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Naturally Occurring Radioactive Materials (NORMs) Analytical Method

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Abstract

Naturally occurring radioactive materials (NORMs) are abundant in the environment and create important causes of anthropological exposure to ionizing radiation. Industrial activities such as mining, oil and gas exploration, fertilizer production, and mineral processing can increase the concentration and redistribution of these radionuclides, thereby increasing potential environmental and health risks. Consequently, reliable analytical methods and techniques are essential for the detection, identification, quantification, and monitoring of NORMs in environmental and industrial samples. This review examines the major methods and techniques employed in NORM analysis, with emphasis on their principles, applications, advantages, and limitations. Gamma-ray spectrometry, particularly using Sodium Iodide [NaI(Tl)] and High-Purity Germanium (HPGe) detectors, remains the most widely utilized technique because of its non-destructive nature, high detection capability, and simultaneous multi-radionuclide analysis. Other important techniques reviewed include alpha spectrometry, liquid scintillation counting, neutron activation analysis, inductively coupled plasma mass spectrometry (ICP–MS), radon monitoring methods, X-ray fluorescence, and autoradiography. The review further compares these techniques based on sensitivity, accuracy, operational requirements, and suitability for different sample matrices. Findings indicate that no single analytical method is universally applicable for all NORM investigations; rather, the selection of a technique depends on the radionuclides of interest, sample characteristics, detection limits, and research objectives. The integration of complementary analytical techniques therefore provides more reliable and comprehensive radiological assessments. This review contributes to the understanding of current methodologies in NORM studies and highlights the importance of advanced analytical approaches in environmental radiation monitoring and radiological protection.

Keywords: Naturally occurring radioactive materials (NORMs), radionuclides, spectrometry, electrodeposition, sensitivity, uranium.

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1. Introduction

Naturally occurring radioactive materials (NORMs) refer to radioactive substances that are naturally present in the environment and are mainly derived from the decay chains of uranium-238 (238U), thorium-232 (232Th), and potassium-40 (40K). These radionuclides are widely distributed in environmental media such as rocks, soils, water bodies, atmospheric particulates, phosphate deposits, and biological materials (Vearrier et al., 2009; Egidi, 1997). According to Michalik et al. (2023), NORM comprises radioactive materials that do not contain appreciable quantities of radionuclides other than those occurring naturally. Nevertheless, the interpretation of what constitutes “significant amounts” is not universally standardized and may vary across national and local regulatory frameworks. Consequently, the classification and regulation of NORM differ among countries and across global regions (Brown and Chambers, 2017; Nabhani and Khan, 2020).

Industrial processes including mining, petroleum and gas extraction, phosphate fertilizer production, coal burning, and mineral processing have the potential to increase the concentration and redistribution of naturally occurring radionuclides, thereby generating technologically enhanced naturally occurring radioactive materials (TENORM) (IAEA, 2003; Michalik et al., 2023). For this reeason, the proper characterization and assessment of NORMs are crucial for environmental surveillance, radiation safety in occupational settings, waste disposal practices, and adherence to regulatory standards (UNSCEAR, 2008).

Furthermore, NORMs are frequently associated with mineral ores, fossil fuels, and related geological materials. Various industrial activities such as chemical and physical separation techniques, wastewater and effluent treatment, and flue gas purification can promote the accumulation of radionuclides, even when the initial raw materials contain relatively low concentrations of radioactive substances. Consequently, radioactive residues, wastes, by-products, and finished products may be encountered in numerous industrial sectors that are not directly connected to the nuclear industry (Michalik, 2009; European Commission, 2003; Hofmann et al., 2000; Garcia-Tenorio et al., 2015; Chen, 2022).

Several analytical and radiometric techniques have been developed for the assessment of naturally occurring radioactive materials (NORMs). These techniques vary in terms of sensitivity, accuracy, detection limits, operational requirements, and suitability depending on the radionuclide of interest and the nature of the sample matrix being analyzed (Gilmore, 2011). Commonly applied methods for NORM analysis include Neutron Activation Analysis (NAA), Liquid Scintillation Counting (LSC), Alpha Spectrometry, and Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

Nevertheless, gamma-ray spectrometry remains the most widely utilized analytical technique due to its effectiveness in radionuclide identification and quantification. In addition, X-ray fluorescence spectrometry (XRFS) and other mass spectrometric techniques are employed for more comprehensive radiological investigations (Fathy et al., 2024).

Alpha spectrometry is widely employed for the determination of alpha-emitting radionuclides, particularly uranium and polonium isotopes. The technique involves radiochemical separation of the target radionuclides, followed by electrodeposition onto stainless steel discs prior to measurement. This method provides excellent sensitivity and precise isotopic characterization; however, the sample preparation procedure is often labour-intensive and time-consuming (Eisenbud and Gesell, 1997).

Liquid Scintillation Counting (LSC) is another important technique used in the determination of NORMs, especially for low-energy beta-emitting radionuclides. In this method, radioactive samples are combined with scintillation cocktails, where emitted radiation generates light pulses that are subsequently detected by photomultiplier tubes. The technique is characterized by high analytical sensitivity and low detection limits, making it suitable for the measurement of low-activity radionuclides (Choppin et al., 2002).

Radiochemical analysis represents another important technique employed in the assessment of naturally occurring radioactive materials (NORMs). This method involves the chemical separation of radionuclides from complex sample matrices through procedures such as solvent extraction, precipitation, and ion-exchange techniques prior to radiometric measurement. Radiochemical approaches are particularly valuable when radionuclide concentrations are extremely low or when spectral interferences limit the effectiveness of direct gamma-ray spectrometric analysis (Friedlander et al., 1981).

1.1 Removal Technologies

Several treatment technologies have been developed for the removal of NORMs from water systems. These include adsorption, coagulation, reverse osmosis, ion exchange, electrodialysis, and membrane filtration techniques (Al-Shomali et al., 2025). A review of 108 studies demonstrated that hybrid treatment systems, which integrate two or more technologies, can achieve removal efficiencies approximately 15–25% greater than those obtained using single-treatment methods alone (Al Saadi et al., 2026). Furthermore, Adebiyi et al. (2021) identified electroremediation, bioremediation, and adsorption as some of the most effective remediation strategies for NORM-contaminated environments.

1.2 Health and Environmental Impacts

Naturally occurring radioactive materials contribute to more than 80% of the total human exposure to ionizing radiation (Adebiyi et al., 2021). Studies conducted in mining regions in Nigeria have reported radionuclide concentrations exceeding recommended regulatory limits, with approximately 50% of the investigations recording elevated thorium-232 (^232Th) levels and 83.3% indicating gross alpha activities above established reference values (Samuel et al., 2022). Consequently, regions with elevated NORM concentrations require comprehensive dosimetry assessments and epidemiological studies in order to evaluate the associated radiological health risks (Sohrabi, 1998).

1.3 Regulatory Considerations

Regulatory frameworks governing technologically enhanced naturally occurring radioactive materials (TENORM) vary considerably across industries and jurisdictions. Current regulatory trends indicate a gradual transition from concentration-based standards toward dose-based assessment approaches (Egidi, 1997). In addition, the establishment of standardized treatment procedures and disposal protocols remains essential for achieving effective and sustainable NORM management practices (Al Saadi et al., 2026).

2.0 Gamma-Ray Spectrometry

Gamma-ray spectrometry is one of the most widely employed techniques for the analysis of naturally occurring radioactive materials (NORMs) due to its non-destructive nature, high sensitivity, and ability to simultaneously analyze multiple radionuclides. The technique has extensive applications in environmental radioactivity assessment, nuclear physics, medical diagnostics, geology, radiation protection, and NORM investigations because of its excellent selectivity and multielement analytical capability (Knoll, 2010). Gamma-ray spectrometers are designed to detect gamma emissions within an energy range of approximately 0.1–10 MeV and may achieve an energy resolution of about 3.5 keV full-width at half-maximum (FWHM) for ^60Co at 1332 keV. Advanced systems employing automatically cooled germanium (Ge) detectors have also been developed for space applications. These systems utilize specialized thermal isolation techniques to maintain the detector at cryogenic temperatures of approximately 90 K despite exposure to extreme thermal environments (Goldsten et al., 2007).

2.1 Principle of Gamma-Ray Spectrometry

Gamma-ray spectrometry is a non-destructive analytical method used for the identification and quantification of radionuclides based on the energy and intensity of gamma photons emitted during radioactive decay processes. Owing to its high sensitivity, selectivity, and capability for multielement determination, the method is extensively applied in environmental radioactivity monitoring, geology, nuclear science, medicine, radiation safety, and NORM analysis (Knoll, 2010; Reinhardt & Herrmann, 2019).

The accurate determination of gamma-emitting radionuclides, particularly in large environmental or geological samples, requires careful consideration of self-attenuation or self-absorption effects (Gilmore and Joss, 2024; Knoll, 2010; Tsoulfanidis & Landsberger, 2021). In gamma-ray spectrometric measurements, gamma photons originating from the interior of a sample may be partially absorbed or scattered within the sample matrix before reaching the detector. This attenuation reduces the number of photons detected and may lead to systematic underestimation of radionuclide activity if appropriate correction factors are not applied.

The operating principle of gamma-ray spectrometry is based on the interaction between emitted gamma radiation and the detector material. Each radionuclide emits gamma photons with characteristic energies that are unique to its nuclear structure. When these photons interact with the detector, electrical pulses are generated, with pulse amplitudes proportional to the

energies of the incident gamma rays. The generated signals are subsequently amplified, electronically processed, and displayed as a gamma-ray spectrum, where the number of detected counts is plotted as a function of gamma-ray energy (Gilmore, 2008).

The resulting spectrum contains distinct peaks referred to as photopeaks or full-energy peaks, which are characteristic signatures of specific radionuclides. Identification of radionuclides is achieved by comparing the measured gamma-ray energies with standard reference values, while quantification is performed by relating the net peak area to the radionuclide activity concentration through detector efficiency calibration procedures (IAEA, 1989).
The activity concentration of a radionuclide in gamma-ray spectrometry is commonly calculated using the following expression:

$$A = \frac{N}{\varepsilon\, P_\gamma\, t\, m}$$

Where:

- A= activity concentration of the radionuclide $\left(\mathrm{Bq\ kg^{-1}}\right)$
- N= net count under the photo peak
- ε= detector efficiency at the specific gamma-ray energy
- P_γ= gamma emission probability (gamma yield)
- t= counting time (s)

m= mass of the sample (kg)

This comparison is based on the principle that the number of gamma rays detected from a sample depends on the radionuclide activity, detector efficiency, emission probability of the gamma ray, enumeration period, and the sample mass. The formula is widely used in environmental radioactivity studies and gamma spectrometric analysis for determining the concentration of naturally occurring and artificial radionuclides in different sample matrices.

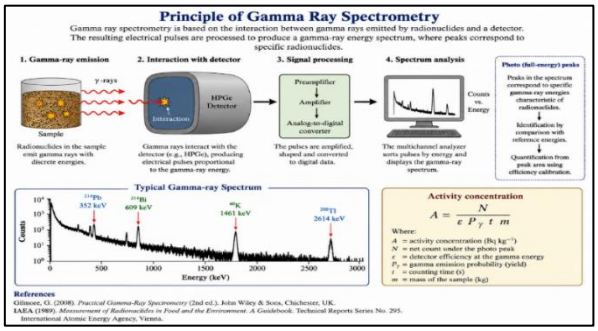

Figure 1: Showing Principle of Gamma-ray spectrometry (Gilmore,2008)

2.2 Gamma-Ray Interaction Mechanisms

The operation of gamma-ray spectrometry is fundamentally based on the interaction of gamma photons with matter. The principal interaction mechanisms include photoelectric absorption, Compton scattering, and pair production.

2.2.1 Photoelectric Absorption

Photoelectric absorption occurs when a gamma photon transfers all of its energy to an orbital electron, resulting in the complete absorption of the photon. The ejected electron subsequently leaves the atom with kinetic energy equivalent to the incident photon energy minus the electron binding energy. This interaction is responsible for the formation of photopeaks in the gamma-ray spectrum and predominates at relatively low gamma-ray energies (Knoll, 2010).

2.2.2 Compton Scattering

Compton scattering takes place when a gamma photon transfers only a portion of its energy to an electron and is subsequently deflected with reduced energy. This interaction contributes to the continuous background region of the spectrum, commonly referred to as the Compton continuum (Gilmore, 2008; Crouthamel et al., 2013).

2.2.3 Pair Production

Pair production occurs when a gamma photon with energy greater than 1.022 MeV interacts with the nuclear field, leading to the formation of an electron–positron pair. This process becomes increasingly significant at higher gamma-ray energies and may produce escape peaks within the measured spectrum (Knoll, 2010).

2.3 Components of a Gamma-Ray Spectrometry System

A typical gamma-ray spectrometry system comprises several essential components that function collectively for the detection, processing, and analysis of gamma radiation. These components include:

- **Detector:** The detector serves as the primary sensing element and converts incoming gamma radiation into measurable electrical signals. Commonly used detectors include sodium iodide [NaI(Tl)] scintillation detectors and high-purity germanium (HPGe) semiconductor detectors due to their efficiency and sensitivity (Chiozzi et al., 2000).
- **Photomultiplier Tube (PMT):** In scintillation detection systems, the photomultiplier tube is used to amplify the light pulses generated during gamma-ray interactions within the scintillation crystal.
- **Preamplifier and Amplifier:** These electronic components are responsible for processing, amplifying, and shaping the electrical signals produced by the detector to ensure accurate signal analysis.
- **Multichannel Analyzer (MCA):** The MCA sorts electrical pulses according to their amplitudes and generates the gamma-ray spectrum by organizing detected events into energy channels.
- **Computer and Analytical Software:** Computer systems and associated software are utilized for spectrum acquisition, data processing, radionuclide identification, and determination of radionuclide activity concentrations (Gilmore, 2008).

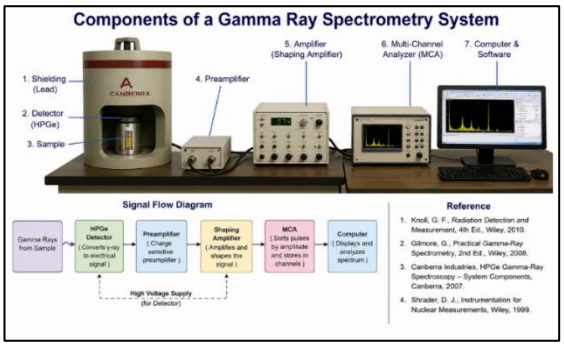

Figure 2: Showing component of Gamma-ray spectrometry (Knoll,2010)

2.4 Detectors

2.4.1 Sodium Iodide [NaI(Tl)] Detector

Sodium iodide doped with thallium [NaI(Tl)] detectors are among the most commonly utilized detectors in gamma-ray spectrometry due to their high detection efficiency and relatively low operational cost. However, these detectors exhibit moderate energy resolution, which may restrict their capability to distinguish between closely spaced gamma-ray peaks in complex spectra (IAEA, 1989).

2.4.2 High-Purity Germanium (HPGe) Detector

High-purity germanium (HPGe) detectors are widely regarded as the standard detectors for high-resolution gamma-ray spectrometry because of their superior energy resolution. Their excellent resolving capability enables precise identification of radionuclides, even in highly complex gamma spectra. Nevertheless, HPGe detectors require continuous cooling, commonly achieved using liquid nitrogen, in order to minimize electronic noise and maintain optimal detector performance (Knoll, 2010).

2.5 Applications of Gamma-Ray Spectrometry

Gamma-ray spectrometry has broad applications across various scientific, environmental, medical, and industrial disciplines. Some of its major applications include:

- Determination of radionuclide concentrations in environmental samples
- Analysis of naturally occurring radioactive materials (NORMs)
- Monitoring and control of nuclear reactors
- Characterization of radioactive waste materials
- Geological investigations and mineral exploration
- Analysis of medical radioisotopes
- Food irradiation and preservation studies
- Radiation protection and health physics assessments (IAEA, 2003)

2.6 Advantages of Gamma-Ray Spectrometry

Gamma-ray spectrometry possesses several important advantages that make it suitable for radionuclide analysis, including:

- Non-destructive nature of analysis
- Simultaneous detection and identification of multiple radionuclides
- High analytical sensitivity and accuracy
- Minimal sample preparation requirements
- Rapid measurement and analysis time
- Capability for both qualitative and quantitative radionuclide determination (Gilmore, 2008)

2.7 Limitations of Gamma-Ray Spectrometry

Despite its numerous advantages, gamma-ray spectrometry also has certain limitations, which include:

- Reduced sensitivity for low-energy gamma-emitting radionuclides
- Requirement for careful detector calibration procedures (Almaz and Landsberger, 2026)
- Interference arising from background radiation
- High acquisition and maintenance costs of HPGe detector systems
- Requirement for shielding and cooling systems in high-resolution detectors such as HPGe systems (Knoll, 2010)

2.8 Recent Advances in Gamma Ray Spectrometry

Recent technological developments have improved the performance and applications of gamma ray spectrometry. Digital signal processing systems, portable spectrometers, electrically cooled HPGe detectors, and advanced computational methods have enhanced measurement accuracy and efficiency. The integration of gamma spectrometry with geographic information systems (GIS) and unmanned aerial vehicles (UAVs) has further expanded its applications in environmental monitoring and radiological emergency assessment.

Artificial intelligence and machine learning techniques are increasingly being explored for automated spectral interpretation and radionuclide identification (IAEA, 2020).

2.9 Conclusions

Naturally occurring radioactive materials (NORM) are widely present in the environment and industrial processes, requiring accurate analytical methods for effective assessment. Gamma-ray spectrometry remains the most commonly used technique because of its reliability and ability to measure multiple radionuclides simultaneously, while other methods such as alpha spectrometry, neutron activation analysis, liquid scintillation counting, and ICP-MS provide improved sensitivity for specific applications. Advances in detection technology and data processing have enhanced analytical performance, although challenges such as calibration uncertainties, matrix effects, and high operational costs still exist. Overall, reliable NORMs assessment requires the combined use of suitable analytical techniques supported by strong quality assurance procedures for effective environmental monitoring.

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