Nuclear Techniques for Ore Grade Estimation

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ABSTRACT

Nuclear techniques have been widely used to produce information on the chemical composition of rocks and ore on conveyer belts, and in the laboratory. The technology is suitable for use in mining operations, in blastholes and exploration holes, both underground and open-pit, but is not yet widely used. Nuclear techniques for ore grade estimation may be divided into passive and active methods. Passive methods are those based on measurement of natural radioactivity emitted from rocks. Active methods involve the use of a manmade source of radiation.

The main passive method is gamma-ray spectrometry in which measurements detect the natural radioactivity originating from the elements uranium (U), thorium (Th) and potassium (K) in rocks. The spectrometer may be in the form of a hand-held instrument or a borehole probe usually with a sodium iodide scintillation detector. With proper calibration, it is possible to estimate uranium ore grades in the presence of thorium. Determinations of concentrations of Th and U in the ppm range and potassium to a fraction of a percent are possible. The determination of these three elements is important because of their relationship to another element of interest such as gold, which may be difficult to directly measure quantitatively.

In active nuclear techniques, the 'active' source may be a commercially produced radioisotope or an electronic source such as an x-ray tube or neutron generator. The latter sources have the advantage that they can be turned off when not in use, but the disadvantage of being rather bulky. The detected radiation can be either the original source radiation which has been modified by the physical properties of the rock through which it travelled, or a secondary radiation emitted from the rock after excitation by the primary source radiation. Active methods with application to ore grade estimation which are described include: (1) density (gamma-gamma), (2) spectral gamma-gamma (SGG), (3) x-ray fluorescence (XRF) and (4) neutron methods. Most of the active methods are used in a borehole configuration, not a surface or 'face-scanner' mode.

INTRODUCTION

Nuclear techniques have been used to solve earth science problems in the field, not just in the laboratory, for over forty years. However, much of the earlier work was related to oil and gas exploration in which the possible advantages of the use of nuclear techniques were recognized and implemented long before their use in mining was seriously considered. A review by Clayton (1967), although heavily oriented towards oil applications, also covered the application of radiation techniques to mineral boreholes. It was also around this time that the International Atomic Energy Agency (IAEA) in Vienna began to more actively foster the development of nuclear techniques applied to mineral exploration (IAEA, 1971). The status of nuclear instrumentation and methodology was reviewed in a volume on 'Nuclear techniques in geochemistry and geophysics' (IAEA, 1976). A wealth of information on nuclear techniques applied to mining and mineral exploration is available in the IAEA Technical Report Series, Panel Proceedings Series, and TECDOC Series of publications.

As part of a Geological Survey of Canada (GSC) review on borehole geophysics applied to metallic mineral prospecting, Killeen (1975) reviewed nuclear techniques for borehole logging in mineral exploration. Morse (1977) edited a book on 'nuclear methods in mineral exploration and production', in which the contributors covered natural radiation methods, XRF methods and activation methods. The 'Metalogger', based on the latter method, developed by Scintrex in Canada for nickel and copper assaying in boreholes, was described by Nargolwalla *et al.* (1977) in that text. Clayton (1983) edited an extensive (479 pages) review volume in which the 32 papers covered nuclear techniques such as airborne, borehole and sea-bed gamma-ray spectrometry, XRF, neutron activation, and applications ranging from coal to gold to uranium. (This book on 'Nuclear Geophysics' was the precursor to a scientific journal by that name, with Clayton as editor, which was only recently discontinued.) Of particular interest in this volume is the description by Shope *et al.* of the Zetatron neutron tube, an electronic means of producing neutrons. The development of the 'neutron generator', as it is called today, made many of the neutron-based methods more attractive for routine application, and added new possibilities for nuclear measurements. In 1984, the first textbook devoted to the subject of nuclear assaying of mining boreholes was published (Wylie, 1984). Based heavily on the work at the Division of Mineral Physics of the

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Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia, it covered applications to coal, iron, manganese, copper and aluminum, in particular.

All of the nuclear techniques rely heavily on a database of known gamma-ray energies for different elements, known half lives, and nuclear cross-sections, etc. The IAEA fostered the collection and documentation of such data in support of these nuclear applications, and in 1984 published the proceedings of the IAEA consultants' meeting on "Nuclear data for borehole and bulk media assay using nuclear techniques" (IAEA, 1984). In 1986, gamma-ray, x-ray and neutron techniques applied to coal were reviewed in an IAEA report (IAEA, 1986a) and again more recently (IAEA, 1995). (See also IAEA, 1987). New information was published by the IAEA (1988a) relating to on-line elemental analysis, mainly for coal and iron, and Schweitzer and Ellis (1988) reviewed nuclear elemental analysis as applied to oil well logging, but applicable to mining.

On the occasion of this fourth decennial conference in 1997, it is interesting to look back at what was said on the subject at the Exploration '87 conference in Toronto, and published in the proceedings volume (Garland, 1989). Nuclear techniques in general were not reviewed in any single paper, but there were reviews of specific applications or methods, such as the paper on airborne gamma-ray spectrometry by Darnley and Ford (1989), and brief mentions of nuclear assay techniques, such as that by Seigel (1989) in his paper on "New horizons in geophysics". Ten years earlier, at the Exploration '77 conference in Ottawa (proceedings edited by Hood, 1979), a good review of nuclear techniques was presented by Czubek, but their actual usage received only brief coverage, such as in the paper by Glenn and Nelson on the application of borehole logging to base metal exploration. Aspects of quantitative gamma-ray spectrometry were covered in detail by Killeen in that volume. The proceedings of Exploration '67, the first of the decennial conferences, which was edited by Morley (1969), contained papers on gamma-ray methods for assaying for uranium by Dodd *et al.*, neutron activation for precious metals by Senftle *et al.*, and a review of 'radioactive methods' by Foote which primarily covered gamma-ray spectrometry and briefly covered XRF methods. It appears that today, at least for mineral assaying or ore grade estimation, progress with nuclear technique development has been relatively slow compared to the rapid acceptance and progress in advancing nuclear techniques in oil and gas applications.

The text to follow is a brief review of some of the developments in nuclear techniques for ore grade estimation since Exploration '87. All of the passive and active methods will be described to some degree to explain the technology, but since most of the significant advances have been made in only a few of the methods, these will be described in greater detail. Developments primarily related to oil and gas applications, although valuable because of their potential application to mining, will not be covered here. Another area indirectly related to mining ore, that of determining geotechnical parameters by nuclear techniques (e.g., Okko and Tornqvist, 1995), is also beyond the scope of this paper.

PASSIVE NUCLEAR METHODS FOR ORE GRADE ESTIMATION

Passive methods are those based on measurement of natural radioactivity emitted from rocks by virtue of their potassium (K), uranium (U) and Thorium (Th) content. Simple gross count or total count gamma-ray measurements with scintillometers cannot distinguish the source of the natural radioactivity, but are often able to be calibrated to produce quantitative uranium ore measurements when there is no significant interference from thorium or potassium in the rock. Dodd and Eschliman (1972) described this application and the detailed description of the calibration and quantitative ore grade calculations were given in IAEA (1982, 1986b), and by Killeen (1982). Further calibration refinements as part of an IAEA-sponsored international intercalibration project carried out by the GSC were described by Killeen and Elliott (1990). Besides ore grade determinations, gamma-ray logs are also important for detecting alteration zones, and for providing information on rock types. Most of the recent advances in passive methods however, are related to gamma-ray spectrometry.

Gamma-ray spectral measurements

Gamma-ray spectral measurements are able to separately detect variations in the natural radioactivity originating from changes in concentrations of each of the trace elements, U and Th as well as changes in concentration of the major rock forming element K.

A gamma-ray sensor is usually a scintillation detector, most often sodium iodide or cesium iodide, although solid-state detectors have also been used in field applications. For surface measuring applications the detectors are usually of dimensions 76 mm × 76 mm and measurements may take a few seconds to a few minutes, depending on the level of natural radioactivity in the rocks. In gamma-ray spectral logging the detectors are often 25 mm × 76 mm or smaller and logging (continuous measurements) occurs while lowering or raising the probe in the hole at about 3 m/minute. The volume sampled is about 0.3 cubic metres of rock surrounding the detector, at each measurement (i.e., 10–30 cm radius depending on the rock density). Unlike a gamma-ray scintillometer which only counts the gamma rays, a gamma-ray spectrometer also measures the energy of each gamma ray detected. Because K, U and Th produce gamma rays with characteristic energies it is possible to estimate the individual concentrations of the three radioelements. Figure 1 illustrates how a gamma-ray spectral probe can produce K, U and Th logs from the measured gamma-ray energy spectra.

Details of calibration facilities for gamma-ray spectral measurements have been given by Killeen and Conaway (1978), Killeen (1986a), and Schock *et al.* (1991). Application and interpretation were discussed by Killeen (1979). Most of the advances since 1987 relate to refinements of these techniques, much of which is simply a result of the rapidly changing computer and electronics technology. Thus, for example, today calibration data can be recorded, the calibration factors derived, and the field assays computed directly by the spectrometer, and stored in memory for autotransfer to a PC for display in various forms. Perhaps one of the more important trends is the use of the quantitative K, U and Th data to derive quantitative ore estimates of other elements indirectly related to the radioelements. One example is the work at the CSIRO in Australia described by Eisler (1994), in which natural gamma-ray logging was used successfully for determination of the aluminum content of ore because it was associated with kaolinitic material within the ore matrix. Phosphorus deposits may also be assayed indirectly due to their association with uranium, and tin/tungsten deposits similarly are associated with certain radioelement values and/or ratios (Darnley and Ford, 1989; Shives *et al.*, 1995; IAEA, 1988b).

Often in base metal exploration areas, the principal source of the natural gamma radiation is potassium because alteration, characterized by the development of sericite (sericitization) is prevalent in some of the lithologic units. Generally sericitization results in an increase in the

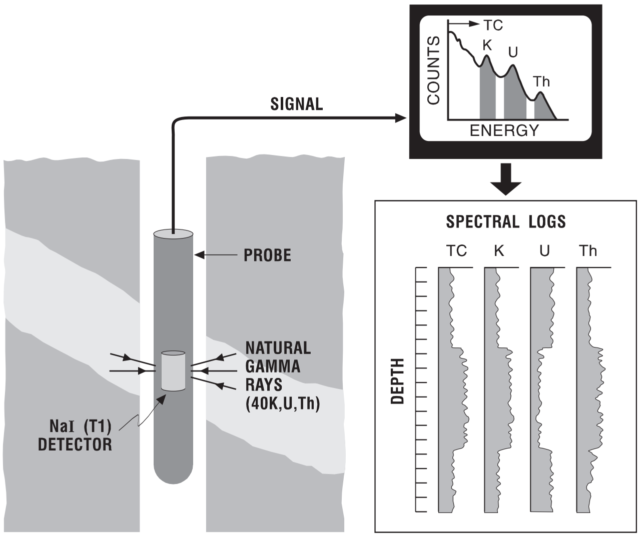

Figure 1: *Total Count, (TC), K , U and Th logs are produced from different energy windows in the gamma-ray energy spectra recorded as the probe moves along the borehole.*

element potassium. This renders sericitized zones excellent targets for gamma-ray detection with potential for ore estimation. Recent work has shown that characteristic potassium alteration, detectable by gamma-ray spectrometry, may be related to gold mineralization (see Shives *et al.*, this volume). The presence of feldspar porphyry sills which contain increased concentrations of K-feldspar minerals would also show higher than normal radioactivity. During metamorphism and hydrothermal alteration processes, uranium and thorium may be preferentially concentrated in certain lithologic units. The gamma-ray spectral measurements can delineate zones of increased radioactivity, and in addition, identify which radioelements are present. In a borehole environment, it may therefore be possible to combine the natural gamma-ray spectral log with other logs to yield quantitative assay data.

ACTIVE NUCLEAR METHODS FOR ORE GRADE ESTIMATION

Active nuclear systems involve the use of a manmade source of radiation. Because of this, they are predominantly used in a borehole logging configuration, in which the source is safely contained in the hole during the measurements. The source may be in the form of a radioactive source produced artificially in a nuclear reactor and sold commercially, or in the form of an electronic source such as an x-ray tube or neutron generator. The latter sources have the advantage that they can be turned off when not in use, but the disadvantage of being bulky for small boreholes. The detected radiation can be of two types: (1) the original source radiation which has been modified by the physical properties of the rock through which it travelled, or (2) a secondary radiation emitted from the rock after excitation by the primary source radiation. The common name or identifier for each method uses the symbol for the source followed by the symbol for the detected radiation (or detector). For example, the neutron-neutron (n, n) method refers to the use of a neutron source and a neutron detector, whereas the neutron-gamma (n, γ) method has a neutron source and a gamma detector.

H 1																	He 2
Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12											Al 13	SI 14	P 15	S 16	CI 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
Cs 55	Ba 56	La 57	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88	Ac 89	Th 90	Pa 91	U 92												

Figure 2: *Periodic table of the elements showing the atomic number Z of each element.*

Gamma-gamma (density)

The gamma-gamma log (or density log) is a measurement of the density of the rock in the borehole wall. The gamma-gamma tool is essentially a natural gamma-ray logging tool with the addition of a weak (say 10 millicurie = 370 MBq) gamma-ray source on the nose of the probe. The tool has a scintillation detector which measures gamma rays from the source that are backscattered by the rock around the borehole. Only a simple gross count of gamma rays is made and no spectrometry is involved; i.e., gamma-ray energies are not measured. In ore tonnage and reserve computations, one of the parameters used is the specific gravity and hence a knowledge of in situ densities of the rocks may provide valuable information for ore reserve estimations.

Two radioactive sources commonly used are Cobalt-60 (1.17 and 1.33 MeV gamma rays), and Cesium-137 (0.66 MeV gamma rays). The source is often collimated and must be shielded from the detector to prevent radiation from reaching the detector directly. With a suitable source and detector the only rock property affecting the detector response is the density of electrons which cause the backscattering. The bulk density of the rock can then be calculated. (A surface or 'face-scanner' version is available, but is designed primarily for flat surfaces such as concrete and is not suitable for the rugged surface of a mine drift for example.) In some cases the density determination can be directly related to the ore grade, such as has been done for coal (IAEA, 1995). For high atomic number elements (say, Z greater than 20; see periodic table, Figure 2), the relation between the number of electrons and the density changes and hence ore grade would be difficult to determine. In a monoelemental ore body, a special relation between measured apparent density and ore could be derived, as in the work in Sweden reported by Wanstedt (1993). In the case of more complex ores such as a Pb/Zn deposit, a combination of natural gamma-ray, density, and magnetic susceptibility logs could be used to characterize the ore (Wanstedt, 1993).

Spectral gamma-gamma (SGG)/density

Unlike a simple gamma-gamma density tool, the SGG/density tool records the energy spectrum of the backscattered gamma rays over an energy range from approximately 0.03 to 1.0 MeV. Density information is determined from the count rate in an energy window from about 0.2 MeV to 0.5 MeV. The presence of minerals containing heavy elements such as base metals tends to increase the overall density of the host rock.

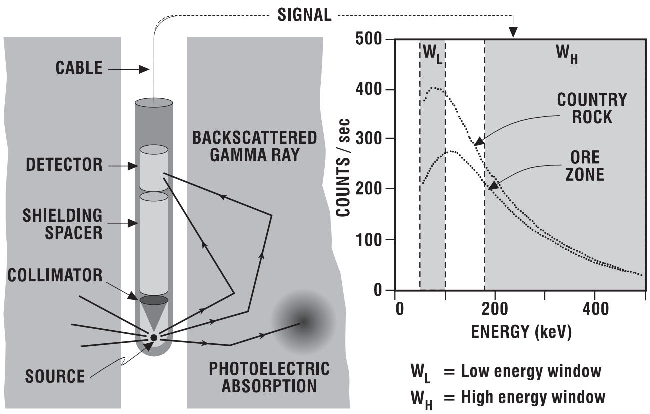

Figure 3: *The spectral gamma-gamma (SGG) method: The SGG ratio is a plot of the ratio of counts in a high energy window divided by the counts in a low energy window. The SGG ratio increases as Z increases.*

Information about the elemental composition of the rock can be obtained from the shape of the backscattered spectrum based on the ratio of the count rates in two energy windows, one at high energy and one at low energy (see Figure 3). This is referred to as the SGG ratio. When there is a change in the density of the rock being measured, the count rates recorded in both windows will increase or decrease due to the associated change in backscattered gamma rays reaching the detector. However, if there is an increase in the content of high Z (atomic number) elements in the rock, the associated increase in photoelectric absorption (which is roughly proportional to Z^5) will cause a significant decrease in count rate in the low energy window with little change in the high energy window. Since the low energy window is affected by both density and Z while the high energy window is mainly affected by density, the SGG ratio can be used to obtain information on changes in Z. This ratio increases when the probe passes through zones containing high Z materials. The SGG ratio log is considered to be a heavy element indicator and can be calibrated to produce assays such as the lead assays at the Yava sandstone lead deposit in Canada described by Killeen and Mwenifumbo (1987, 1988) and Killeen *et al.* (1989), results of which are shown in Figure 4a and Figure 4b.

The research work by the GSC on the SGG method has been described in several papers by Killeen and Schock (1991), Cinq-Mars *et al.* (1992) and Mwenifumbo *et al.* (1993). The possibility of discriminating between economic and non-economic sulphides with the SGG technique was described by Mwenifumbo (1993a) and is illustrated in Figure 5. A novel method to enhance the SGG data by colour contouring the backscattered spectra in an energy spectrum vs. depth plot was also presented by Mwenifumbo (1993b). The work of the CSIRO on the SGG method, particularily with respect to iron ore assaying, was described by Charbucinski *et al.* (1977), Eisler *et al.* (1987), and in the more recent review by Eisler (1994).

The sample volume is smaller than for natural gamma-ray logging since the gamma rays must travel out from the probe, into the rock and back to the detector. A 10 to 15 cm radius around the probe is "seen". Data are typically acquired with a logging speed of 6.0 m/minute with a sample time of 1 second giving a measurement every 10 cm. Commercial versions of the SGG probe have been developed in Canada and Australia.

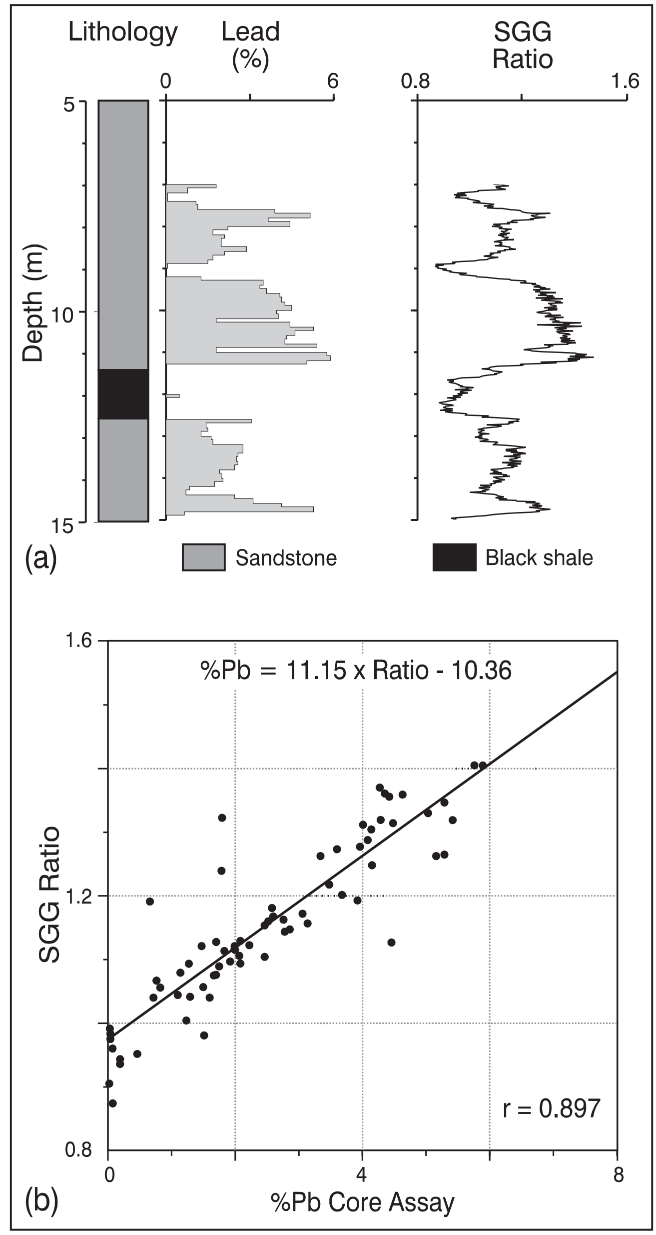

Figure 4a: *SGG ratio log and lead assay log (laboratory assays of 10 cm drill core samples) in the Yava lead deposit, Nova Scotia, Canada.*

Figure 4b: *SGG ratio vs % lead shows a linear relationship suitable for computing ore grades from SGG ratio logs. The correlation coefficient of 0.897 implies a high accuracy is possible for Pb assays based on SGG logs.*

X-ray fluorescence

The x-ray fluorescence method is one of the active techniques which is suitable for use as a surface scanner. Portable XRF instruments for use on outcrops have existed for many years. An XRF drillhole probe was described as early as 1969 (Rhodes *et al.*, 1969). The technique uses an isotopic source of gamma rays to irradiate the borehole wall which in

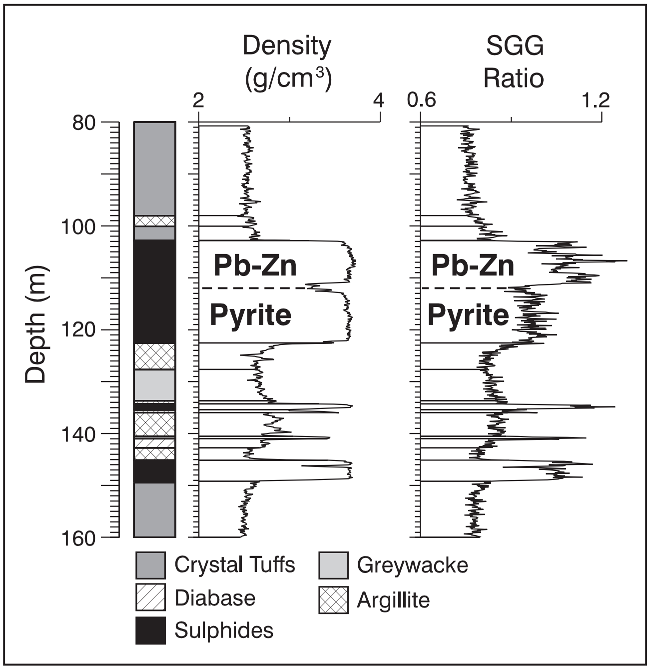

Figure 5: *The density log and SGG ratio log show that the high density of massive sulphides appears about the same in the case of pyrite and Pb/Zn sulphides, but the SGG ratio which is sensitive to atomic number Z, can distinguish between them.*

turn emits x-rays with energies characteristic of the elements in the rock. The technique is still not widely used in exploration and mining borehole logging primarily because of the low energies involved and hence the shallow depth of penetration (virtually a surface analysis only) and because the borehole conditions (surface rugosity) have a large effect on the results. The low energies detected also require a relatively thin window over the detector, which is vulnerable under water-filled borehole conditions. The advantages of the technique are that it is applicable to a wide variety of elements, the sensitivity is high and the technique of XRF is well documented. It has been suggested that its main application may be in development drilling to locate ore-grade cutoff in shallow dry holes (IAEA, 1988b).

Neutron-based techniques

The several types of neutron techniques are measurements of rock properties made by utilizing neutron sources. There are several radioactive neutron sources available. One of these (Californium-252) emits neutrons by spontaneous fission. The other sources utilize an (α, n) reaction to produce neutrons in which an alpha-particle source such as Radium bombards the element Beryllium which then emits neutrons (e.g., Radium-Beryllium and Americium-Beryllium neutron sources). Neutrons may be generated electronically with a 'neutron tube' or neutron generator. There are few suppliers of these neutron guns and their costs vary according to their estimated lifetime and how much of the associated electronics are supplied as part of them, such as high voltage power supplies, etc. These tubes are essentially accelerators which accelerate particles via the high voltage. When the accelerated particles strike a target in the neutron tube, neutrons are emitted. It is the life of the target that determines the operating life of the tube. This may be from 100 to 1000 hrs or more, and the tube is then sent back to the supplier for a refurbishing. Thus a replacement tube must be kept on hand to avoid any significant downtime. Neutron techniques are most often used in a borehole environment, and the simplest is called the neutron log.

Neutrons, when first emitted may be considered to be 'fast' neutrons. They interact with the rock and lose energy, becoming 'epithermal' neutrons, and at even lower energy are called 'thermal' neutrons. The neutrons may also produce gamma-rays during these interactions, either delayed (activation gammas); prompt, due to capture of the neutron; or prompt, but due to inelastic scattering (to be discussed below). The gamma rays may be simply counted, or their energies may be measured with a gamma-ray spectrometer to derive additional information about the atom with which the neutron interacted (via their characteristic energies). A neutron log usually refers to counting either neutrons or gamma-rays without any spectrometry involved (i.e., no energy measurements are made). The basic principle of the neutron log is that the neutrons emitted by the source are slowed down and scattered by collisions with atomic nuclei. The maximum energy loss in a collision occurs when the target nucleus has a mass similar to the neutron. Thus the hydrogen atom has the greatest effect in slowing down the neutrons to thermal energies after which they are soon captured. The neutron log has been often referred to as the hydrogen log. Upon capture of a neutron the excited target nucleus emits a gamma ray called a 'prompt' gamma or a 'capture' gamma-ray. There are three common measurements that can be made: a) the fast neutrons using a short source-detector spacing (n, n epithermal); b) the slow neutrons using a long source-detector spacing (n, n thermal); and c) the capture gamma rays (n, γ or prompt γ), all of which are related to porosity. Figure 6 summarizes most of the interactions a), b), and c), which are the basis of the neutron methods, including those mentioned below.

The detector response in all three cases is related to the hydrogen content of the rock, usually in the form of water in pores, and is therefore a measure of porosity. The source-detector spacings vary between 30 and 60 cm and logging probe diameters of under 50 mm are available. An ordinary gamma-ray log is usually run in conjunction with the (n-γ) log, to enable the natural gamma radiation background to be subtracted from the neutron-induced gamma radiation.

A variation on the (n-γ) log is possible if a spectrometer is included such that the energy of the prompt gamma rays is measured. This has been done to produce a "chlorine log" wherein characteristic gamma rays of chlorine are measured. In principle this technique can be extended to determine the elemental composition of ores, although the difficulties involved are considerable. The application of this method to Ni in laterites and porphyry Cu was studied by several groups including Scintrex Ltd. (Nargolwalla, 1973), and the U.S. Geological Survey (Senftle *et al.*, 1971). The neutron gamma-ray spectral method is a promising field for further investigation since there are several advantages to the measurement of prompt gamma rays (prompt gamma neutron activation analysis; PGNAA). Many of the gamma-ray energies are high (above 3 MeV) and therefore the effective radius of penetration or sampling volume is large and borehole effects are minimal. The natural radiation background is also negligible since it is of lower energy. It is also possible to measure the energies of a second type of gamma ray, namely activation gamma rays, emitted by the decaying unstable isotope produced by the capture of the neutrons (delayed gamma neutron acti-

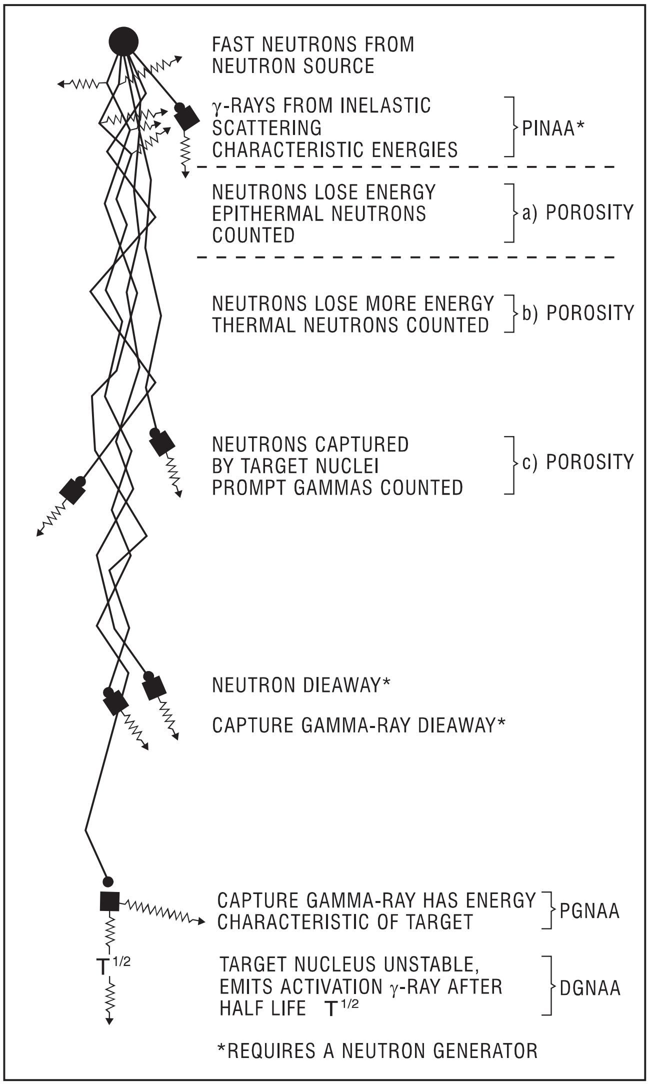

Figure 6: *Summary of possible neutron interactions with rock in the neutron-based techniques. Porosity-related methods based on simple counting; a), b) and c), and three spectrometric methods; PGNAA, DGNAA and PINAA are shown.*

vation analysis; DGNAA). These gamma rays are emitted after a short time which is the half-life of the particular isotope involved, and they have energies characteristic of the emitting element. The disadvantage is that the energy is usually less than 3 MeV, so the natural background radiation may produce interference, and the effective radius of penetration is smaller than for most prompt gamma rays. The measurement of these activation gamma rays, however, has been very highly developed in the laboratory environment, and a great deal of literature is available on the various energies and half-lives of the different activated elements. Eisler (1994) reported successful results using a prompt gamma neutron system and a neutron activation system for iron, manganese and nickel ores in Australia.

A third type of gamma ray besides the prompt and activation gamma rays exists. These are gamma rays produced during the slowing down of the neutrons by inelastic scattering (n, nγ) (prompt inelastic neutron activation analysis; PINAA). During inelastic scattering the nucleus of the atom involved in the collision becomes excited and a gamma ray with a characteristic energy is emitted. The nuclear data presently available on the various energies is rather limited. These gamma rays are emitted early in the life of the neutron, which leads to the requirement of timed measurements. This is only possible with a pulsed-neutron source which can be shut off intermittently.

The introduction of the pulsed-neutron generator, an electronic device, made it possible to make any of the above measurements at specific times after the pulse or burst of neutrons is over. Thus the gamma rays from inelastic scattering (n, nγ) could be measured during the first 50 microseconds, then several neutron counting measurements could be made to determine the shape of the decay curve of the neutrons (i.e., the die-away curve), and similarly for the capture gamma rays which would die away with a half-life dependent on the hydrogen content of the rock, and finally the half-life of the activation gamma rays could be determined by making several successive measurements of gamma ray counts at specific energies. An analogy in base metal exploration geophysics is the Time-Domain E.M. system measurements of a decay curve after the primary electromagnetic field is turned off.

The effects of borehole fluids and casing can be eliminated by these timed measurements since the half-life of the neutrons in the borehole and casing is different from the surrounding rock. If measurements are taken 500 µs after the pulse, the results are entirely dependent on the rock properties as interactions in the borehole are over by that time. The many variants of times and types of measurements have been called Neutron Lifetime Log (NLL) and Thermal-neutron Decay Time Log (TDT).

The possibilities for application of pulsed-neutron logging to borehole mineral exploration are considerable. Cyclic activation has also been made possible with the development of pulsed-neutron generators. In this case the activity of a very short-lived activation product can be measured at the appropriate time after each of several neutron pulses, yielding a much higher count rate than if only one measurement were made. This is possible because the pulse rate is high and many measurements are made over a short distance in the hole since the probe velocity is relatively slow. This makes it possible to do continuous activation borehole logging by measuring very short-lived activities. Small-diameter neutron-lifetime tools have been developed for use in 43 mm tubing.

CONCLUSIONS

No single nuclear technique can solve all ore estimation problems. However, some methods are more preferable for certain ore environments, especially non-complex ores. For a method to be practical and acceptable for routine use it must be of reasonable cost, rugged, easy and safe to use in a mine environment, and be able to provide results in a reasonable time.

The best solution may be to have a probe that measures physical properties and uses nuclear techniques. For example, a probe could measure conductivity to delineate the conductive sulphides, magnetic susceptibility to delineate the magnetic sulphides (e.g., pyrrhotite), and the SGG ratio to delineate the total sulphides including those that are non-conductive and non-magnetic such as sphalerite. For any given mine, an algorithm could be developed to combine these data to provide the required ore estimations in real time at the measurement site.

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REFERENCES

Charbucinski, J., Eisler, P.L., Mathew, P.J., and Wylie, A.W., 1977, Use of backscattered gamma radiation for determining grade of iron ores in blast holes and development drill holes; Proc. Australian Inst. Min. Metall., no 262, p. 29-37.

Cinq-Mars, A., Mwenifumbo, C.J., Killeen, P.G., and Chouteau, M., 1992, Multiparameter geophysical logging at the Yava lead deposit: A statistical approach; *in* Geophysical Prospecting, Vol. 40, p. 829-848.

Clayton, C.G., 1967, A survey of the application of radiation techniques in oil and mineral boreholes; United Kingdom Atomic Energy Authority Report A.E.R.E.R 5368, 59p. plus 23 figures.

Clayton, C.G., 1983, Nuclear Geophysics; Clayton, C.G., ed., Pergamon Press, Oxford., 479p.

Darnley, A.G., and Ford K.L., 1989, Regional airborne gamma-ray surveys: a review, *in* Proceedings of Exploration '87; conference on Geophysical and Geochemical Exploration for Minerals and Groundwater, Garland, G.D., ed., Ontario Geological Survey Special Volume 3, p. 229-240.

Dodd, P.H., and Eschliman, D.H., 1972, Borehole logging techniques for uranium exploration and evaluation; *in* Uranium Prospecting Handbook, Bowie, S.H.U., Davis, M., and Ostle, D., eds., Inst. Min. Metall., London, p. 244-276.

Eisler, P.L., 1994, A new borehole logging technology for enhancing performance in metalliferous mining; *in* Proceedings of the Symposium on the Application of Borehole Logging to Mineral Exploration and Mining, 20 February, 1994, Perth, W.A., 26 pp.

Eisler, P.L., Charbucinski, J., Borsaru, M., and A.P. Indrans, 1987, Spectral Gamma-gamma logs in iron ore mining; *in* Proceedings of the 2nd Int'l. Symposium on Borehole Geophysics for Minerals, Geotechnical and Groundwater Applications, 6-8 Oct. 1987, Golden, Colorado, p. 189-201.

Garland, G.D., 1989, Proceedings of Exploration '87; conference on Geophysical and Geochemical Exploration for Minerals and Groundwater, Garland, G.D., ed., Ontario Geological Survey Special Volume 3, 960pp.

Hood, P.J., 1979, Geophysics and Geochemistry in the Search for Metallic Ores; Hood, P.J., ed., Geol. Surv. Can., Economic Geology Report 31; 811 p.

IAEA 1971, Nuclear techniques for mineral exploration and exploitation; proceedings of a panel, Cracow, 8-12 Dec. 1969, 169pp.

IAEA 1976, Nuclear techniques in geochemistry and geophysics; proceedings of a panel, Vienna, 25-29 Nov 1974, 271pp.

IAEA, 1982, Borehole logging for uranium exploration—a manual; IAEA Technical Report Series No. 212, 279 p.

IAEA, 1984, Proceedings of the IAEA consultants' meeting on Nuclear Data for Borehole and Bulk-Media Assay using Nuclear Techniques; IAEA—Vienna, INDC (NDS)—151/L, 348 p.

IAEA, 1986a, Proceedings of an Advisory Group Meeting on Gamma, X-Ray and Neutron Techniques for the Coal Industry; International Atomic Energy Agency, Vienna, 4-7 December 1984, IAEA Panel Proceedings Series STI/PUB/707, 216 p.

IAEA, 1986b, Practical borehole logging procedures for mineral exploration, with emphasis on uranium; IAEA Technical Report Series No. 259, 44p.

IAEA, 1987, Nuclear analytical techniques for mineral exploration, Mining and Processing Plants; IAEA, Vienna—IAEA/RL/139, 225 p.

IAEA, 1988a, Nuclear analytical techniques for on-line elemental analysis in industry; IAEA—TECDOC-459, 80 p.

IAEA, 1988b, Current Trends in Nuclear Borehole Logging Techniques for Elemental Analysis; IAEA-TECDOC-464, p. 23-31.

IAEA 1995, Nuclear techniques in the coal industry; proceedings of a final research coordination meeting, Krakow, Poland, 9-12 May, 1994, IAEA TECDOC-845, 145pp.

Killeen, P.G., 1975, Nuclear techniques for borehole logging in mineral exploration; *in* Borehole Geophysics Applied to Metallic Mineral Prospecting: A Review; by Dyck, A.V., Hood, P.J., Hunter, J.A.M., Killeen, P.G., Overton, A., Jessop, A., and Judge, A. Geol. Surv. Can., Paper 75-31, p. 39-52.

Killeen, P.G., 1979, Gamma ray spectrometric methods in uranium exploration—application and interpretation; *in* Geophysics and Geochemistry in the Search for Metallic Ores; Hood, P.J., ed., Geol. Surv. Can., Economic Geology Report 31, p. 163-229.

Killeen, P.G., 1982, Gamma-ray logging and interpretation; Chapter 4 *in* "Developments in Geophysical Exploration Methods", Vol. 3, Applied Science Publishers Ltd. (Elsevier), p. 95-150.

Killeen, P.G., 1986a, A system of deep test holes and calibration facilities for developing and testing new borehole geophysical techniques; *in* Borehole Geophysics for Mining and Geotechnical Applications, Killeen, P.G., ed., Geol. Surv. Can., Paper 85-27, 1986, p. 29-46.

Killeen, P.G., 1986, Borehole Geophysics for Mining and Geotechnical Applications, Killeen, P.G., ed., Geol. Surv. Can., Paper 85-27, 400 p.

Killeen, P.G., and Conaway, J.G., 1978, New facilities for calibrating gamma-ray spectrometric logging and surface exploration equipment; CIM Bull., Vol. 71, No. 793, p. 84-87.

Killeen, P.G., and Elliott, B.E., 1990, Model boreholes for gamma ray logging: Intercalibration of North American and European Calibration Facilities; *in* Transactions of the 13th SPWLA European Formation Evaluation Symposium, Budapest, Oct. 22-26, 1990, paper GG, 14 pages.

Killeen, P.G., and Mwenifumbo, C.J., 1987, Interpretation of new generation geophysical logs in Canadian mineral exploration; *in* 2nd Int'l. Symposium on Borehole Geophysics for Minerals, Geotechnical and Groundwater Applications, Oct. 6-8, 1987, Golden, Colorado, p. 167-178.

Killeen, P.G., and Mwenifumbo, C.J., 1988, Downhole assaying in Canadian mineral deposits with the spectral gamma-gamma method; *in* Current Trends in Nuclear Borehole Logging Techniques for Elemental Analysis. International Atomic Energy Agency Technical Document IAEA-TECDOC-464, p. 23-31.

Killeen, P.G., and Schock, L.D., 1991, Borehole assaying with the spectral gamma-gamma method: some parameters affecting the SGG ratio: Oral presentation and Proceedings; *in* 4th Int'l. Symposium on Borehole Geophysics for Mineral and Geotechnical Logging, August 18-22, Toronto, Ontario.

Killeen, P.G., Schock, L.D., and Elliott, B.E., 1989, A slim hole assaying technique for base metals and heavy elements based on spectral gamma-gamma logging; *in* Proceedings of the 3rd Int'l. Symposium on Borehole Geophysics for Minerals and Geotechnical Logging, 2-5 Oct., 1989, Las Vegas, Nevada, p. 435-454.

Morley, L.W., 1969, Mining and Groundwater Geophysics/1967, Morley, L.W., ed., Geol. Surv. Can. Economic Geology Report 26, 722pp.

Morse, J.G., 1977, Nuclear Methods in Mineral Exploration and Production, Morse, J.G., Elsevier Pub. Co, 280pp.

Mwenifumbo, C.J., 1993a, On the possibility of discriminating between economic and non-economic sulphides by the spectral gamma-gamma method; *in* Proceedings of the 5th Int'l. Symposium on Minerals and Geotechnical Logging , Tulsa, 24-28 October 1993, paper J, p. 1-14.

Mwenifumbo, C.J., 1993b, Colour contour plot of the Kernel Density estimate. The Log Analyst, (On the Cover); September-October, 1993.

Mwenifumbo, C.J., Killeen, P.G., and Elliott, B.E., 1993, Classic examples from the Geological Survey of Canada data files illustrating the utility of borehole geophysics; *in* Proceedings of the 5th Int'l. Symposium on Borehole Geophysics for Minerals and Geotechnical Logging, Tulsa, 24-28 October 1993, paper K, p. 1-15.

Nargolwalla, S.S., 1973, Nuclear technique for borehole logging of geologic materials; Scintrex Ltd. Applic. Brief 73-1, 222 Snidercroft Rd., Concord, Ontario.

Nargolwalla, S.S., Nguyen, N.D. and Rehman, A.U., 1977, Radioactivation methods; *in* Nuclear Methods in Mineral Exploration and Production; Morse, J.G., ed., Elsevier, p. 113-200.

Okko, O., and Tornqvist, J., 1995, Derivation of conventional geotechnical parameters from nuclear borehole logging; *in* Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems; 23-26 April, 1995, Orlando, Florida, p. 829-833.

Rhodes, J.R., Furuta, T., and Berry, P.F., 1969, A radioisotope X-ray fluorescence drill hole probe; *in* Nuclear Techniques and Mineral Resources, IAEA, Vienna, 353-364.

Schock, L.D., Killeen, P.G., Elliott, B.E., and Bernius, G.R., 1991, A review of Canadian calibration facilities for borehole geophysical measurements: Poster and Proceedings; *in* 4th Int'l. Symposium on Borehole Geophysics for Mineral and Geotechnical Logging, August 18-22, Toronto, Ontario.

Schweitzer, J.S., and Ellis, D.V., 1988, Review of nuclear techniques in subsurface geology; IEEE Transactions on Nuclear Science, v. 35, no. 1, p. 800-805.

Senftle, F.E., Evans, A.G., Duffey, D., and Wiggins, P.F., 1971, Construction materials for neutron capture gamma-ray measurement assembly using ^{252}Cf; Nuclear Tech., **10**, 204-210.

Shives, R.B.K., Ford, K.L., and Charbonneau, B.W., 1995, Applications of gamma-ray spectrometry, magnetic/VLF-EM surveys "Workshop Manual"; Geological Survey of Canada, Open File 3061, 82p.

Wanstedt, S., 1993, An overview of recent research on geophysical logging in underground mines in Sweden; *in* Proceedings of the 5th Int'l. Symposium on Borehole Geophysics for Minerals and Geotechnical Logging, Tulsa, 24-28 October 1993, paper D, p. 1-7.

Wylie, A.W., 1984, Nuclear Assaying of Mining Boreholes; Elsevier, Amsterdam, 344pp.