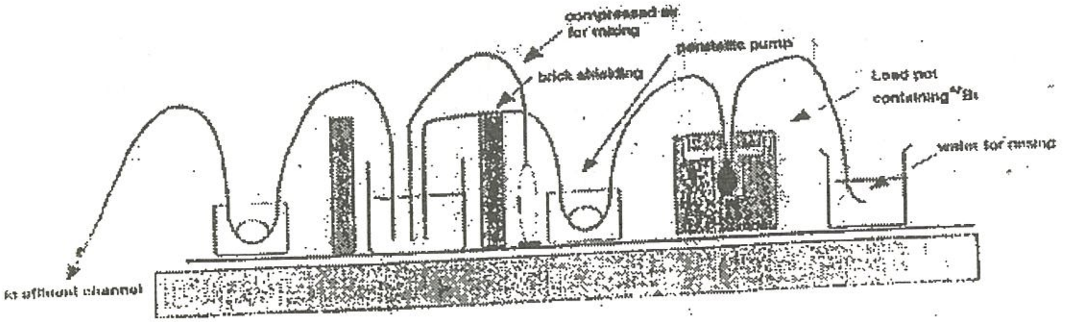

Fig. 2 Schematic of radiotracer injection into the effluent channel

The first experiment was conducted during ebb tide from the 3.4 km Worli outfall diffuser location. About 110 GBq of radiotracer ^{82}Br was diluted in 15 L of water and injected at the rate of 250 mL/min into the sewage in the equalization tank after grit chamber to ensure even distribution and proper mixing. The injection was continued for one hour.

Rhodamine WT was added as slug dose of 10 kg dissolved in 100 L of water to indicate visual appearance of wastewater plume coming out of diffuser and the time taken for travel of tracer from the injection point to the sea surface near diffuser. The application of Rhodmine WT also helped to evaluate the functioning and distribution pattern of diffusers.

The second set of experiments were carried out during flood tide at the diffuser. About 64 GBq (1.72 Ci) of ^{82}Br was transferred into a barrel and diluted with 25 L of water Fig. 2 present the schematic of injection system. Mixing was accomplished by bubbling compressed air. Peristaltic pump was used for injection of radiotracer with a rate of 424 mL/min for 1 hour. 5 kg of Rhodamine WT dye was dissolved in 100 L of water and this solution was introduced at the rate of 7 L per minute for about 35 minutes. Both the tracers were simultaneously and continuously pumped at a constant rate.

Three boats were stationed at different locations along the expected path of the activity plume, decided on the basis of prevailing current patterns in the study area. To detect the radioactivity for near field region one boat was placed very close to the diffuser section in a stationary position. Other two boats were moving with the arrangements to do transacts across the plume of the activity. The activity profiling was carried out for 1.5 hours after the first count for radiotracer was recorded. Positions of the radioactivity measurement were recorded by Differential Global Positioning System (Del Norte Technology).

S4 current meter was employed to measure the temporal variation of the ambient current velocities. Concentrations of radiotracer were monitored using waterproof scintillation detectors connected to scalar rate meters. Lateral transacts at various longitudinal distances were undertaken to monitor the levels of radiotracer. Depth profiles of activities were also established.

The data generated was analyzed to find out the dilution and dispersion of wastefield in the vicinity of diffuser section of outfall. (Tables 1 and 2, Figs. 3 and 4). Initial dilution of radiotracer is presented in Table 1.

Table 1 : Dilution factor obtained from the First Experiment Based on Radiotracer Count

Conc. (cpm)	Distance from the Diffuser (m)	Max. spread (m)	Dilution factor
35000	27	620	20
15000	85	1280	40
10000	160	1425	70
5000	416	1470	130
1000	—	1985	630

concentration at diffuser = ~10 MBq.m^{-3} (Note:-sensitivity of the detector = 0.062 cpm.Bq^{-1}m^{3})

Table 2 : Dilution factor obtained from second experiment based on radiotracer count and fluorescent dye concentration

Sl.No.	Latitude	Longitude	Distance from East pole in (m)	Radiotracer (CPM*)	Dye (ppt)	Diltion with CPM	Dilution with Dye
1.	19°00.13	72°47.38	220	6400	36.8	20.7	21.0
2.	19°00.07	72°47.44	240	5900	41.2	22.5	19.0
3.	19°00.26	72°47.42	280	5400	34.9	24.5	23.0
4.	19°00.06	72°47.44	310	4400	27.3	30	28.5
5.	19°00.09	72°47.41	350	3900	17.0	34	45.7
6.	19°00.01	72°47.41	350	3900	26.4	34	29.4
7.	19°00.01	72°47.52	350	3900	23.4	34	33.2
8.	18°59.85	72°47.34	359	3900	37.8	34	20.5
9.	19°00.01	72°47.56	380	2900	27.3	46	28.5
10.	18°59.90	72°47.28	410	1900	25.8	70	30.0
11.	18°59.87	72°47.41	440	1400	8.4	95	92.0

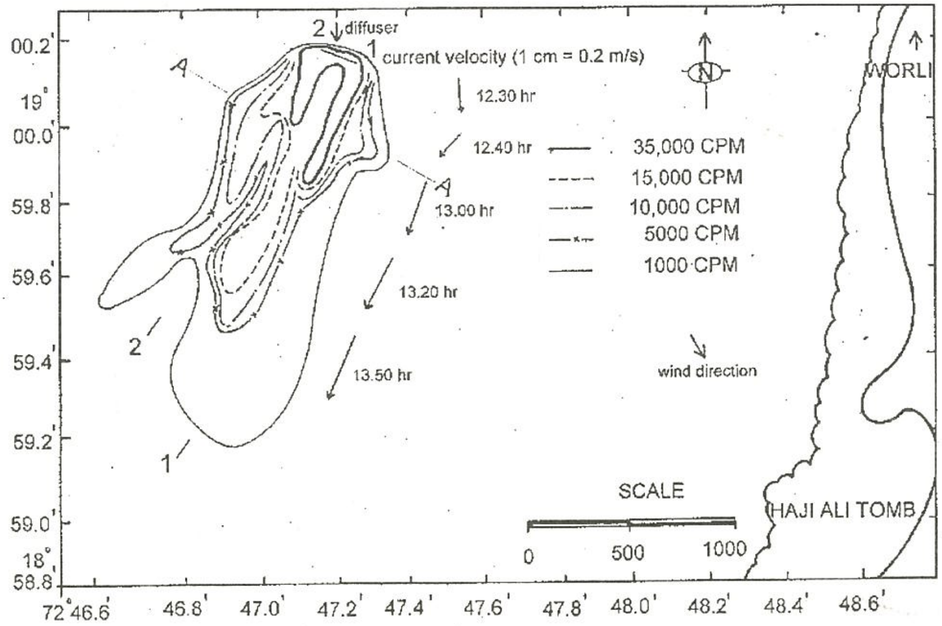

Fig. 3 Areal distribution pattern of the radiotracer concentration at 1 m depth from free surface

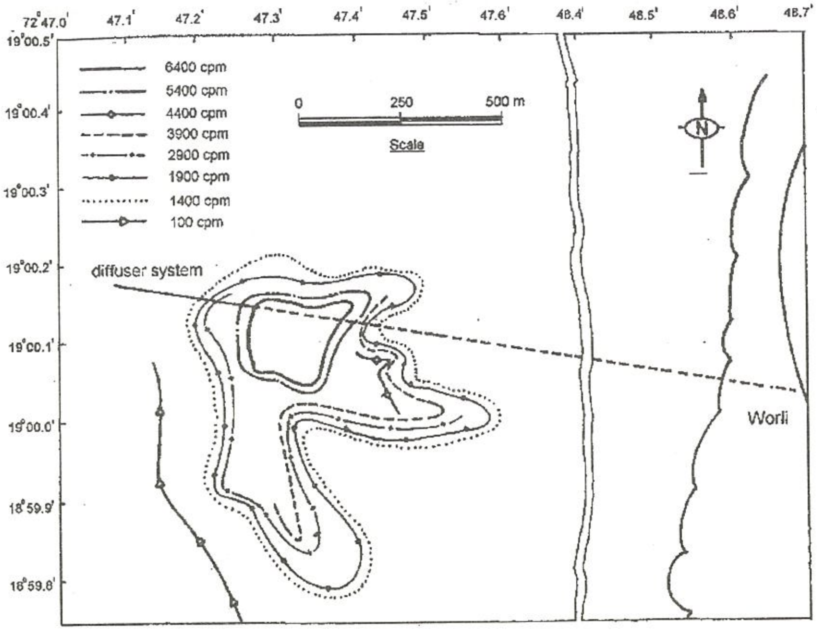

Fig. 4 Distribution of radiotracer concentration at the water surface

The radiotracer data of first experiment were corrected for decay and background and plotted on the site plan to get isocount contours as shown in Fig. 3. As seen in this figure the movement of the sewage predominantly follows the current direction (arrows shown with time) and is almost parallel to the shore. At the near-field, the sewage comes out to the surface through the risers of the diffuser without merging (i.e., non-merging and surfacing plume) which is a characteristic of a shallow coastal water submarine outfall [2]. The surfacial movement is observed as two distinct plumes (indicated as 1-1 & 2-2 in the figure), out of which plume 1-1 again divides after some distance and one part of it joins with the plume 2-2. The two distinct plumes seen probably characterizes the difference in the functioning of the individual diffusers. Also, a good correlation between wind direction and the surfacial spread of tracers was seen.

Dilution factors of the plume at various longitudinal distances from the diffuser is given in Table 1. As seen from the table, the near-field dilution factor is about 20. A near-field Lagrangian Model, JETLAG [2] also gave a comparable value.

During second experiment data on radiotracer concentration at the water surface was analyzed and integration of data from the plume monitoring programme allowed a picture of the sewage field constructed in the form of iso-activity contours as shown in Fig. 4. The resultant trajectory of the effluent movement was elliptical with the major axis parallel to the coast. It was observed that tracer flow was not uniform throughout the diffuser. The flows were mainly localized at diffuser situated near the eastern port. This observation indicated disposal of wastewater from the first 5-6 only. The observations are covering an area of 220 to 400 meters from the east pole of the diffuser. Iso-activity contours indicated that sewage movement is normally tide drifted with occasional strong onshore wind induced currents which may deflect the surface plume eastward (towards the shore especially during slack periods). Also more surfacial spread was observed compared to deeper depth which may be attributed to the strong wind effect on the day of experiment. Dilution factor calculated from radiotracer and dye tracer data in the predominant direction of transport as indicated in Table 2 show good agreement for with both tracers.

An attempt was made to consider BOD as one of the parameter to find out dilution factor. However extent of dilution of wastewater calculated from BOD values do not match with those obtained with radiotracer and fluorescent dye.

Conclusions

Experiments carried out in the laboratory to assess the impact of turbidity, sewage concentration and salinity on the fluorescence intensity of Rhodamine WT had indicated that under the selected field conditions, the impact of above factors on florescence intensity was insignificant and less than 5%. Since in the first experiment, Rhodamine WT injection was in the form of slug dose, the observed values could not give any comparative status of initial dilution of the sewage coming out of the diffuser. However, in the second experiment both the tracers were simultaneously injected and observations on radiotracer and fluorescent dye concentration has shown comparable results for initial dilution. ^{82}Br as radioisotope provides the best estimates in terms of near field dilution values

The comparison results for dilution calculated from radiotracer and fluorescent dye are not in agreement with that obtained from BOD. While considering BOD as indicator parameter for calculation of initial dilution, there was varying background BOD value for sea water.

Due to long length of tunnel and low discharged quantities of wastewater compared to design value, the tracer could be detected near diffuser only after about 135 minutes.

Initial dilution analysis indicates that the plumes are not completely merged

The tracer studies conducted so far have revealed that outfall operational parameters have not yet been optimized by the agency operating the same. Large variation in the flows were seen during the experiments

The outfall discharges in marine water system require much more critical evaluation as the tides, current and its direction, wind, sewage discharges etc. keep varying. It is, therefore, necessary that such systems are studied with regard to their features and a proper planning should follow every time for to careful evaluation. Simultaneous use of fluorescent dye and radioisotope should be attempted to compare the usefulness of these two tracers for a longer period of injection and monitoring

Acknowledgement

The authors are thankful to Director, NEERI and BARC for encouragement and assistance provided while carrying out these studies. Thanks are also due to BMC, BSDP Stage II for according permission to conduct the experiments near outfall diffuser and within the premises of Love Grove Pumping Station.

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Radiotracer Applications in Oil Fields

__Dr. Prabuddha Jain__ obtained M.Sc. and Ph.D. from University of Indore. Dr. Jain got AMA Diploma in Management and CFA in Petroleum Research Engineering. At present Dr. Jain is Chief Manager (Reservoir) of ONGC. He was nominated as reservoir engineering of the year 1989 for developing and executing single well tracer test for establishing residual oil saturation in flooded wells of ONGC. He has wide experience and expertise in the use of radiotracers, simulation development of reservoir operation and monitoring. He has used polymer gels for water and gas shut offs chemical problems in petroleum production.

Introduction

It has been recognized for a number of years that oil does not produce by itself, but instead requires energy from some other source to cause the movement of oil to the well bore where it is produced. This is accomplished by fluid injection such as gas injection, pressure maintenance or water flood operations. Success of an enhanced oil recovery process is often dependent upon determining the extent of oil de-saturation in an area and early discovery of detrimental flow paths by injected fluids.

Tracers have been used to trace the movement of a particular fluid at a well since the turn of the century. Their use in petroleum reservoirs was mainly in water floods until the growth of thermal recovery methods in 1960's. It is recognized that a properly designed and implemented radioactive tracing program can highly be cost effective in tracking the movement of oil field waters. Radioactive tracer results provide a practical link between macroscopic field interpretation from seismic and geological studies and localized core, log and performance data from injection and production wells. The radioactive tracer studies [1] are helpful to:

- Determine the source of water breakthrough.
- Optimize the balance between injection and production rates.
- Evaluate flood performance and the potential for improvements from interval selective injection and/or production.
- Identify the flow pattern and rate of movement of injected fluids, including the influence of permeability trends and fractures.
- Improve the accuracy of reservoir models.
- Provide information for reservoir management decisions on well work-over, flow balancing, in-fill drilling and enhanced oil recovery (EOR) programs.

Tritium is probably the best suited and most widely used tracer in the oil industry. It is easily detectable in low concentrations during its 12.4 years half life, is relatively inexpensive, requires very thin shielding to contain its low energy radiation, and thus presents no practical radiation hazard. Other radioisotopes such as ^{14}C and ^{60}Co are also used.

Tracer could be directly injected into the well head. Gamma-emitting radiotracers are injected using a pump. For injection of beta emitting tracer with injection pump, a secondary radiotracer with short half life and low gamma energy is preferably mixed with the main tracer which can be traced from outside the walls of injection system and the well head with the help of a scintillation detector. This ensures that the total injection fluid has been delivered into the well.

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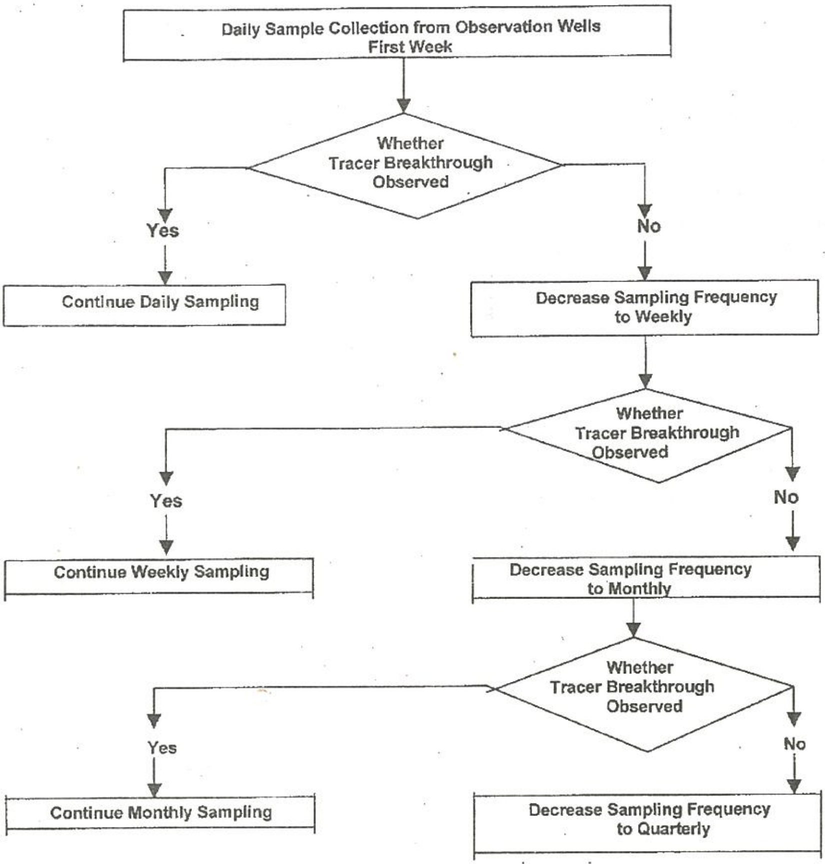

Fig. 1 Sampling strategy flow chart

Sampling

Sampling frequency depends on the fluid injection and production rates, inter-well distances, pay thickness and expected heterogeneity. A flexible sampling schedule is to accommodate for any unexpected early/late breakthrough. For the first seven days after injection, daily sampling is planned. If breakthrough occurs in any of the wells, daily sampling is to be continued. Otherwise, for no breakthrough, the sampling frequency is weekly. For next four weeks, weekly sampling is to be done, if no breakthrough occurs. For no breakthrough, the sampling frequency is to be changed to monthly. The flow chart in Fig. 1 gives sampling strategy.

Separation of Water from Emulsion Samples

Water samples from wells can be obtained from separator in the offshore platform. If emulsion samples are available, these will need to be separated. A laboratory demulsification unit can be used for both demulsification of emulsion samples and separate water for tracer analysis. The demulsification unit consists of a step up transformer to obtain 15 kV in secondary side. The secondary terminals are connected to two brass electrodes placed in a cup. The electrodes are fixed on the opposite sides of the cup. The water in oil emulsion is taken in the cup and current is passed for a suitable period of time (~ 15 minutes). Due to electrostatic forces, the emulsion breaks and water separates out. It is preferred if water can be separated from emulsion without using de-emulsifiers, as this may quench the signal in radiation measurement.

Enrichment before Analysis

Tritium enrichment is normally not required. KS^{14}CN enrichment may be needed at the later stage, particularly in far off wells. Traces of thiocynide can be increased in concentration from large volume sample (1000 mL) into a 10 mL sample, which is compatible with commercially available liquid scintillation cocktail. The sample preparation includes filtration (0.2 micron pore size) and addition of potassium thiocyanate to a final concentration of 0.02 meq/L. This is preconcentrated by ion exchange using AGI-X8 (Bio-Rad) 50-100 mesh size. Activity breakthrough starts to become significant at about 1000 mL loaded volume. The reason for this relatively low loading capacity is not fully known at present. The ion-exchange capacity of the column has been calculated to be 7.2 meq. Theoretically, the column should be able to absorb thiocyanate from more than 300 L sample water when there is no competition from other ions. However, seawater contains Cl^- (570 meq/L), SO_4^{2-} (58 meq/L) and HCO $^{3-}$ (2.5 meq/L). Breakthrough is around 1000 mL. 2.8 M sodium perchlorate is the eluent and optimum flow rate is 0.3 mL/min. The chemical yield in the elution process is 100% with 99.5% is collected in a volume of 10 mL. The derived detection limit is 0.015 Bq/L.

Interpretation of Tracer Data

The main objective of reservoir characterization is to aid field development and reservoir management teams in :

- Describing the reservoir in sufficient detail.
- Outsmarting nature to obtain higher recoveries at minimum cost through optimization, for a given reservoir description.
- Reducing uncertainty level to a minimum in production forecasts.

One of the most important developments in reservoir characterization in recent years is the possibility of modelling detailed geological heterogeneity (both in a deterministic and stochastic manner) due to availability of new tools, techniques, data and more grid blocks, particularly near injection and production wells.

There are several different approaches to stochastic modelling of heterogeneity. The choice of technique depends on the objective, scale of the study, skills of the people involved, software availability and the most importantly, the available input data and geological understanding of the reservoir under study.

Discrete models have been deployed to describe geological features of discrete nature. These include locations and dimensions of sand bodies in fluvial rocks; distribution and size of shales suspended in sands; distribution, orientations, and lengths of fractures and faults and lithofacies modeling. Continuous models on the other hand, were developed to describe phenomena like rock properties, seismic velocities and dimension parameters of the reservoir and OWC. Most of the discrete and continuous models may be combined in a hybrid approach. Almost any stochastic technique can be used for conditional stochastic simulation. In conditional simulation, the goal is to introduce small scale and/or large-scale heterogeneities in the reservoir model in a realistic and time efficient way while still honouring the observations. Noise is added to an interpolated surface in a systematic way. At the location of the observation the noise is zero, so that observed values are honoured. It will give a much more realistic visual impression compared to interpolation. The dynamic flow behaviour of the resulting simulated realization is believed to be much closer to reality.

Fractal Geostatistics and Streamtube model can be used to interpret tracer test data. Tracer performance evaluation is based on the following procedure:

Permeability character of the reservoir is established from well logs and determine the statistical structure with the concept of random fractals. Fractals are characterized by the variations at all scales of observations and partial correlation over all scales. The assumption of this method is that the natural processes cause porosity/permeability distribution with a fractal character. The geometry of fractal distributions is characterized by their intermittent or spotty naturem quantified by intermittancy exponent, H. Log analysis data using the R/S procedure typically indicates an average exponent, H of 0.8 to 0.9.

A random fractal interpolation scheme was used which is based on the fractal characteristics as determined from the well logs to project the well data to the inter,well region. A stochastic interpolator is used to generate a cross sectional resistivity map between wells. The interpolation scheme recursively divides the interval between data points by linearly interpolating values to mid point of each interval and then adds a random component with a variance that decreases with each level of recursion. The initial variance is determined by calculating mean square variation of values on a point by point basis between wells. This is a measure of scale of variation at the interwell distance. The magnitude of variance is reduced with each level of recursion according to a power law determined by the values of H observed in well logs.

Down Hole Tracer Applications

Tracers are also used to investigate the region in and around the oil well, the link connecting the oil-bearing reservoir with the surface facilities. It is the only path of communication with the reservoir, the conduit for production of oil, gas and water from the reservoir, and for the secondary and tertiary injections into the reservoir. A large number of tracer applications have been used to study the integrity of the well bore, how fluids enter and leave it, and conditions affecting well operation down hole. Virtually all monitoring operations in the well bore, are carried out by special logging tools that are moved up and down the well bore on a wire line. Most of these operations are carried out by independent logging companies that provide both wire line and tools.

While there are many kinds of logging operations, the nuclear logs are of main interest in tracer studies. These allow the use and detection of gamma-emitting radioactive tracers for tracing the movement of fluids in the neighbourhood of the bore hole.

Three kinds of tracer operations involving radioactivity are used to tag gases, liquids, or solids moving in or about the well bore [2-9].

- In the conventional procedure, the fluid tagged with radioisotope material is injected in to the well and a radiation monitor on a wire line used to follow its movement or location down hole for well treatments and production logging.
- In a second method, a non-radioactive tracer is activated down hole by neutron irradiation, producing a new gamma emitting tracer and is monitored by a detector. This may be a naturally occurring material, such as fast neutron activation of oxygen in water used to trace leaks behind casing, or an added material, activated for this purpose such as barium activated by neutrons.
- In the third method, capture gamma radiation induced by neutron irradiation of a non-radioactive material, is related to the macroscopic thermal neutron cross-section and hence to a measure of the amount of absorbing material present. This is illustrated by the log-inject-log tracer procedure for residual water.

Currently, only radioactive tracers that emit penetrating gamma radiation are used for down hole measurements. However, it is also possible to use beta emitting tracers for gas tracing down hole. An ion chamber can be used as a beta detector, so long as the gas that enters the chamber is free of condensate liquid phase such as oil or water. Ion chambers can be designed to operate under borehole temperatures and pressures.

The principal detector used for monitoring gamma radiation down hole is the sodium iodide scintillation detector. This detector has high sensitivity for gamma radiation and can operate under borehole conditions (although temperature and pressure protection is usually required). However, it has relatively poor energy resolution. The detector for resolving gamma spectra is the intrinsic germanium detector, used for virtually all laboratory spectral analysis. Unfortunately it requires liquid nitrogen cooling to operate, is much more expensive, and is considerably less sensitive than sodium iodide scintillation detector. As a result, with some exceptions, it is not used for oilfield logging. The Geiger-Mueller counter has largely been replaced by the scintillation detector but is still in use in wells where high temperatures and other conditions make the use of scintillation detectors unsuitable. The principal down hole neutron detector is the ^{3}He filled proportional counter. Some of the important applications are:

Nuclear Logging

- Formation density log (FDL)
- Litho density logging (LDT)
- Neutron logging (NL)

Drilling and Completion

- Depth of filtrate invasion studies
- Detection of lost circulation
- Drill-bit erosion control
- Permanent tubular markers
- Perforation position marking
- Primary cement measurements
- Gravel pack operations
- Well stimulation treatments
- Channeling behind casing

Production

- Production profiling
- Corrosion measurements
- Water injection profiles

Summary

The use of radioisotopes provides a rapid, generally quantitative and economically feasible means of providing fluid movements in and adjacent to well bore and subsurface fluid movement. Tracer information is a small but very important part of the informations used for building up the reservoir model. It should be used along with other information such as obtained from logs, well test data, production logs and other data to get a complete picture. Tracer data alone is usually not sufficient, but it becomes very useful when applied with other reservoir information.

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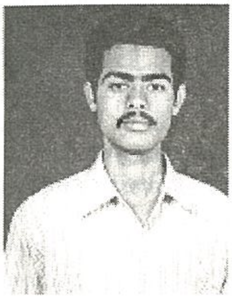
Non-Power Applications of Nuclear Energy



Shri Raghubir Singh Chauhan is a student of final year B.Sc. from Jai Narayan Vyas University, Jodhpur, Rajasthan. He participated in the Department of Atomic Energy's XII All India Essay Contest on Nuclear Science and Technology under Non-Power Applications of Nuclear Energy. Shri Chauhan was awarded first prize in the essay contest. The gist of the essay submitted by Shri Chauhan is included here.

On December 2, 1942, a group of Physicists were gathered in the Chicago University squash court anxiously watching Professor Enrico Fermi. Then at 3.25 one of the dials on the panel flickered and an instrument began ticking. Professor Fermi smiled and said, "Gentlemen, the chain reaction is self sustaining". That historic statement pointed to the beginning of the concept of nuclear reactor. Apart from the technically and economically viable and reliable use of Nuclear energy as a source of power, it has thousands of non-power applications in the form of radiations and radioisotopes.

Production of Radioisotopes

A number of isotopes of elements found in the Earth are radioactive. Isotope of elements above bismuth are radioactive. ^{238}U decays through a series of 14 radioactive decay products before ending as a stable isotope ^{206}Pb. Radioisotopes are artificially produced by bombarding a non radioactive element with neutrons or charged particles.

Applications of Isotope and Radiation Techniques

The spectrum of applications varies from tracer techniques, using radioactivity of the order of milli curies to techniques like sterilization of medical products and production of polymer composites, using several thousand curies of radioactivity.

Application of Nuclear Energy in Agriculture

Nuclear energy is widely used in agricultural research. Breeding varieties of crop plants, insect pest management, fertilizer use efficiency, fate and management of pesticides residue in soils and crops and micropropagation of valuable plants are the main applications of radiations and isotopes in agriculture.

Applications of Nuclear Energy in Food and Nutrition

The radioisotope technique proves to be very useful for reducing the huge post harvest losses occurring in agricultural, animals and fishing products. The process of irradiation involves exposure of food, either prepackaged or in bulk to radiation energy from gamma rays, X-rays or electrons.

The duration of exposure to ionizing radiation, the density of food and amount of energy emitted by the irradiation determine the dose of irradiation to which the food is exposed. At low doses, irradiation inhibits regrowth or sprouting in bulb and tuber crops, delays ripening of fruits, substitutes chemical fumigants used to control insect pests in stored rice, wheat, dry fruits, whole spices and dry fish. At higher doses irradiation pasturises or retards spoilages of meat, poultry and fishrey products by killing and/or reducing becteria causing spoilage to these foods. It also ensures safety by destroying food borne pathogenic bacteria and parasitic organisms. Still higher doses can improve quality and microbial safety of spices and dried herbs.

The cost addition to the product by irradiation processing is estimated to range from 5-10%.

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Nutrient loss, particularly changes in proteins, fats and carbohydrates are minimal in irradiated foods and are often comparatively less than nutrient losses associated with other methods of preservation such as drying, heating pasteurisation and canning.

Applications of Nuclear Energy in Healthcare and Medicine

One of the earliest and most important contributions of nuclear science is the application of radioisotopes and radiations in the field of human healthcare. The ready availability of wide range of reactor produced isotopes enhanced the scope of radioisotopes application in medicine for diagnostics as well as treatment. The diagnostic procedures are practical both in vivo and in vitro.

Radiotherapy deals with treatment of cancer using radiations emitted from radioisotopes or X-ray machines or using high energy electrons. Radiotherapy is invariably resorted to, to destroy remanant tumour masses after surgery. Radiotherapy is the only method of treatment for cancer which is difficult to treat by surgery. It is often used as a pallative treatment in cancer patients with advanced cancers. Radiotherapy is very effective in treatment of cancers of head and neck cervix, colon and rectum.

Radiopharmaceuticals

These are a special class of radiochemical formulations of high purity, suitable for administration of human orally or intravenously and to carry out organ investigation in vivo (or for bringing about therapeutic effect). These are used for liver imaging, imaging of the blood to brain and imaging of metastatic sites of thyroid cancer. Organ scientigraphy provides valuable physiological information of organs. Evaluation of renal and cardiac function is done by dynamic imaging procedures. Detection of bone metastasis of cancer patient is also done.

Applications of Nuclear Energy for Industry

Today almost every branch of industry uses radioisotope and radiations in some way or the other and a few of them are described here.

Radiography

Since radioisotopes do not need electric power and are portable, they are ideal for field work. Radioisotopes have wide applications including manufacturing of pressure vessels, ship, aircraft, nuclear and thermal power stations, fertilizer and petrochemical complexes. Gamma radiography is frequently used to check the welds in pipelines. Neutron radiography is used for testing of nuclear reactor fuels and detection of hydrogenous materials.

Nucleonic Gauging

Attenuation property of radioisotopes is used in thickness gauges which are widely used in production, measurement and control of variety of material such as paper, plastic sheets and steel plates.

Levels of corrosive liquid in closed container can be measured and controlled using non contact type radioisotopes. Radioisotopes gauges are used for checking up the filling of domestic gases in cylinders and detergent powders in their packages.

Density gauges, based on the absorption of gamma radiation, are used in automatic determination and control of density of liquids, solids and slurries. Nucleonic gauging and on steam analyser are employed in monitoring and control of ash and moisture content in coal and coke.

Radioisotope gauges are also used in coating and galvenising to keep a check on the thickness of coating.

Leak Detection

Radioisotopes are used in leak detection in buried pipelines and equipment of chemical process plants. An outstanding example of this application is the detection of leak in 140 km long Viramgaon-Koyali pipeline which enabled saving of one precious year in addition to saving in the expenditure.

Silt Movement or Land Slides

Radiotracer techniques are also cost effective in selection of suitable dumping sites for dredged silt in ports and harbours and for checking suitability of the alignment of proposed shipping channel of a new harbour.

Radiotracers enables to determine the wear rate precisely and continuously at low costs. In industries the validity of design data can be checked by measuring mean residence time of process material in vessels by using radiotracer technique.

To replace the natural Gem stones, Gamma irradiation is used in some cheaply available stones like quartz to colour them artificially. It is a new trend of making semi precious stones by nuclear energy.

Radiations are used to induce certain desired chemical reactions in materials and is hence extensively used in vulcanisation of rubber, manufacturing new polymers and in wood and printing industries.

Isotope Hydrology

Radioisotopes have proved to be indespensible tools in investigating problems in hydrology and water management. It has proved to be useful in the measurement of recharge to ground water by tagging moisture layers with tritium tracer and following its movement in the soil. Seepages in canals and dams can be effectively detected using radioisotopes techniques. For such applications alternative techniques are either not available or do not provide the data with required precision and ease. Radioisotope tracers are widely used for measurement of recharge of ground water in arid zones, detection of seepages in a many dams and rivers as also for measurement of high turbulent rivers.

Isotope Geology

In various methods of geochronology, isotopes are the only techniques to detect precise age of rocks, metamorphic events etc. specially for Precambrian rocks. Some of the examples include:

(i) O^{16}/O^{18} ratio is of use to differentiate between volcanogenic carbonatites and sedimentary carbonate rocks like limestone, dolomites etc. This key to detect the origin of host is of great significance to explore mineral deposits, specially of rare earths.

(ii) Volcanogenic or biogenic origin of sulphide ores, specially of lead, zinc, copper and pyrite deposits be detected or extended on the basis of S^{34}/S^{32} ratio of Pyrites.

(iii) C^{13}/C^{14} used in dating younger soils, rocks or desert sand etc.

(iv) Palaeochannels, like Saraswati river, can be identified on the basis of oxygen isotopes of old water and present water.

Isotope Archeology

Dating of Archeological materials like pots, woods, paintings, tools of earlier man can be done using isotopes especially ^{14}C.

Conclusion

Nuclear energy has advantages in many areas, including some that have been traditionally viewed as possible areas. Electron beam processing of flue gas has proven its potential for improving air quality and eliminating pollution, thereby converting toxic components into byproducts of commercial value as agricultural fertilizers.

With the anticipated advances in the future, both in the field of radioisotope products technology and instrumentation, radioisotopes are bound to play an increasingly active role in improving the quality in all walks of life. And it would be appropriate with no exaggerations to call the present era as :

"A Powerful Age of Non-power Applications of Nuclear Energy".

Literature Update

During the last five decades, radioisotopes find a large number of applications in various fields like nuclear medicine, agriculture, physicochemical sciences, food preservation and industry. There is a large number of publications on applications of radioisotopes. IAEA has brought out periodically technical reports on Industrial Applications of Radioisotopes. There are many web sites in which various applications of isotopes are described. An attempt is made to present a few web sites and a list of selected latest publications in what follows.

Some Useful Web Sites

1. http://www.nrc.gov/NRC/NUREGS/BR0217/br0217.html
2. http://www.uic.com.au/nip27.html
3. http://www.webelements.com/webelements/elements/text/S/radio.html
4. http://radioisotopes.jstage.jst.go.jp/en
5. http://www.ansto.gov.au/ansto/nucmed.html
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7. http://www.triumf.ca/welcome/text_only/radioisotopes.html
8. http://heg-school.awl.com/bc/companion/cmr2e/activity/RI/rI02.htm
9. http://www.icr.org/pubs/imp/imp-290.htm
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