Mineral exploration, mining and processing

by Yu. G. Sevastyanov*

At present many laboratories around the world devote substantial effort to the development of nuclear techniques for mineral industries. There are several reasons for this. Since the re-emergence of coal as a major energy source, there has been a need for improved exploration techniques, for improved on-line analysis in coal preparation and processing, and for boiler control in power generating plants.

The development of nuclear techniques has also benefited from an increased intensity in uranium exploration, especially in the USA and Canada, where new borehole-logging techniques that measure uranium directly are being introduced into routine operation. Improvements in the performance of equipment for measuring natural-gamma radiation also reflect favourably on the performance of equipment designed to measure the intensity of induced, rather than natural-gamma, radiation.

Although the development of oil-logging equipment is confined to a few laboratories, the frequent and significant improvements in performance and extensions in the range of measurement act to stimulate the development of similar equipment for use in exploration for other minerals. Since it is well known that the reserves of certain metalliferous minerals are likely to approach exhaustion, the search for new high-grade deposits is an urgent matter.

The training seminar in Ottawa** sought to provide the participants, mainly scientists from developing Member States, with the most important nuclear analytical technology in current use, and those believed to have the greatest potential for future application. It also pointed out industries, especially those in developing Member States, which already benefit or could further benefit from the application of nuclear techniques. As was emphasized at this training seminar, there are several nuclear techniques useful in the mineral industries: energy dispersive X-ray fluorescence analysis; measurement of natural gamma radiation; gamma-gamma techniques; and neutron interaction techniques.

Energy dispersive X-ray fluorescence techniques are well-developed for mineral analysis, mining and process control. The principal advantage of these techniques are low limits of detection (about a few ppm for most elements) and their ability to measure the concentration of up to 40 elements simultaneously. Relatively simple equipment has also been designed for measuring the concentration of one or more elements in the field. The disadvantages of this system are: small sample size analysed; interference of X-ray lines from one element on other elements; the limited penetration of the excited X-ray.

Measurement of natural gamma radiation: There are a variety of natural γ-rays emitted from isotopes of the primordial elements U, Th and K which can be measured by well-developed techniques. Principal applications are for uranium exploration, potash mining, and mineral stratification during coal and oil exploration. Natural γ-rays are also good indications of the presence of certain other minerals. (For example, phosphoric deposits have high uranium concentration; they thus can be located by the measurement of U.) The main disadvantages of the natural γ-rays measurements techniques arise from the requirement that the mineral of interest be correlated with U, Th or K, and the possible unknown degree of equilibrium between U, Th and their daughters.

Gamma-gamma techniques: Although selective gamma-gamma techniques can be used for specific elemental analysis of medium- and high-Z elements at high concentrations (≥0.1%) in low-Z matrices, the intensive development of these techniques for exploration does not appear to be a very profitable line of investigation. Non-selective gamma-gamma techniques are restricted to density measurement. Typically the strong gamma-ray source used in proximity to the detector necessitates the use of special shield configurations to isolate the detector from viewing the source directly. In addition to this problem, special methods of holding the highly radioactive source must be used.

Neutron interaction analysis: In general, neutron interaction analytical techniques are characterized by a high degree of elemental specificity and by penetration

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** Training seminar on nuclear analytical technology and application in mineral exploration, mining and processing, organized by the IAEA and held in Ottawa, Canada, 28 June to 2 July 1982 at the invitation of the Government of Canada. The training seminar was attended by 51 participants representing 18 countries and one international organization. Twenty papers were presented in eight sessions.

to a range varying from 20 to 100 cm. Both of these properties are attractive for *in situ* analysis in exploration. The techniques are multi-element whereby some sixty elements can be measured, though not all at the same time, under a given set of neutron irradiation conditions and sample matrices. Of several techniques which can be used, the most important is analysis of measurement of prompt gamma rays from neutron capture, measurement of gamma rays from inelastic neutron scattering, and measurement of gamma rays from the subsequent decay of activated nuclei. The choice depends on a number of factors of which the most important are: the cross-section for the particular reaction; the abundance and energy of the particular gamma ray; the significance of interfering reactions; the possibility of using a high-resolution detector; and the constraints imposed by the system design.

Radiation sources and detectors

A variety of radiation sources are used when nuclear methods are applied to mineral exploration. For example, X-ray fluorescence technology has usually used the radioactive species ^{109}Cd, ^{241}Am, ^{55}Fe, ^{57}Co, and sometimes ^{153}Gd and ^{244}Cm.

Technology using gamma-gamma techniques uses several radioisotopic sources. The principal ones are ^{241}Am, ^{137}Cs, ^{57}Co and ^{60}Co.

Neutron interaction analysis permits a variety of neutron sources. For direct application to investigation of the minerals, isotopic neutron sources, especially ^{252}Cf, $^{238}Pu/Be$ and $^{241}Am/Be$, are preferred because of their small size and independence from power supplies.

There are two primary types of detectors which have been applied to the detection of radiation. The first type is the neutron detector which typically uses BF_3 or ^3H. The second detector type is used to detect photons: either X-rays or gamma rays. Low-resolution detectors are the scintillators NaJ(Tl) and plastic phosphors; high-resolution detectors are made from coaxial Ge(Li), coaxial high-purity Ge, or planar Si(Li).

The advantage of using the low-resolution spectrometers is that they require no cooling. However, they often cannot separate all the photopeaks in a given spectrum. In general, therefore, the high-resolution detectors are used for resolution of photopeaks.

The training seminar also noted that nuclear-based techniques play a significant role in the exploration and subsequent recovery of mineral resources, which in certain countries constitute an important part of the national wealth. They have been successfully used for a number of years in underground and surface exploration in studies carried out in mines. For example, the application of nuclear techniques – principally natural-gamma radiation, $(\gamma-\gamma)$, (n, n^1), (n, γ), (pulsed n, γ), and (n, p) – is well-established in the oil industry. New techniques are still being developed, for which there remain problems in data interpretation and in equipment design. In coal exploration programmes, nuclear logging techniques – especially $(\gamma-\gamma)$ and (natural-γ) – are essential. In addition, measurement of the ash content of coal by means of low-energy X-ray scattering is well-established. The refinement of neutron techniques promises even more accurate measurement of ash content, continuous measurement of calorific energy and determination of the concentration of important elements such as sulphur, chlorine, silicon, calcium, aluminium, and iron – measurements that are required for controlling the efficiency of special combustion furnaces.

Because of natural radioactivity of uranium, techniques for measuring γ-radiation were first applied in ground surveys during uranium exploration. During the past decade, they have been extended to borehole-logging and to airborne surveys. The most up-to-date radiation detectors, associated electronics, and data handling and display systems are now quite generally available.

Low-energy X-ray and (γ,γ) equipment is already in routine use for process control of metalliferous minerals in several developed countries, and equipment is available which is highly suitable for use in developing countries, but some expertise is required for successful application.

The seminar also considered the use of nuclear analytical technology in marine applications. Recently developed nuclear techniques for recognizing sea-bed mineral concentrations as well as some established techniques can be applied for example to delineate placer deposits, submarine phosphorite deposits and manganese modules. As many of the deposits lie off-shore from developing countries (mainly in Southeast Asia), the possibility for early benefit from these techniques is very attractive.