Application of Nucleonic Gauges in Industry

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Abstract

Nucleonic gauges based on ionizing radiations emitted from sealed radiation sources are extensively used for quality control and online monitoring of production processes in Indian industry. The applications of nucleonic gauges are well-established and their socio-economic benefits have been amply demonstrated and recognized. Different types of gauges are commercially available and being utilized in various industries in India. The general principles of nucleonic gauges and their applications with regulatory requirements are briefly discussed.

Keywords: *Nucleonic gauges, radioisotope, Gamma-radiation, X-rays, neutron, transmission, backscatter, fluorescence, density, thickness, moisture, belt-weigher*

1. Introduction

The ionizing radiation sources such as radioisotopes and X-rays are extensively used for non-destructive examination, measurement of process parameters, process optimization / control and quality assurance in industry leading to significant revenue savings. The typical applications of nucleonic gauges (NG) or nucleonic control systems (NCS) include in-situ determination of thickness of industrial products, measurement/control of level of process material in closed containers, measurement of density and composition of the matter, analysis of ores and minerals, and measurement of moisture content in various systems. A nucleonic gauge consists of one or more than one sealed radiation sources and a detector system integrated with a data acquisition system, arranged in a fixed geometrical configuration depending upon the type of application. Some of the nucleonic gauges used in industry are also based on the measurement of the natural radiation emitted from the examined material itself.

One of the most important advantages of NGs is the online measurement without direct contact between the radiation source and the material being examined. As a consequence of this, NGs are preferred in high speed production lines and harsh process conditions such as high temperature, pressure and corrosive medium. The measurements are accomplished non-destructively and without disturbing and changing properties of the examined material. The penetrating nature of high energy gamma radiation enables measurements to be made through the walls of sealed containers. The sampling volume of most of the NGs is usually larger than that sampled by conventional methods for laboratory analysis. In addition to this, the NGs are robust and adaptable to a variety of industrial process and applications [1, 2].

2. Principles of nucleonic gauges

The NGs utilises the various types of interaction observed which occur between beta, gamma ray, X-ray, neutron radiation and charged particles and material under investigation. These are typically: attenuation (single energy or dual/multi-energy), scattering, excitation, nuclear reactions, secondary radiation emission, or even a combination of these processes. Nucleonic gauges include simple single parameter units such as: level gauges, bulk density gauges, thickness gauges, mass per unit area gauges, flow rate gauges, etc. More complex instrumentation includes nucleonic multi-component analysers using X-ray fluorescence (XRF) and neutron activation analysis (NAA) [1, 2]. The types of radiation sources used in NGs include alpha, beta, gamma, neutron, X-rays. The activity of the sources varies from several kBq to few GBq (100 μCi to 30 Ci) and X-ray operating in the energy range of 30 kV to 160 kV. The various applications of nucleonic gauges and typical sources in use are as given in Table 1. The principles that form the basis of nucleonic gauging in industry are briefly discussed below.

2.1 Natural gamma ray technique

The technique is based on the *in-situ* measurement of gamma ray spectrum of naturally occurring radionuclide present in the process material and correlating the intensity of the gamma radiations recorded in preselected windows and the concentration of specific elements (e.g. U, Th, K) or the value of a particular parameter (e.g. ash in coal). The technique is based on the fact that the material (ore, coal) mined from different geological strata will contain different quantities of the naturally occurring radioactive elements, such as uranium, thorium and potassium. These elements emit gamma rays of different energies which can be measured with spectrometric scintillation detector.

A typical example of application of this technique is delineation of coal seams in coal deposits intersected by exploration or production borehole. Radioactive elements are present in shale and other sediments associated with coal seams. The level of radioactivity depends on petrographically type of inter-sediments. Shale will have higher radioactivity level than sandstone or mudstone, but lower than clay. On the other hand, there is very little natural radioactivity associated with the organic material of coal. Consequently, the minimal in the natural radioactivity profile will correspond to coal seams, and the maximal to clay or shale strata [1].

2.2 Transmission technique

The principle of transmission technique is shown in Fig. 1. The technique is based upon transmission or absorption of radiations through the matter or any object. If a collimated beam of

Table 1: The principles that form the basis of nucleonic gauging in industry are briefly discussed below.

Type of gauge	Technique	Radiation sources used	Typical applications
Level and interface	Transmission	Cesium-137 (Gamma) Cobalt-60 (Gamma)	Level and interface measurements in process vessels in industry
	Backscattering	^{241}Americium-Beryllium (Neutron)	Level measurements of hydrogenous materials
Thickness or mass per unit area	Transmission, Backscattering	Krypton-85 (Beta) Strontium-90 (Beta) Promethium-147 (Beta) Thulium-170 (Beta)	Thickness measurement of paper and plastic sheets
	Transmission, Backscattering	Cesium-137 (Gamma) Cobalt-60 (Gamma) Americium-241(Gamma)	Aluminum and metal sheets in industry, mass of materials on conveyor belts
Coating thickness	Differential transmission method	Krypton-85 (Beta) Strontium-90 (Beta)	Coatings on textiles papers and leather clothes
	Backscattering	Promethium-147 (Beta) Thulium-170 (Beta)	Metal coatings on metal sheets and coatings on photographic paper
	X-ray fluorescence	Iron-55, Cadmium-109, Americium-241 (Gamma) etc.	Measurements of thickness coating on metal sheets
Density	Transmission	Krypton-85 (Beta) Strontium-90 (Beta) Promethium-147 (Beta) Thulium-170 (Beta)	Cigarettes, fluids and slurries in pipes and tanks, gas and gas-fluidized solids, gas-liquid emulsions, steam-water ratios etc.
	Transmission	Americium-241 (Gamma) Cesium-137 (Gamma) Cobalt-60 (Gamma)	Fluids and slurries in pipes and process vessels in industry
Bulk density	Transmission, Backscattering	Americium-241 (Gamma) Cesium-137 (Gamma) Cobalt-60 (Gamma)	Soil, borehole cores, rocks and ore measurements in boreholes
Moisture	Slowing down of neutron and backscattering	Americium-241/ Beryllium (Neutron)	Soil, rocks and ores, agricultural products.
Elemental analyzer	Emission of characteristic X rays and their backscattering	Iron-55 (Gamma) Cadmium-109 (Gamma) Americium-241 (Gamma) Characteristic X- rays	Elemental analysis in metals, minerals, petroleum product etc.
Air quality/Dust monitor	Absorption of low energy beta radiations	Carbon-14 (Beta) Promethium-147 (Beta) Krypton-85 (Beta)	Environmental control

gamma radiations of intensity I_o impinges on an object of thickness x and density ρ, then the relationship between transmitted and the incident intensity of the radiation is given as:

$$I = BI_o e^{-\mu\rho x} \tag{1}$$

where, μ is known as mass absorption coefficient and B is the buildup factor. For narrow beam geometry, the value of B equals unity. So for more practical purposes, the above equation can be written as:

$$I = I_o e^{-\mu_{eff}.\rho x} \tag{2}$$

where, μ_{eff} is the effective absorption coefficient determined empirically. There are three processes that are responsible for attenuation of the radiation by the intervening object, they include photoelectric effect, Compton scattering and pair production. The photoelectric effect is

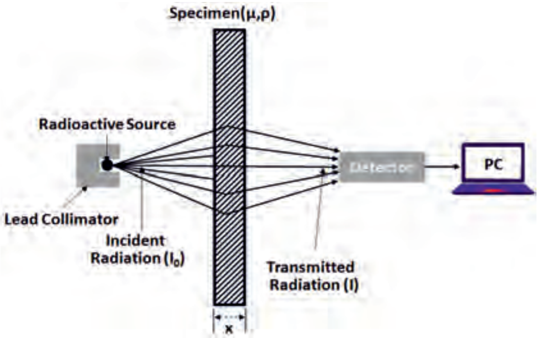

Figure 1: Principle of transmission technique

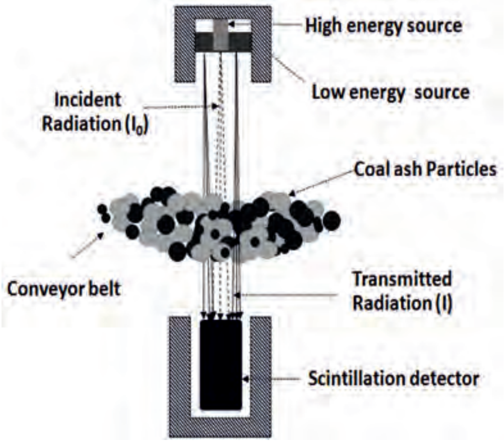

Figure 2: Principle of dual gamma ray transmission technique

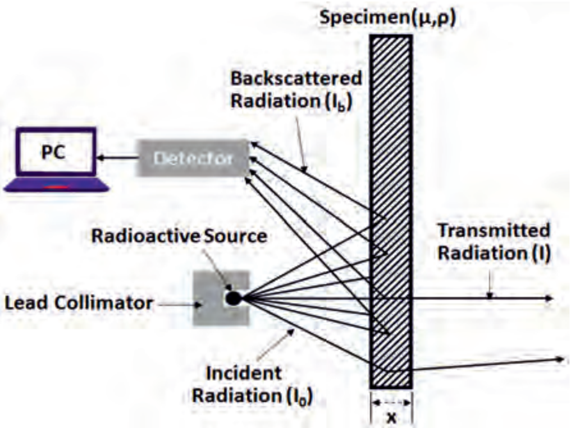

Figure 3: Principle of backscatter technique

dominant only in lower energy range, while pair production occurs only when the energy of the gamma radiation exceeds more than 1.02 MeV. The Compton scattering occurs in the energy range of 0.5-2.5 MeV and is utilized in most of the gauging applications as lower energy radiations are not capable to penetrate the object.

The principle of dual energy gamma ray transmission technique is shown in Fig. 2. The technique is based on the use of two gamma ray beams of different energies emitted from two independent gamma ray sources. Determination of ash content in coal being transported in conveyor-belts in coal industry is one of the common applications of the technique. The lower energy gamma rays are sensitive to the difference in the ratio of the mass absorption coefficients of the gamma rays between the combustible and mineral components whereas the higher energy gamma rays are much less sensitive to average atomic number and essentially detect only the total mass on the conveyor belt. The quantity of the ash is determined from the combined intensity of the two beams and does not depend on the bed thickness and the mass of the coal.

2.3 Backscatter techniques

The principle of gamma ray backscattering technique is shown in Fig. 3. When a beam of gamma rays impinges and interacts with the material of an object, a fraction of the beam gets absorbed whereas the other fraction is scattered from its original path and gets reflected back towards the source with reduced energy. The intensity of the backscattered radiations depends on bulk density, chemical composition and equivalent atomic number (Z_{eq}) of the material. This forms the basis of backscattering gauging technique. There are numerous applications of the gamma ray backscatter technique in on-the-belt applications in mineral industry. The sources usually used in gamma backscatter gauges are given in Table 1.

The neutron backscatter technique involves use of neutron sources such as californium-252 (^{252}Cf) or ^{241}Am-Be emitting neutrons of energy of the order of MeV. The neutron backscatter gauges are commonly used for gauging applications in hydrogenous materials. A succession of scattering events reduces the high energies of neutrons to thermal energies. In general, more energy is lost by the neutrons when they collide with light nuclei than heavy nuclei. Hydrogen is the most effective in moderating neutrons due to its light nucleus. As hydrogen is the major constituent of most of the liquids, the scattering of neutrons with the lighter nuclei dominates and allows the measurements of different physical properties of the liquid through container walls made of materials of high atomic number [1,2]. The gauges based on the backscattering principle offer specific advantages in situations where only one side of the sample is accessible or there is not enough space to mount the detector to measure the intensity of the transmitted radiation.

2.4 Prompt gamma neutron activation analysis

Prompt gamma-ray neutron activation analysis (PGNAA) technique is used for elemental analysis of materials in industry. The technique is based on irradiation of a sample by a neutron beam that induces elemental nuclei to capture neutrons and emit characteristic prompt gamma rays upon de-excitation. The prompt gamma rays are emitted within 10^{-12} seconds of their interaction, while delayed, arising from the decay of the induced radioactivity. The prompt gamma ray spectrum of the emitted radiations is measured using a high resolution germanium detector (HPGe) and analysed to identify the neutron-capturing elements and their concentrations. The ratio of count rate of the characteristic peak of the sample to the rate of a known mass of the elemental standard (irradiated under the same conditions) provides the amount of analyte element. The PGNAA technique has been developed and commercially applied for the bulk analysis of coal, cement and ores and also to the analysis of coal, cement and mineral slurries in industry. Elemental composition of the coal is determined by neutron capture based on the measurement of the gamma rays being emitted during the capture process. The intensity of the gamma rays released by a chemical element in the coal, determines the concentration of that element. Commercial PGNAA analysers use ^{252}Cf as the excitation source and a large volume scintillation detector or a solid-state detector for measuring the intensity of emitted gamma rays [1].

2.5 X-ray fluorescence technique

The X-ray fluorescence (XRF) involves bombardment of X-rays or gamma rays from a radioisotope source on a material resulting in emission of characteristic "secondary" X-rays of an element. The characteristic X-rays are backscattered and detected by a suitably mounted detector. The radioisotope sources usually used to excite the X-rays are iron-55, cadmium-109 and americium-241 (Table 1). Proportional counters are used for detection of secondary radiation. Analyzers employing radioisotope sources will be preferable in field applications. In industry, the XRF technique is widely used for elemental analysis and determination of composition of materials. Various kinds of nuclear analyzers are now commercially available from several manufacturers. A schematic diagram of a thickness gauge for measurement of coating thickness based on X-ray fluorescence technique is shown in Fig. 4.

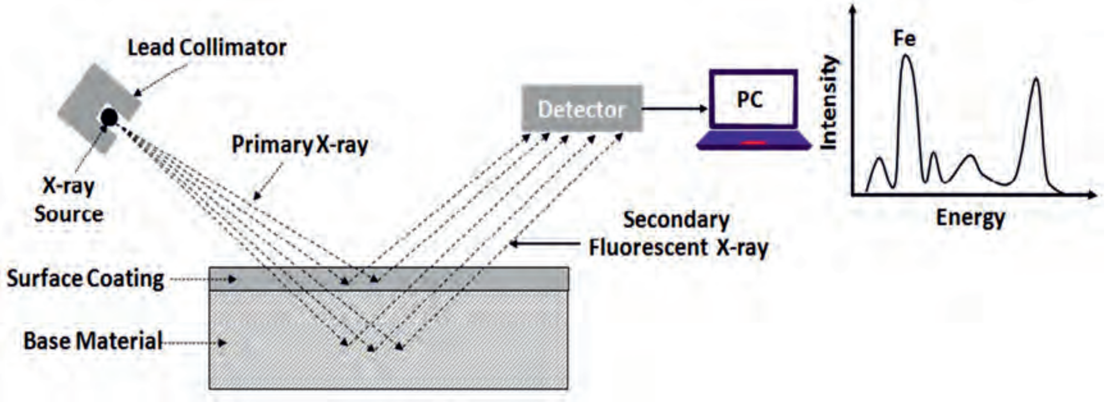

Figure 4: Principle of x-ray fluorescence technique (coating thickness measurement)

3. Type of nucleonic gauges

Some of the commonly used nucleonic gauges based on the transmission/absorption and backscatter techniques used in industry are briefly discussed below. The types of gauges for typical applications in industry are listed in Table 1.

3.1 Level and interface gauges

The level and interface gauges, based on the gamma ray transmission technique, are the simplest and most widely used nucleonic gauges in process industry. The common configurations of the nucleonic gauges used in industry are shown in Fig. 5, Fig. 6 and Fig. 7. A transmission level gauge consists of a source and detector placed on opposite sides of a vessel. The source and the detector are so arranged that changes in level cause a complete or partial interruption of the radiation beam, resulting in changes in intensity of radiation at the detector. The radiation sources usually used in level or interface gauges are gamma emitting sources and are shown in Table 1. When the level of the liquid in the vessel rises and the medium reaches the radiation beam, the intensity recorded by the detector decreases and associated electronics provides a signal or raises an alarm and accordingly control the filling or emptying process [1,2].

Gauges based on the backscattering principle are also used for level measurements in industrial process vessels. They offer specific advantages in case when only one side of the sample is accessible or there is not enough space to mount the detector to measure the intensity of the transmitted radiation.

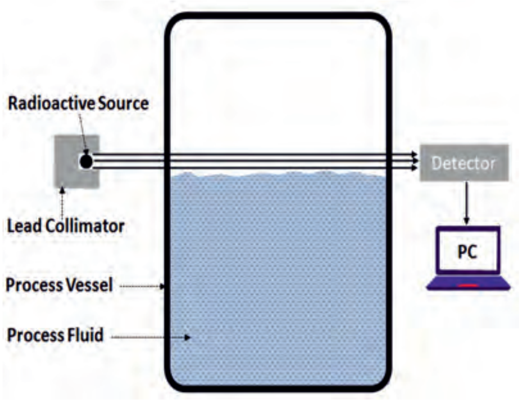

Figure 5: Principle of relay/static gamma level gauge

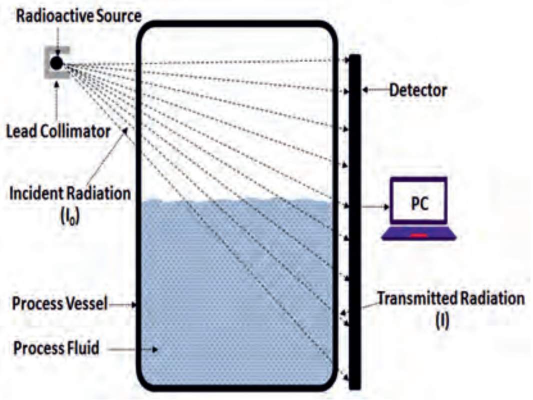

Figure 6: Principle of continuous gamma level gauge

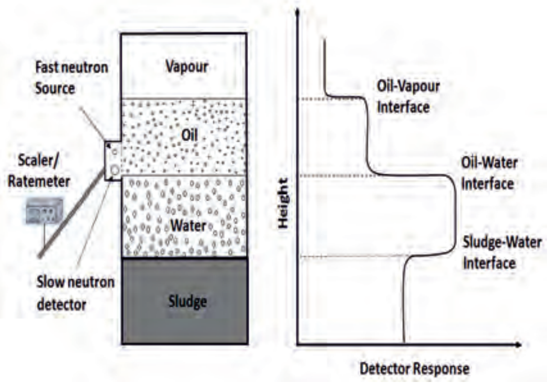

Figure 7: Measurement of levels and interfaces using a neutron backscatter technique

3.2 Thickness and mass per unit area gauges

Thickness gauges, based on gamma ray transmission technique, are commonly used for measurement of thickness of paper, plastic and metal sheets in process industry (Fig. 1) and mass per unit area in conveyor belts (Fig. 8). In a thickness gauge, the radiation source and the detector are placed on opposite sides of the sheet whose thickness is to be measured and the intensity of the transmitted radiations is recorded. The absorption of the radiations depends upon the weight per unit area of the sheet. Thus for a constant density of the sheet, the thickness changes are measured using equation 2. The radiation sources used in thickness gauges are beta and gamma ray emitters and given in Table 1. For materials such as paper, plastics and metals having mass per unit area ranging from 1-1000 mg/cm^2, beta sources are used. The accuracy of determination is generally better than 1 % except for very light materials (<5 mg/cm^2), whereas it is about 2% for thicker materials [1, 2].

Backscatter gauges are also used for thickness measurements and are advantageous in situations where thin coatings are to be measured on a thick base material provided atomic numbers of the coating and base materials differ significantly. However, measurement with backscatter gauges depends on the chemical composition of the material to be gauged. This is generally a clear disadvantage, since it limits the measuring accuracy for various material compositions. For the measurement of plastic on steel, an application often found in industrial processes, approximately the same accuracies (1-2 %) are achieved with backscatter gauges as with transmission gauges. The useful ranges lie in the region of 30 % of the transmission gauge ranges [1, 2].

Radioisotope X-ray fluorescence (XRF) based gauges are also used for accurate and online determination of the coating weights. In an XRF gauge, X-rays from a radioisotope source (^{241}Am) cause the coating layer and the base to fluoresce, emitting X-rays of characteristic energy of the excited element. The characteristic X-rays are backscattered and detected by the suitably mounted detector. One of the important applications of the XRF gauge is the online and continuous determination of thickness of coating or weight per unit area on hot and cold rolled steel sheets [1, 2]. To maintain the specifications of the product, the thickness or coating weight per unit area needs to be constant. Various kinds of XRF gauges are commercially available for determination of thickness or weight per unit area of the coatings in industry. The process control based on this determination results significant savings to the industry.

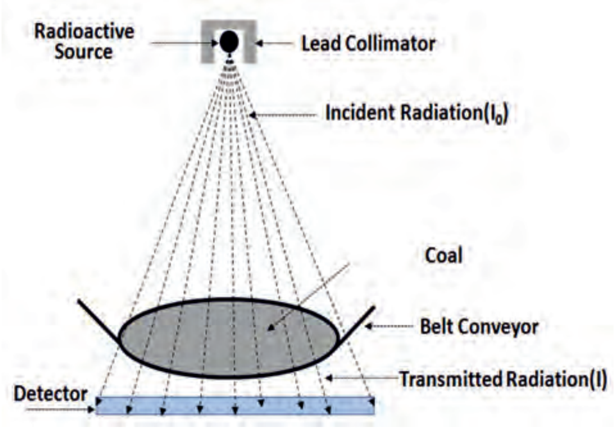

Figure 8: Principle of conveyor belt weigher

Measurement of weight of material being transported on conveyor belt is an essential requirement for estimation of inventory and control the production process in many industries. Nucleonic belt-weighers are most suitable devices used for continuous as well as online measurement of mass per unit time and total weight on conveyors. A nucleonic belt-weigher consists of a transmission gauge to measure the mass per unit length of the belt, a tachometer for measurement of belt velocity and an electronic unit for processing of the measured signals. The geometry of the measuring head is designed to give an equal weighting for each element of load, irrespective of where it is on the belt, and thus make the measurement sensibly independent of material profile or profile shift. There are two main configurations of conveyor belt-weighers that are common in use; first one utilizes a point source and a line detector whereas the second one uses a line source and a line detector. Cesium-137 (^{137}Cs) is the usually preferred source except for the heavy loadings, wherein cobalt-60 (^{60}Co) is used (Table 1). An accuracy of better than 1% can be achieved. Compared to mechanical belt weighers, nucleonic weighers have similar accuracy but require less maintenance and calibration [1, 2].

3.3 Density/bulk density gauges

Density gauges are mostly based on the transmission technique and are widely used in production of cement, glass, tobacco, paper, plastics, mineral processing, chemical, petroleum and gas industries. Measurement of density is usually carried out for quality control of manufactured products or control of technological processes. The principle of the density gauges is based on the equation 2 and illustrated in Fig. 1. In case of density gauging applications, the intensity of the transmitted gamma rays for a material of constant thickness is correlated with the weight per unit area or density. Beta and gamma radiation sources used in density gauges are generally the same as those used in thickness gauges. In case of measurement of density of paper sheets and cigarettes, beta emitting radiation sources are used, whereas for density gauging of plastic and metal sheets, gamma-emitting sources such as ^{137}Cs or ^{241}Am are used. For materials of constant chemical composition the accuracy of measurement is often ±0.1% relative. The density can often be used as an indicator for other physical or chemical properties of a substance, such as concentrations of solutions, viscosity or composition of two-substance mixtures. Therefore a density gauge can be devised for various specific applications [1,2]. In addition to gauges based on transmission principle, the backscatter density gauges such as on-site measurement in road construction are also used in industry.

Backscatter density gauges have been successfully applied to the measurement of soil density or moisture in civil engineering. Two different types of gauges i.e. subsurface type (4π-geometry) and surface type (2π-geometry) are generally available for soil-density measurements. The subsurface type backscatter density gauge is also used in various applications in petroleum and gas, coal, mining and exploration industries. In well-logging applications, the gamma-gamma logging method, also called density-log is one of the most used well-logging techniques in oil and gas exploration industry. The individual gauges (logging tools) differ from each another with regards to the technical design (like source-to-detector distance, number of detectors, collimator design, etc.) but conceptually they all are the backscatter density gauges [1, 2].

Gamma ray backscattering technique provides the basis for routine measurements of the ash content in coal seams and control of metalliferous ore for *in-situ* determinations. Variations in mineral content reflect directly in the bulk density of coal provided the composition is reasonably constant. Thus, the measurement of bulk density can provide information on raw ash content. However, the correlation between the bulk density and the coal ash is not universally good, which limits the method's overall accuracy. Another approach for coal ash determination is through its correlation with an average chemical composition of coal, described by Z_{eq}. The spectrometric gamma-gamma technique utilises information obtained from both energy regions (low and high) for ash in coal or ore grade determinations [1,2].

3.4 Nuclear analyzers

Nuclear analyzers have been developed for analysis of different materials in industry. A nuclear analyzer consists of a suitable radiation source and a spectrometric radiation detector. The types of nuclear analyzers are either energy specific or non-energy specific. The energy-specific gauges are based upon principle of PGNAA, DGNAA, XRF, whereas the non-energy specific analyzers are based on the principle of backscattering or transmission of gamma or X-rays. Binary mixture can however be analyzed provided that the scattering cross-sections of the two elements are distinctly different. Complex materials can be analyzed if they behave effectively as binary mixtures.

Coal ash analysis is a typical example of a non-specific type of analyzer used for analysis of a binary mixture. The coal is regarded as having two bulk components, a combustible component (C, O, H) with an average atomic number of 6 and mineral matter component (ash) with an average atomic number of about 12. The nuclear analyzers based on the dual energy gamma-ray transmission technique are the most commonly used analyzers for online determination of ash content in coal. The quantity of ash in coal is determined by measuring the combined intensity of transmitted low and high energy gamma ray beams through coal. The ash content primarily absorbs lower energy gamma than the combustible coal matter due to its higher average atomic number and does not depend on the mass per unit area of coal [1, 2].

X-ray fluorescence (XRF) analysis is applied in continuous analysis of most elements in slurry or solution streams as well as in dry material streams (Fig. 4). Single element probes with a scintillation detector and the multi element probes containing a solid state detector are used. The applications include base metals, industrial metals, gold, iron ore, paper manufacture, alumina industry, chemical industry, smelter feed streams, mineral sand and others. The XRF analyzers are energy specific. The most important shortcomings of these analyzers are their very limited depth range and dependence on matrix type and grain size. Other applications of XRF analyzers include analysis of grades of ores in mineral industry, soil surveys, cement production processes, quality control in metallurgical industry, particulate matter on air filters, and sulfur content in crude oils and petroleum products in petroleum industry. The XRF technique is widely used for investigations that involve bulk chemical analysis of major elements (Si, Ti, Al, Fe, Mn, Mg, P etc.) and trace elements (abundances >1 ppm; Ba, Ce, Co, Cr, Cu, Ga, La, Nb, Ni, etc.) in rock and sediments. The sensitivity of the technique for detection of trace elements is typically of the order of a few parts per million (ppm).

4. Nucleonic gauges in India

The applications of NGs in India have registered a reasonably good growth in different industries for process and quality control of the products. As per the national inventory, there are about 7559 NGs installed and operated in about 1119 industrial installations all over India including a few research institutions. The types of NGs for various applications used in Indian industry are as shown in Fig. 9 [3].

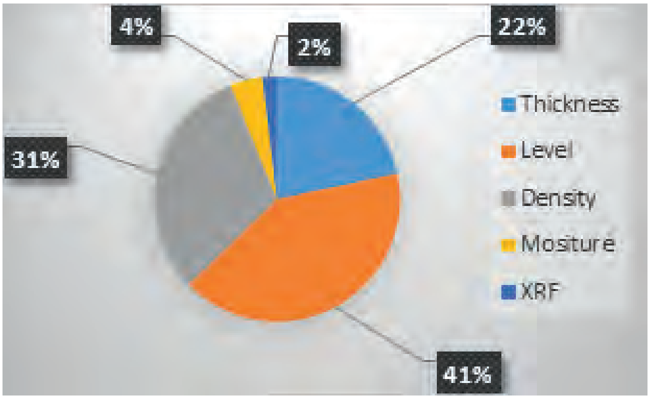

Figure 9: Statistics of NGs for various applications in India

Though majority of the NGs used in Indian industry are imported, M/s Electronic Corporation of India Ltd (ECIL), Hyderabad, a public sector company of department of Atomic Energy (DAE), has been indigenously manufacturing and supplying different types of NGs to many Indian industry. The Board of Radiation and Isotope Technology (BRIT), Mumbai supplies the various sources used in NGs. In addition to this there are a few private companies who also manufacture and supply custom-built NGs to the Indian industry.

5. Regulatory aspects

The nucleonic gauges use ionizing radiation source(s) and thus radiation hazards are associated with their applications. Therefore, adequate protection measures must be adopted to minimize the hazards to as low as possible. The AERB, Mumbai, which is the national regulatory authority in India, stipulates the regulatory requirements and regulations (under the applicable Act and Rules) for safe handling of nucleonic gauges in public domain.

The Atomic Energy Act, 1962 enacted by the Government of India provides the basic legislative framework for all activities including health and safety concerning the atomic energy programme in India. The use of radioactive substances and radiation generating equipment is governed by the said Act. Section 16 and 17 of the Act empowers Atomic Energy Regulatory Board (AERB) to exercise control over radioactive substances and radiation generating equipment. The Chairman, AERB is the Competent Authority to enforce provisions for radiation safety in India.

The authorized user has to obtain license for handling of nucleonic gauges as per Atomic Energy (Radiation Protection) Rule, 2004 issued under the Atomic Energy Act, 1962. Prior to issuance of such license, AERB reviews the compliances with respect of the following:

- Availability of trained personnel, such as Radiological Safety Officer (RSO)
- The NGs are having type approval certificate
- Availability of radiation measuring and monitoring instruments
- Justification of procurement of NGs
- Undertaking from the supplier to accept the disused sources, for safe disposal

Regulatory control for safe transport of radioactive material in public domain in India is governed by the Atomic Energy (Radiation Protection) Rules, 2004 and the AERB Safety Code on “Safe Transport of Radioactive Materials” [AERB/NRF-TS/SC-1, (Rev. 1) (2015)]. A nucleonic gauge itself is a Type-A package and a prior approval from AERB is required for its safe movement from one place to another for intended purposes. The decayed sources in nucleonic gauges that cannot be used for justified/intended purpose are known as disused sources. Such disused sources, when no longer required by the user, should be sent back to the original supplier/country of origin with the prior approval of AERB, Mumbai.

With regard to the security of NG source(s), it is the responsibility of the employer, as the custodian of radiation source(s), to ensure physical security of the NG source(s) at all times by taking into account the security threat perceptions at the location of installation, during storage and transport [3-6].

6. Conclusions

Different types of nucleonic gauges have been in use in Indian industry for more than four decades. The end user industries have been benefitted enormously by the use of nucleonic gauges. The main benefits are achieved from online monitoring of the process parameters, production of desired quality of the products and process optimization. Besides a few private suppliers, the Electronics Corporation of India Limited (ECIL), Hyderabad, a public sector company under the Department of Atomic Energy (DAE), manufactures and supplies the various types of gauges to the Indian Industry. The sources used in these gauges are supplied by Board of Radiation and Isotope Technology (BRIT), Mumbai. In recent years, there has been a significant growth in applications of nucleonic gauges in India because of their ease of availability, but not commensurate with the size of the Indian industry. Considering the size, expansion and modernization taking place in Indian industry, there is scope for enhanced growth of application of nucleonic gauges in India.

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