Nuclear techniques in mineral exploration, extraction, and processing

Overview of typical applications and the IAEA's activities in the field

by Rolf J. Rosenberg and Jacques Guizerix

Mineral raw materials form the basis for energy production and the manufacturing industry. Raw material costs may or may not constitute an essential part of the cost of the final product. Yet the availability of the raw material is essential in either case. In developing countries, domestic raw materials serve two purposes: They are a direct source of income, and a natural basis for developing a domestic manufacturing industry.

A common denominator of mineral raw materials is that they are not renewable. Even now, when only a small part of the world has a high consumption level, we can see the exhaustion of some of them. If we want to assure future availability, actions have to be taken. More efficient and cost-saving methods of exploration and extraction of ores have to be developed. Efficient production methods that save energy and raw materials have to be employed. Wastes have to be recycled.

Nuclear analytical techniques have great potential to improve the efficiency of raw materials exploration, extraction, and processing, with savings in energy and materials. They can, therefore, contribute to national economies and development programmes. Advantages are that they are rapid, often specific or multi-element, and simple to use. For some applications, they can be used in places where no other techniques can — for example, in hot, dustry, or aggressive environments or where control measurements must be made through the walls of vessels. Also, because they can sample all or most of a process stream they can give more representative results than analyses based on individual samples. Most importantly, results can be obtained in near real time, thus enabling the measurements to be used for on-line process control applications.

Basic geological research

All mineral exploration is based on an overall understanding of geological processes and the geology of the particular area investigated. Nuclear techniques are particularly useful for age determination and to obtain knowledge of the distribution of elements in different rock types.

For analysing elements, neutron activation analysis (NAA) has been widely used in basic geological research. It is one of the most sensitive analytical methods for many elements. Even small, very rare samples, such as lunar samples or separated minerals, can be analysed. Overall, NAA is accurate, can be applied without destroying the sample, can be used for multi-element analysis, and is easy to automate.

Through instrumental NAA, more than 40 different elements can be determined in rock samples. (In lunar samples and small mineral samples, it has been commonly used to analyse 40 elements.) In ordinary rock samples, NAA (compared with non-nuclear technique) is most favourably used for analysis of halogens, antimony, rare earth elements, gold, the platinum group elements, uranium, and thorium.

Geochemical exploration

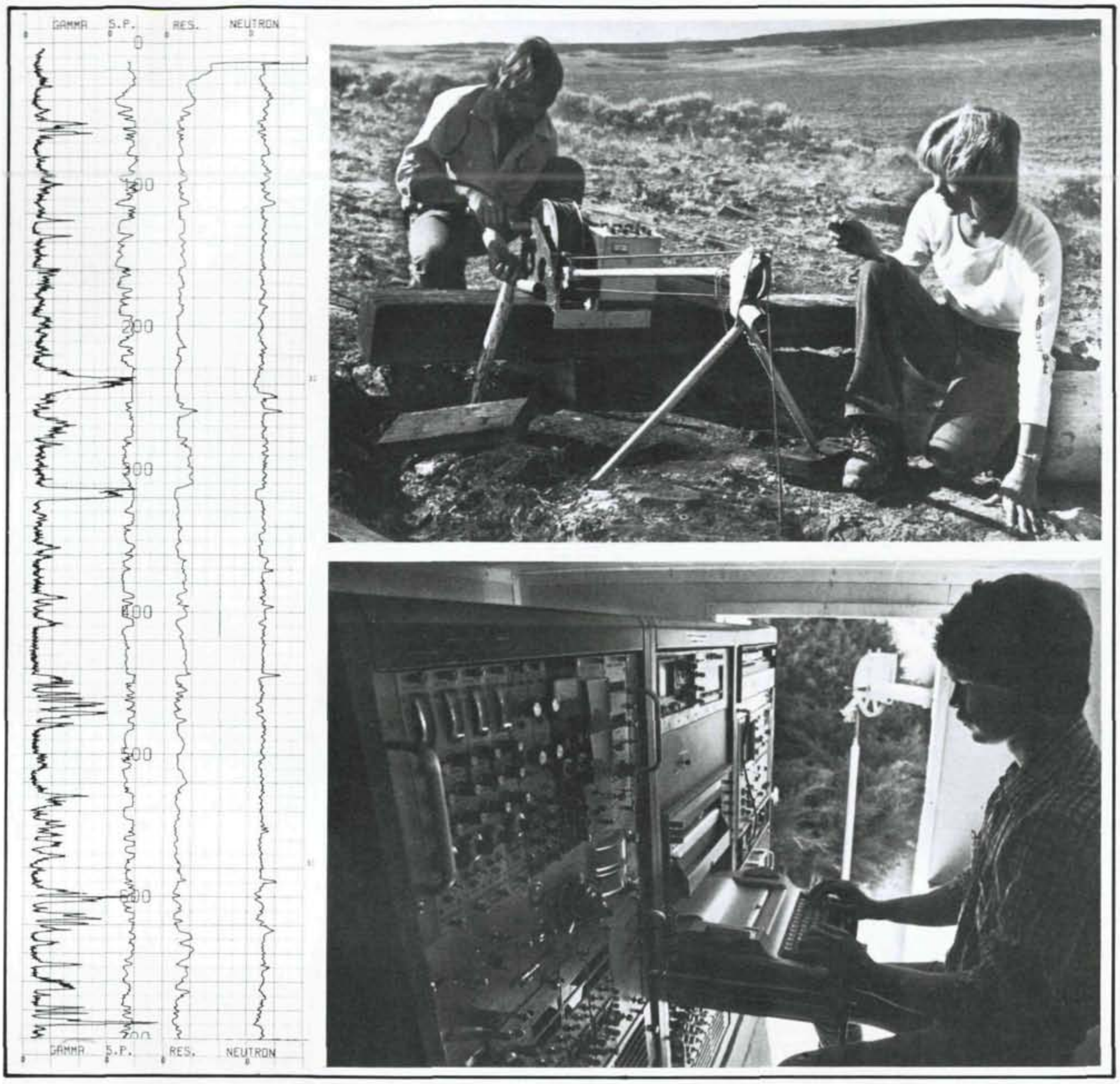
The chemical composition of organic and inorganic sediments, plants, and water may reflect that of the underlying rocks. Some other types of sediments are more or less displaced from their original location and may reflect the chemical composition of rocks located somewhere along the route of transport. Thus, the elemental composition of sediments and water can be used to trace economical mineralization. Typically most elements appear in concentrations of parts-per-million in the sediments; therefore, sensitive analytical methods are needed.

In geochemical composition, NAA is used in several countries, especially for analysing gold, platinum metals, and in some cases uranium. Highly automated procedures are frequently used, which makes the analysis inexpensive. Some countries, including Canada, Finland, the United Kingdom, and the United States, have NAA laboratories analysing 10 or several tens of thousands of geological samples annually.

Geophysical exploration for uranium

The uranium element consists of a mixture of radioactive isotopes that decay, forming a series of daughter nuclides. These are radioactive and can be used to trace

Mr Guizerix is head of the Industrial Applications and Chemistry Section of the Agency's Division of Physical and Chemical Sciences, and Mr Rosenberg is a staff member in the section.



Gamma-gamma and neutron-neutron logs, and the equipment needed for obtaining the results.

uranium mineralizations. One is based on direct measurement of the gamma radioactivity of the daughter nuclides of uranium (in particular bismuth-214). This can be done by simply measuring the total background radiation level above ground, or by measuring the total activity of a rock surface or separate boulders, with a portable gamma survey meter. The measurements also can be done by using gamma ray measurement systems carried in vehicles or aircraft.

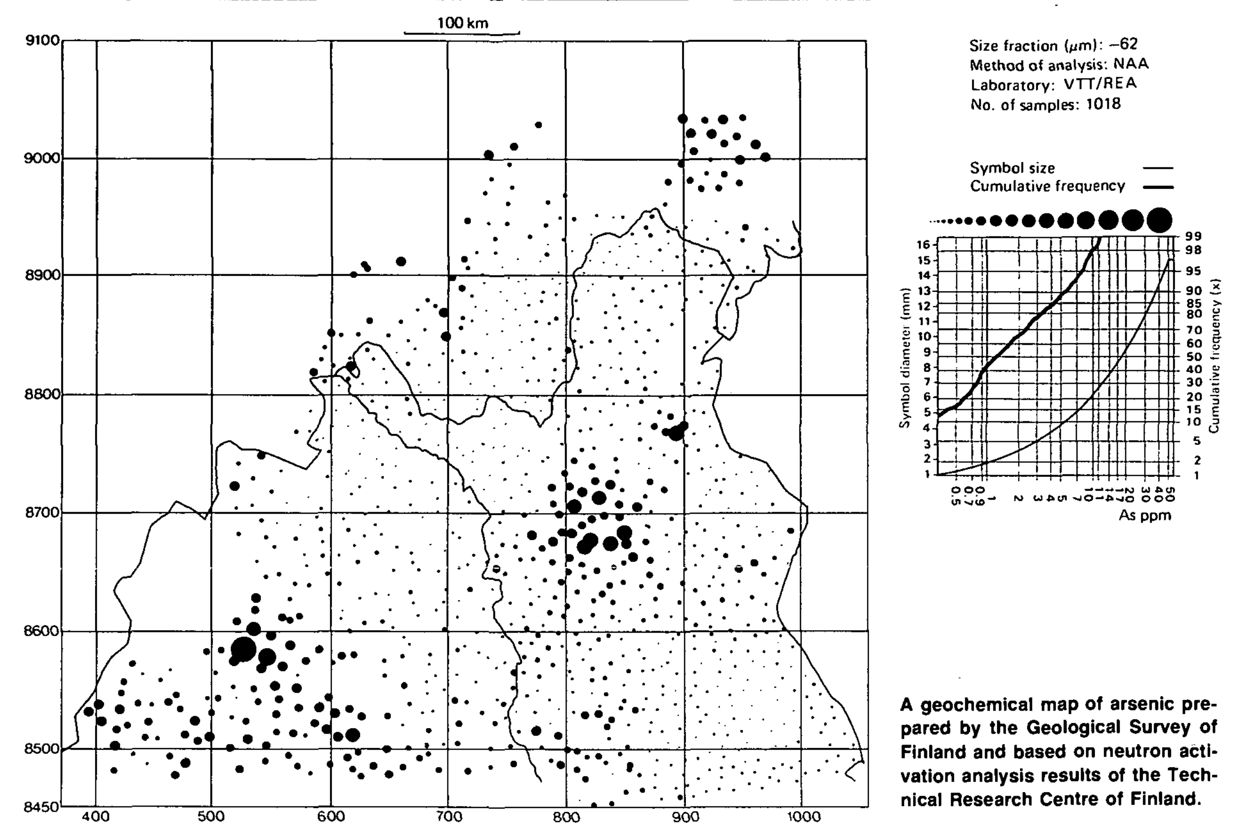
Another method is to measure radon isotopes, which are decay products of uranium. Radon is a very mobile inert gas that moves from the rock through fissures up to the ground. It can be measured through its alpha activity.

Borehole logging

In oil and mineral exploration, drilling is required before it is possible to determine if the ore is worth exploiting. Drilling is always expensive, but especially so when several thousands of holes (1-metre deep) are drilled. Therefore, all possible information from the hole must be gathered.

Core samples could be taken to the laboratory for analysis. However, in most cases it is faster to analyse it on the spot. Several X-ray fluorescence analysers that are energy dispersive (either portable or vehicle-borne) have been developed for this purpose. One very convenient technique is to run a probe through the hole and obtain an analysis of the surrounding rock.

A number of nuclear borehole logging devices are in routine use and some others are in the process of development. The most straightforward technique is to log natural radioactivity (gross or gamma spectrometric). This gives information directly about uranium, thorium, and potassium and, indirectly, about mineral composition. Thus, for instance, information about coal can be obtained. The coal seams have a different concentration of radioactive elements than the surrounding rock.



A geochemical map of arsenic prepared by the Geological Survey of Finland and based on neutron activation analysis results of the Technical Research Centre of Finland.

The other nuclear borehole logging probes are based on the interaction of radiation with the surrounding rock. The probes consist of a radiation source and a detector shielded from the source. The radiation from the source undergoes reactions with the surrounding material. In these reactions the properties of the radiation are changed. The new radiation is measured and conclusions about the composition of the rock can be drawn. The advantage of using nuclear radiation is that it is usually very penetrating. Thus, information can be obtained in water-filled boreholes and a large volume of the rock is simultaneously analysed.

Gamma-gamma probes. These consist of a gamma source and one or several instruments — scintillation detectors — suitable for measurement of gamma radiation. The intensity of the gamma radiation scattered back to the detector from the rock depends on the rock's density. Therefore, the technique is most commonly used in coal and oil exploration. Coal has a much lower density than the surrounding rock and can easily be seen in gamma-gamma logs. The method detects variations in porosity as well, which makes it useful for detecting rock layers bearing oil, gas, or water. High-density metallic ores also can be detected.

Neutron-neutron tools. A number of borehole logging tools based on the interaction of neutron particles with materials are now being used. When fast neutrons interact with matter, the most important reactions are the scattering and capture of neutrons. In processes known as elastic scattering, the initial high velocity of the fast neutrons is gradually slowed down. This process of slowing down is most effective in an environment containing hydrogen. By measuring the thermal neutron flux during irradiation of the rock with fast neutrons, the hydrogen content can be determined. This method also can be used in logging for oil, gas, or water. It is commonly used in oil and gas exploration and several different varieties of neutron-neutron logging tools are in routine use.

Elemental analysis in boreholes can be performed by X-ray fluorescence and a technique called "capture gamma activation analysis". Neither are yet in wide use, but several very promising applications have been identified. The gamma technique would be especially useful in coal exploration. Almost all components of coal can be determined, which means that both the ash content and calorific value can be accurately assessed. The method can also be used to log specific metals, and good results have been obtained for copper and silver.

Mining applications

In the mining process, nuclear techniques are mainly used for recovery of uranium, coal, and oil. In uranium mining, the radioactivity of the rock is used to separate ore and waste rock and to determine the grade of the ore. In coal mining, it is important to know the thickness of the coal layer in tunnels to avoid mining waste rock. One technique successfully used has been absorption of the natural gamma radiation from the rock, but it is not applicable when the host rock has low radioactivity. Gamma backscatter techniques have been tried instead, but results have not yet been very successful.

In oil recovery, radioactive tracers are used to solve different kinds of problems. One example is the investigation of oil recovery through injection of water. When the pressure in an oil reservoir is too low the oil does not come up by its own force. In such cases, it is common to force out the oil by injecting a variety of fluids into the oil field. The efficiency of this process is then studied by injecting a radioactive tracer into one well. Pressure is applied and the transport of the radiotracer to other nearby wells is analysed.

Processing of ores

Several possibilities of using nuclear techniques exist in ore processing and in the recovery and purification of metals, coal, and oil. Nucleonic control systems, elemental analysers, and tracer methods are used in different stages of the processes.

In ore processing, the most commonly used nuclear technique is X-ray fluorescence spectrometry, which enables on-line analysis of elements. Commercial X-ray fluorescence analysers are offered by a few companies in the world, and several installations are in use. Several processing points can be analysed at once. Usually, at least the input material, the final product, and the tailing are analysed. Two different systems are generally considered. In one, the probes are inserted into the containers or pipes of the main process. In the other, one automatic sampling is performed and the samples are carried through pipes to the analyser. Several elements can be determined simultaneously with one probe.

The level of a material in a closed container can be measured with nuclear techniques, namely gamma ray absorption and scattering. The first is more efficient, but when access is limited to only one side of the container, or the diameter of the container is too large, backscattering can be used. Typical applications are automatic control of the filling level in furnaces, storage vessels, and transport devices. Gamma absorption techniques can be used when heat, corrosive materials, or the physical state of the material prevents the use of other methods.

When the diameter of a flow channel, such as a pipe, is constant, gamma ray absorption can be used to measure the density of the material. In mixtures of water and ground ore, the amount of transported ore can be directly measured when the flow rate is known. Special probes can also be inserted into a slurry to determine the density. In controlled circumstances, the density is proportional to the amount of ore, coal, or a specific metal in the slurry.

If the density of the material is known, gamma ray absorption can be used to measure the weight of material. A typical application is of material flow on a conveyor belt.

The water content of coal is commonly determined on line using the neutron technique mentioned earlier, with the principle being the same as in the determination of water and oil in boreholes. In general, NAA, capture-gamma, or delayed-gamma techniques are very useful for process analysis for the same reasons as in borehole logging. Nuclear radiation is very penetrating, allowing analysis of coarse material at large volume. Despite the obvious advantages of neutron activation techniques, they do not have wide use. The probable reason is a reluctance to use radioactive sources in industrial plants.

However, in coal production and utilization plants, neutron activation analysers are preferred because coal

Part of a geochemical and radiometric survey in Colombia. Local geologists benefited from on-the-job training while carrying out the survey under the supervision of an IAEA expert.
(Credit: M. Tauchid/IAEA)

is a very favourable matrix for NAA. Carbon and all important components of the ash can be accurately and rapidly determined.

Tracers in ore processing

Radioactive tracer techniques are widely used for investigation and optimization of mineral processing, for several good reasons. In mineral processing, most operations are performed on a very large scale. Therefore, the performance is not always the same as predicted by pilot scale tests. Relatively small improvements in industrial processes result in considerable savings, and radiotracer methods offer unique possibilities to study their behaviour.

Among many other applications, radiotracer methods are used for studying flow, blending, and crushing of materials. Other uses include the study of physical-chemical reactions, separation of metal and slag, determination of volumes of process materials in reaction vessels, and the wear of reaction vessels. In quality control, radiotracer methods are also used for identifying non-metallic inclusion in metals.

IAEA activities in the field

The Agency has a long tradition in promoting the use of nuclear methods in the field of mineral resources. Several symposia, conferences, panels, advisory groups, and consultants' meetings have been organized, and many technical reports have been issued.

Through its technical co-operation programme the Agency also continues to support the needs of developing countries. Three areas have drawn the most attention: exploration and development of uranium deposits; development of laboratories using nuclear analytical techniques for support of mineral exploration programmes; and the use of tracers in mineral processing. The Agency has supported, for example, the development of reactor neutron activation analysis; 14-megavolt neutron activation analysis; and energy dispersive X-ray fluorescence laboratories and their application in geological research and mineral exploration. Equipment and training through courses, expert missions, and fellowships have been provided.

In Romania, for instance, the IAEA is supporting development of borehole logging tools for oil exploration in very deep holes. Projects on uranium exploration and development are already implemented in several countries.

A rather extensive research programme in the field is under the auspices of the Agency's Division of Physical and Chemical Sciences. In 1986, it completed a co-ordinated research programme (CRP) on nuclear analytical techniques for mineral exploration, mining, and processing. Among ongoing and planned activities, through the division and other Agency units:

- The first research co-ordination meeting of a programme in exploration and exploitation of natural resources will be held in November 1987 in the USA. This CRP, which is into its second year, includes five contracts and five agreements from Australia, Canada, China, Hungary, Japan, Poland, USA, USSR, and Viet Nam.
- An advisory group meeting on nuclear analytical techniques for on-line elemental analysis in industry was scheduled in June 1987 in Finland.
- A consultants' meeting on current trends in nuclear borehole logging techniques for elemental analysis will be held in November 1987 in the USA.
- The IAEA's Nuclear Data Section is conducting a programme on compilation of neutron cross-section data needed in geophysics and nuclear analytical techniques. A series of meetings has been held and additional ones are planned.
- The Division of Nuclear Fuel Cycle has an extensive programme on exploration, mining, and processing of uranium ores. Thirteen meetings are planned in 1987 on uranium exploration techniques, the geology of uranium, mining and ore processing, and uranium resources. Several meetings are directly aimed at producing a guidebook for use by research teams in developing countries.