

RADIATION TECHNOLOGY APPLICATIONS IN MINING AND MINERAL PROCESSING

III-1. Introduction

Radiotracers and nucleonic gauges are increasingly being applied by the mining, metallurgy and mineral processing industries for the exploration and efficient extraction of natural resources. Such industries exist in most countries and are often major contributors to national economies. Radiotracers are excellent tools for deriving data in a simple manner from a variety of complex and closed fluidic systems. Various processes, such as grinding, flotation and homogenization, are employed in the mineral processing industries, and vital information can be gathered from these processes for optimal recovery of the ore and extraction of the desired mineral. The information provided by the radiotracers helps with troubleshooting, process control and optimization, investigation of flow patterns, and development and verification of mathematical models.

Geophysical techniques are well established in the oil, gas, uranium, coal and minerals industries. Nuclear borehole logging, which takes advantage of the deep penetration of neutrons and gamma rays, has been widely used in the oil, gas and uranium industries for a long time. Owing to the attractive benefits, the use of radiotracers and nucleonic gauges in such industries is expanding and continuously evolving. New radiotracers, more user-friendly software, and new detectors and data acquisition systems are being developed and introduced.

In addition, various nuclear spectrometry methods have been successfully used for more than 30 years in the field and in industrial environments. Apart from natural gamma radiation measurements for the exploration of radioactive ores, techniques such as gamma ray transmission, gamma ray backscattering, neutron activation analysis (NAA) and its variants (prompt gamma NAA (PGNAA) and delayed gamma NAA (DGNAA)), as well as X-ray fluorescence (XRF) are used at various stages in the mining and metallurgy industries. A modern portable nuclear spectrometer enables in-situ analysis resulting in savings in time without compromising on performance, which often matches that of a laboratory instrument.

III-2. Radiotracers, nucleonic gauges and nuclear analytical techniques

Radiotracers and nucleonic gauges have been widely used by mining industries to improve the quality of products, optimize processes, and save energy and materials. Many large industries in this field have recognized the high socio-economic as well as technical benefits of radioisotope technology and use such techniques extensively. It is estimated, that a benefit to cost ratio of 40:1 is reasonably achievable.

Nuclear analytical techniques (NATs) for the characterization of materials are based on the utilization of certain properties of the nucleus itself, in contrast to non-nuclear techniques which utilize the properties of the atom as a whole, primarily governed by the properties of electrons in the shells. NATs are frequently associated with the phenomena of ionizing radiation and isotopes. Thus, besides nuclear excitations, nuclear reactions and/or radioactive decay, the processes involved in electron inner shell excitations are also pertinent to NATs. Moreover, some of the NATs of the latter category, such as the synchrotron radiation-induced X-ray emission technique can only be performed using nuclear instrumentation, namely various accelerators. Widely used techniques in this category are:

- X-ray fluorescence (XRF)
- Ion beam analysis (IBA) techniques, including proton induced X-ray emission (PIXE), proton induced gamma-ray emission (PIGE), and Rutherford backscattering (RBS)
- Synchrotron based techniques
- Prompt and delayed gamma neutron activation analysis (PGNAA and DGNAA)

If the cost-effectiveness of radioisotope applications were more widely known, even more industries might use these technologies. Portable nuclear analysis systems, such as portable miniature and compact nucleonic gauges for multipurpose services have been gaining popularity in recent times, especially in the case of a new generation of nucleonic gauges designed and manufactured for elemental analysis in mining industries.

Radiotracers, nuclear analytical techniques and nucleonic gauges can beneficially be used in the mining industries to improve quality and recovery of the mineral from the ore, monitor rapidly the quality of the manufactured product, reduce production downtime, reduce industrial pollution, save raw materials, reduce waste and rejects, reduce labour cost, and make workers' performance easier.

The radiation techniques that are commonly employed in the exploration, extraction and processing of mineral resources are listed in Table I.

Table I. Radiation techniques and applications in mining and mineral industries

Techniques	FIELDS OF APPLICATION					
	LOGGING		MINERAL PROCESSING IN-SITU			Elemental composition laboratory analysis
	Delineation of deposit	In-situ assaying	On & off belt analysis	Slurry analysis	Density, weight, level/fill	
Natural γ radiation	X	X	X	X	X	
γ -ray transmission			X	X	X	
γ -ray backscatter	X	X	X	X	X	
PGNAA & DGNAA	X	X	X			X
XRF analysis		X		X		X
IBA						X
Synchrotron beam analysis						X
PIXE, PIGE analysis						X
RBS						X

III-3. Techniques for characterization of minerals

III-3.1. Online and in-situ analysers

Online analysers are mainly based on NAA, but XRF portable systems can be used for online analysis while logging, as well as for in-situ analysis on samples. XRF based systems have more limitations than neutron based ones because of their geometric requirements and their lower thickness penetration.

Neutron generators, typically of 14 MeV neutrons, are employed to activate samples of coal, cement, etc. on conveyor belts for online analysis to determine their elemental composition. Such online generators are commercially available from several manufacturers and more than 400 such units are operating in cement factories and other mineral industries. The high throughput and analysis of nearly

90% of the sample are the major advantages of this method compared to conventional sampling methods which cover about 4–10%. Another kind of online analyser continuously controls coal quality as it moves through a coal chute in power plants. The oxygen and carbon in the coal are measured based on the fast neutron reaction. Neutrons are thermalized by the large volume of carbon, and thus prompt gamma rays from thermal neutron capture in hydrogen, sulphur and chlorine can also be measured. Delayed gamma rays from radioactive isotopes (such as sodium-24) are also collected. These three types of spectra (gamma rays from fast neutron reactions, prompt gamma rays from the capture of slowed down neutrons, and decay gamma rays) are collected using appropriate time windows. For the gamma detection a scintillator and digital electronics are used. A prototype, installed on a trailer, was recently tried out in Europe using eight loads of different coal samples with a mass of 600 kg each. The compositions were then compared to those from averages of several small samples taken from the load, and analysed with good results.

III-3.2. Offline analysis

III-3.2.1. Neutrons and ion beam based techniques

In geological prospecting, neutron generator (NG) based NAA is applied by well logging devices for determining the major components in situ. This type of work is usually subcontracted to companies specialized in logging services. It has been shown that NGs can be used for uranium detection using delayed neutron counting.

The sensitivity of NG based activation analysis, when compared to reactor based NAA and other analytical techniques, is limited for online applications. When higher sensitivity is required laboratory instruments and techniques have to be selected.

III-3.2.2. X-ray fluorescence based applications

In nearly all geochemical and environmental materials, such as minerals, ores, soils and sediments, many elements are present at levels that can be directly assessed with conventional XRF. The only sample preparation required is usually grinding followed by pelletizing or fusion with a suitable flux, in order to reduce mineralogical effects and improve the accuracy. XRF also continues to be applied to the study of sediments as monitors of heavy metal pollution in water.

XRF has great potential in the field of geochemistry. The possibility of tuning the photon energy to optimize the excitation of specific elements and suppress the excitation of others can be very useful, for example in the detection of noble metals in minerals. The non-destructive character and high penetration power of both the excitation and the fluorescence X-rays makes micro-synchrotron radiation-XRF (micro-SR-XRF) ideal for analysing unopened fluid inclusions in minerals. The composition of the fluid inclusion can reveal information on conditions during mineral genesis of basic geological interest, but also on the conditions for the formation of economically important ones.

Currently, one of the most widely-used applications of portable XRF instrumentation is for assessing the environmental impact of lead contamination in soil. In the case of contaminated land, the main benefit of portable XRF instrumentation is that detection limits are 5 to 10 times lower than 'permissible' limits for lead in soil. For many of the other toxic metals of environmental interest, although the detection limits of portable XRF are not adequately sensitive for the purpose of qualifying the samples as safe, they could still be used for estimating gross contamination.

III-3.2.3. Synchrotron based applications

During the past decade, synchrotron techniques have found a wide range of applications in the field of environmental monitoring, particularly related to the management of mine tailings. Straightforward yet powerful techniques such as X-ray absorption spectroscopy (XAS) and X-ray diffraction (XRD)

can provide detailed information about elemental concentrations and mineral composition, including speciation, without the need for complicated and potentially unreliable sample preparation. Examples include the analysis of arsenic, selenium and chromium, where speciation measurements are vital. Other examples include the assessment of airborne pollution, such as that from sulphur, lead and nickel, that can result from smelting processes.

Great advances are being made in using synchrotron radiation, partially due to the presence of reliable XAS and XRD beam lines in existing synchrotron facilities, which are typically in very high demand. Improved detectors have resulted in better detection limits, and the basic research is resulting in proven data analysis methods. These developments have occurred at a time of growing concern about the legacy of worldwide mining operations. Governments are having to deal with abandoned mine sites, and mining companies are increasingly focused on improved extraction and processing technologies that will lower environmental impacts.

To give a specific example, the industrial science programme at the Canadian Light Source has been highly successful in engaging mining companies to use synchrotron techniques for issues related to mine waste management and airborne pollution. The rapid growth of research in this area may soon lead to the development of an international research centre focusing on environmentally sustainable mining.

III-4. Case studies on radiotracer applications in mineral processing

Brief descriptions of radiotracer studies conducted in Member States for troubleshooting in their industrial sectors are given below to illustrate the benefits of these applications.

III-4.1. Radiotracer investigation of leaching process in a gold processing plant in Ghana

In 2009, a radiotracer study was carried out at a gold processing plant (Fig. III-1) in Ghana to estimate the residence time distribution (RTD) in the leaching tank using an iodine-131 radiotracer with the aim of increasing the leaching efficiency.



FIG. III-1. Gold processing plant where a radiotracer was used to investigate the flow pattern.

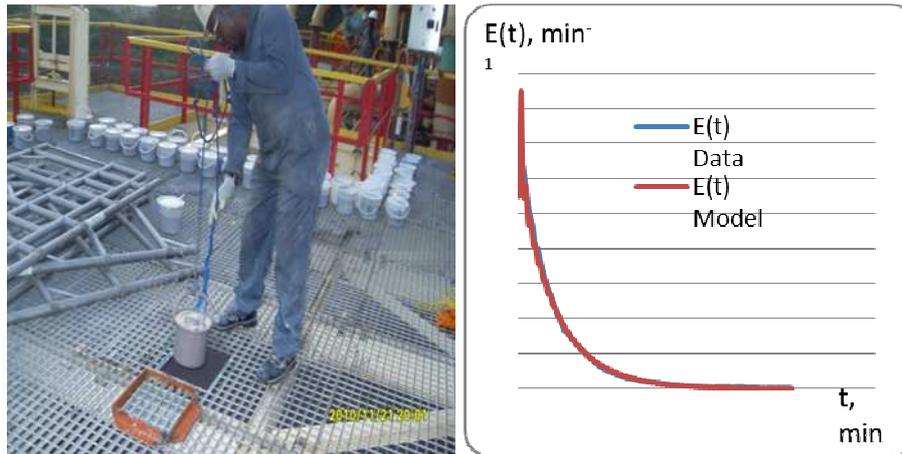


FIG. III-2. Experimental RTD sampling and modelling.

The shape of the experimental RTD (Fig. III-2) curve indicated that the flow behaviour in the tank was close to that of an ideal mixer. Modelling of the experimental data, however, revealed that the tank was not behaving as a single perfect mixer but consisted of two mixing zones, corresponding to regions of vigorous mixing (75%) and pockets of stagnant zones (25%), indicated by the unusual long tail in the RTD curve. Stagnant zones decrease productivity as dissolved gold can be trapped in them. Based on these radiotracer results, the slurry homogenization within the tank was remediated and an increase in gold recovery by a few percentage points was achieved.

III-4.2. Radiotracer investigation of the grinding process in a copper processing plant in Chile

Radiotracer studies were carried out during a recently completed coordinated research project in a copper mining plant in Chile to characterize the fluid dynamic behaviour of three mills of the regrinding circuit (Fig. III-3) in the concentrator plant. Fine and coarse tailings from the plant were activated with neutrons in the nuclear reactor of the Chilean Nuclear Energy Commission and used as radiotracers to study the granulometry of the tailings while bromium-82 as potassium bromide (KBr) was used as the tracer to study liquid flow. The radiotracer was injected into the feed flow and was measured in the outputs of each circuit in real time.

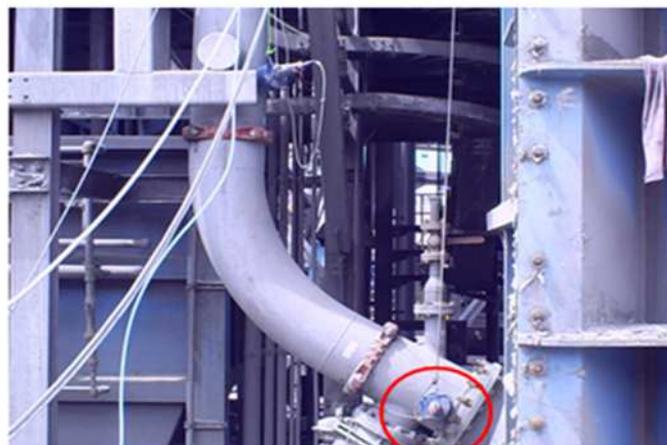


FIG. III-3. Experimental RTD measuring point.

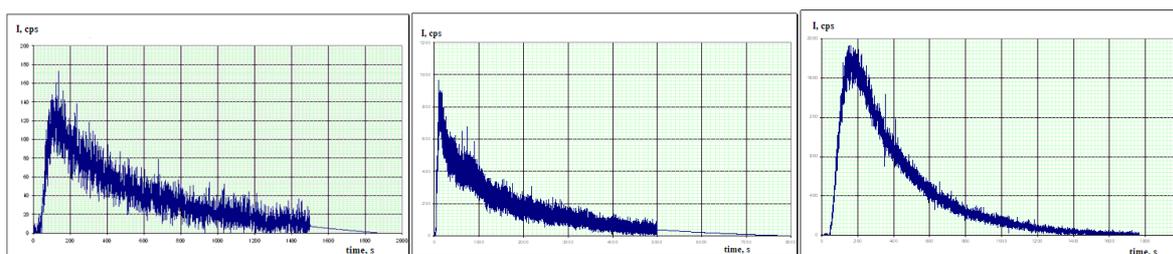


FIG. III-4. Experimental RTD curves for fine and coarse tailing grains, as well as for liquid phase.

The experimental RTD curves (Fig. III-4) showed different flow patterns for fine, coarse and liquid phases; the respective mean residence times (MRTs) through the mill system were found to be 386 seconds, 1693 seconds and 407 seconds, which indicate a relatively low performance of the grinding system. These studies helped the authorities to plan appropriate action such as modifying the design of the system.

III-5. Portable nuclear analysis systems for borehole logging

Among the many physically different borehole logging techniques, nuclear borehole logging is practically the only one that has the capacity for providing quantitative in-situ mineral quality information in real time. Nuclear borehole logging, apart from its capacity to deliver data instantaneously, also has the advantage that the highly penetrating gamma and/or neutron radiation effectively analyses much larger sample volumes than either percussion or core drill samples.

Nuclear borehole logging techniques involve detection and measurement of radiation, which may be counted as accumulated radiation or could be processed further to obtain the radiation energy distribution. These two approaches to data acquisition result in spectrometric and non-spectrometric (total count) logging, respectively.

III-5.1. Low activity gamma spectrometric borehole logging probe for coal delineation and coal raw ash content

Gamma spectrometric bore hole logging yields very useful information in the coal mining industry. Most commercially available logging technologies for the coal mining industry are non-spectrometric (i.e. measure all the gamma radiation received without discrimination in energy). Non-spectrometric gamma-gamma (i.e. gamma ray backscattering) and natural-gamma (i.e. direct measurement of natural gamma radiation) techniques are now being used routinely for the delineation of coal and mineral seam sediments. The coal seams are easily identifiable in the gamma-gamma logs because of the difference in density between coal and sediments.

This approach is satisfactory for the delineation of the roof, floor and thickness of a coal seam. However, it does not always provide an accurate measurement of the ash content in coal seams. This is because the correlation between ash and coal density is not always high. While coal deposits do exist where there is a high correlation between ash content and density, in most deposits there are significant fluctuations in this relationship due to the non-uniform chemical composition of ash in coal and variations in other physical properties of the coal, such as rank and porosity. Only spectrometric techniques can provide direct and accurate estimations of ash content, and its elemental constituents, in coal.

The majority of nucleonic gauges apply substantial radioisotope activity, but there are a number of ingenious small nucleonic gauges using low radioactivity sources of under 3.7 MBq. This activity is defined in some countries as the minimum activity of a radioactive source requiring a licence for

possession, use and transport of radioactive substances. These gauges are currently being implemented for several industrial applications in Australia and Japan.

Low radiation intensity (1.1 MBq) gamma spectrometric borehole logging probes (Fig. III-5) for coal delineation and coal raw ash content utilize single-scattered gamma rays to provide information about the bulk density of the formation, and multi-scattered rays of lower energies to determine coal raw ash content.

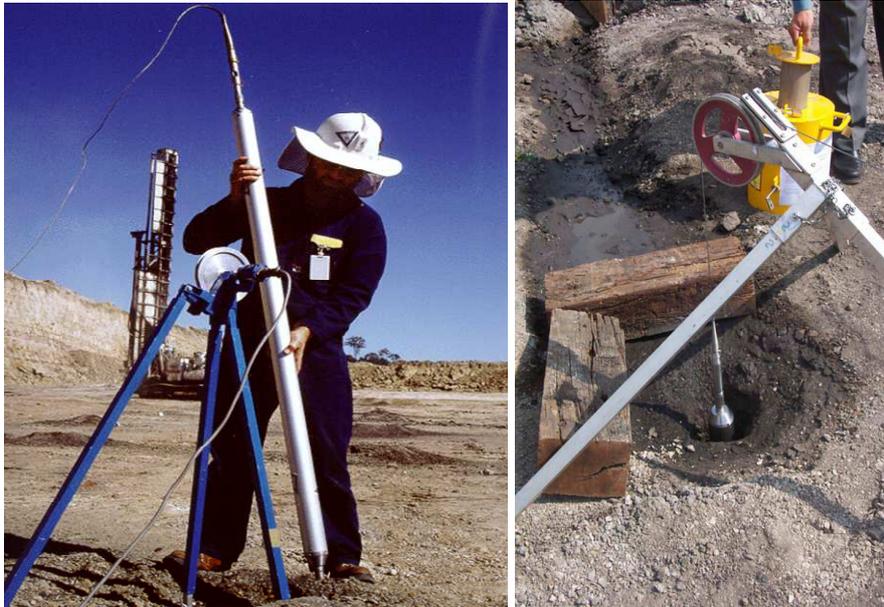


FIG. III-5. Low radiation intensity (1.1 MBq) gamma spectrometric borehole logging probe for coal delineation and coal raw ash content.

III-5.2. PGNAA borehole logging for copper grade analysis in Chile

The PGNAA technique was initially developed for offline applications but has recently been used for on-conveyor belt analysis and borehole logging. When a thermalized, or slow, neutron comes close enough to a nucleus, it will be absorbed by that nucleus. This absorption process causes the nucleus to become excited, a condition that is relieved by the nearly instantaneous release of a unique set of gamma ray energies. Californium-252 is mostly used as a neutron source together with thallium doped sodium iodide (NaI(Tl)) or bismuth germanate (BGO) scintillation detectors. The PGNAA technique is applied successfully both in borehole logging and processing of various minerals.

The PGNAA technique is well suited for many mining applications and has two major advantages over the conventional X-ray fluorescence technique: the deep penetrating ability of the neutrons and gamma rays allows full measurement of material on a conveyor belt or in a chute or a bucket, whereas X-rays penetrate so little that their analysis is strictly a surface phenomenon; and PGNAA can detect many light elements (e.g. Si, Al, K Na, Mg, P and S) which XRF cannot in online applications.

Figure III-6 shows the borehole logging process for copper ore analysis in the Chuquicamata (Chile) open cut copper mine using a PGNAA probe.



FIG. III-6. PGNAA borehole logging for copper grade analysis in Chile.

The PGNAA measured a copper content lower than 1% with 10% accuracy. Using this technique, a new estimation of copper reserves was conducted in Chile which kindled interest in the industry in processing the relatively low grade copper mineral ore.

III-5.3. PGNAA for elemental analysis of raw materials in cement processing in Thailand

The main requirement for a modern cement processing plant is prompt (less than 10 minutes) and accurate analysis of various elements that move on belt conveyors. This can be achieved only with PGNAA, which uses a californium-252 neutron source and BGO scintillation detectors to determine elemental composition based on thermal neutron capture gamma rays.

The PGNAA technique is typically used in modern cement plants for pre-blending optimization as well as raw mix optimization processes. This means that PGNAA equipment replaces huge silos. Despite its relatively high price the initial cost is paid back in a few months. Further benefits include an increase in quality and in quantity bringing additional incomes of millions of dollars a year.

Figure III-7 shows the schematic design of two PGNAA crossbelt analysers in a big, modern cement plant in Thailand. The system, called the 'Raw Mix Optimization System (RAMOS)' has been performing well for the past five years. It is used to determine the composition of both raw and mixed materials before kilning. It works automatically on the conveyor belt. It is accurate, saves time and has lower operational costs in comparison to conventional methods that use silos and conduct sampling and chemical analysis in a laboratory.

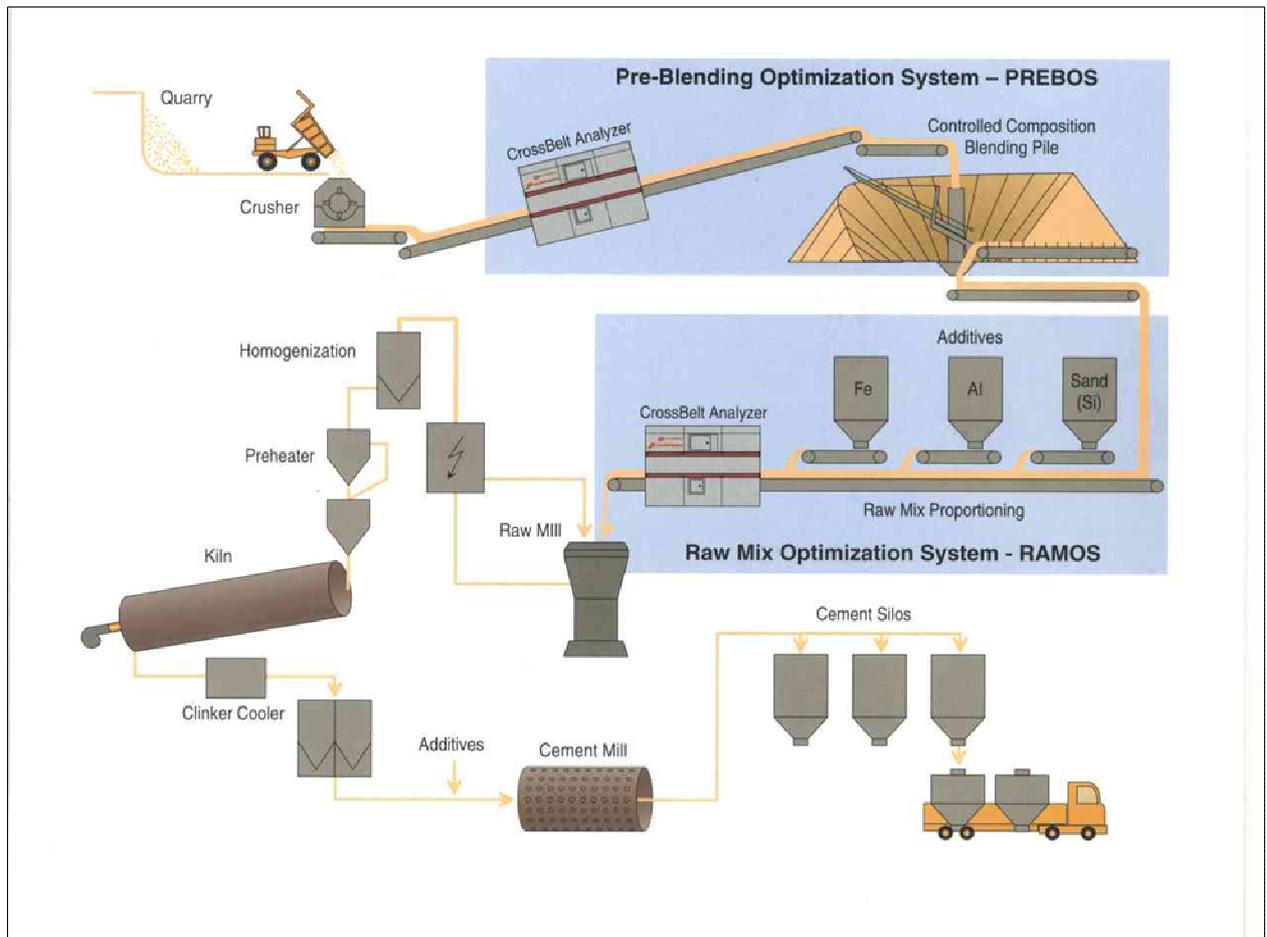


FIG. III-7. The schematic design of PGNAA equipment in a cement plant in Thailand.

The PGNAA technique is well established in online cement, coal ash and mineral ore analyser systems. The next generation of PGNAA analysers will greatly benefit from neutron generators due to their superior life cycle economics and versatility.

III-6. Synchrotron applications for assessing arsenic in soils and mine tailings in former industrial sites in Northern Canada

Synchrotron-based techniques, in particular x-ray absorption spectroscopy (XAS), are powerful tools to enhance our understanding of the geochemistry of mine waste. Owing to its toxicity, arsenic has drawn worldwide attention in recent years over environmental and health concerns. Arsenic levels in the aquatic environment can be elevated by geological processes such as mineral weathering and dissolution, or more importantly by anthropogenic activities in particular mining and smelting activities. Thus it is important to investigate arsenic-bearing phases with respect to their concentrations, distribution, speciation, mobility and stability.

Arsenic is a natural element that can be found distributed throughout the Earth's crust, either alone or along with ores of minerals such as uranium and gold. For example arsenopyrite, an ore of arsenic, is a rock in which gold is often embedded. Some uranium ores contain significant amounts of arsenic. It is therefore important to monitor arsenic levels as well as its speciation in the effluents and tailings from mining sites which use such ores, in order to ensure that the arsenic does not find its way into the

food chain or potable water. X-ray absorption fine structure (XAFS) spectroscopy is one of the few techniques that can be used to identify and quantify metal and metalloid species, such as the arsenic species, in complex solid mixtures; the principles of the technique and its benefits/drawbacks have been described in numerous publications. Over the past decade, XAFS spectroscopic studies have been used for the quantification of various chemical species of arsenic.

The mining of the high-grade uranium deposits located in northern Saskatchewan, Canada, accounts for approximately one-third of the world's total uranium production. Along with uranium, arsenic co-mineralization is present and the amounts are significant in the ore from some deposits. In a typical acid leach uranium ore processing facility, most of this arsenic is leached into solution. Following uranium removal by solvent extraction and precipitation processes, the arsenic remains in an acidic sulphate waste solution referred to as raffinate. The raffinate is then subjected to a lime neutralization process where arsenic is removed by precipitation with ferric iron, thereby producing low solubility iron-arsenates. After neutralization, the tailings are placed in a tailings disposal facility. A potential concern is about the soluble arsenic originating from the neutralized raffinate solids in the water of the final tailings.

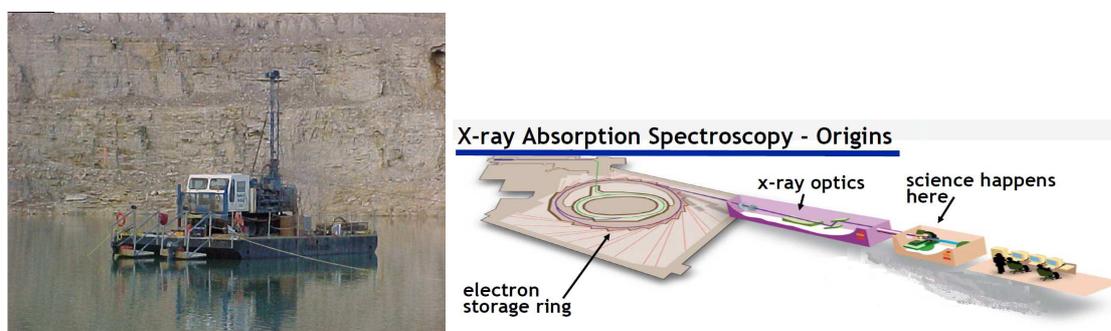


FIG. III-8. Left: A barge mounted drill rig at the mine site was used to sample pore waters and to obtain cores of the tailing material. Right: X-ray absorption experiment schematic design at the synchrotron facility.

Through a systematic XAFS structural study on the iron (III)-arsenate precipitates obtained by the neutralization of the process effluent from the above-mentioned uranium mines, it could be established that with time arsenic was getting transformed to the least soluble state As(V), which is desirable.

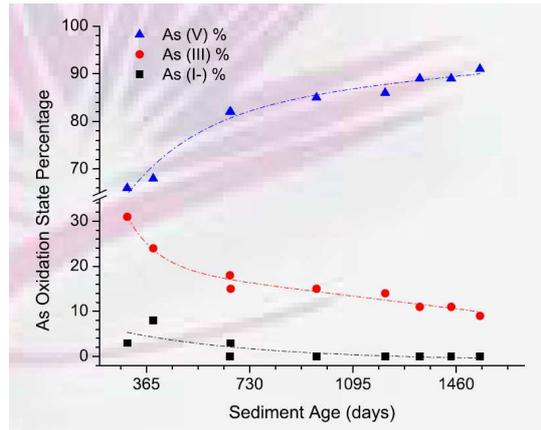


FIG. III-9. Over four years of exposure in the tailing management facility environment a trend can be clearly seen in the three solid phases of arsenic (black, red and blue data points). Both arsenide (As(I), black) and arsenite (As(III) red) phases show decreases over time with a simultaneous increase in the As(V) oxidation state (blue).

Figure III-9 presents the results of an assessment of the stability and long term fate of mill tailings, indicating that the disposal of arsenic in the mine tailings as amorphous ferric arsenate would result in the conversion of >90% arsenic to the preferred As(V) state over a period of 4 years, which is one-sixtieth as toxic as As(III) and much less mobile in groundwater.

These investigations show that XAFS is a useful tool to probe the arsenic local structural environment in an amorphous material such as amorphous ferric iron-arsenate co-precipitate. XAFS has provided direct local structural evidence of the transformation of amorphous scorodite to crystalline scorodite through the ageing process, which is of potential environmental significance.

III-7. Conclusion

A wide range of techniques and technologies that employ radioisotopes or radiation sources offer great advantages to the mining industries, be it for exploration, optimization of processes, troubleshooting, assessment of mining sites or ensuring environmental protection. This is evident from the increasing use of such technologies by the mining industries and the continuous evolution, innovations and improvements in the techniques and instruments used.