

# **NUCLEAR BOREHOLE LOGGING TECHNIQUES DEVELOPED BY CSIRO EXPLORATION AND MINING FOR THE METALLIFEROUS MINING INDUSTRY**

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## **ABSTRACT**

Commonwealth Scientific and Industrial Research Organisation (CSIRO), Exploration and Mining, has developed nuclear spectrometric techniques for borehole logging. The paper reviews the latest developments of this technology for the metalliferous mining industries. The SIROLOG logging system developed by CSIRO Exploration and Mining has been commercialised and is available to the mining industry.

## **INTRODUCTION**

Geophysical techniques are well established in the resource industries like oil, gas, uranium, coal and minerals. Nuclear borehole logging, which represents a subset of this group, has been widely used in the oil, gas, uranium and coal industries for a long time. Nuclear borehole logging tools encompass 3 types: neutron source and gamma-ray detector, gamma-ray source and gamma-ray detector and finally, gamma-ray detector with no source. Due to the deep penetration of neutrons and gamma rays, nuclear techniques are suitable for borehole logging applications and they are making inroads in the metalliferous mining industry.

Many holes drilled in the coal and metalliferous mining industries are cored and a chemical analysis performed. This analysis typically is the only source of information from a borehole. However, this does not make nuclear borehole logging redundant. The benefits that can be derived from nuclear logging are:

- i. It samples a much larger volume of the material surrounding the borehole than the core sample and therefore provides better sampling statistics especially in heterogeneous deposits.
- ii. The results are instantaneous.

iii. The cost of drilling open holes is cheaper than the cost of cored holes.

Considering that the full information provided by the laboratory analysis is not always needed and that in some mineral deposits the core cannot be fully recovered, nuclear logging and laboratory analysis of the core are complementary.

CSIRO Exploration and Mining has developed the spectrometric nuclear logging system, SIROLOG, based on natural-gamma, gamma-gamma and neutron-gamma techniques. In this system the whole gamma ray spectrum is recorded for each preset logging interval. By recording and analysing the whole gamma-ray energy spectrum from a spectrometric measurement one can extract more information from the logging data. A dedicated software package for spectrometric data analysis and interpretation has also been developed. The data interpretation and the source/detector configuration are usually specific to the type of application, that is, tuned for each specific application.

## **INSTRUMENTATION**

Gain stabilisation is an essential part of a spectrometric system. SIROLOG has been upgraded to a fully digital system. Pulses produced by the gamma-ray detector are processed by a microprocessor incorporated in the probe and transmitted to the uphole computer. The digital transmission of the signal is noise proof and is not susceptible to attenuation in the cable. The whole system consists of the probe, winch and a laptop computer. When low activity sources are used and a source transporter is not required, the system is portable and does not require a dedicated logging vehicle. This makes SIROLOG suitable for logging in areas where the only access is by helicopter.

The standard logging probe has a diameter of 60 mm and can accommodate a scintillation detector of 37 mm diameter. The length of the probe is about 2 m. When logging large diameter boreholes it is advantageous to use larger volume detectors, which are more efficient for gamma ray detection. Larger diameter probes are constructed for these applications. Scintillation detectors are used in the SIROLOG system. The most common type used in the gamma-gamma tool is NaI(Tl), while BGO (bismuth germanate) is the preferred scintillator for natural-gamma and neutron-gamma logging.

## APPLICATIONS

### Iron Ore Mining Industry

The three nuclear borehole logging techniques, prompt gamma neutron activation, gamma-gamma and natural gamma have found applications in the iron ore mining industry

One of the features of nuclear logging is that it samples a much larger volume than coring and subsequent chemical analysis. The following example shows the weight of ore sampled by the conventional sampling and nuclear logging for a typical production bench. The bench consists of a 10 m regular grid of holes to a depth of 20 m intersecting ore of density  $2.8 \text{ t/m}^3$ . Consequently, each hole represents an ore-block weighing 5600 t. In conventional sampling, a sample of around 4 kg taken manually from the cone of drill cuttings represents the 5600 t ore-block, giving a sample to ore-block ratio of approx. 1:1 400 000. Both gamma-gamma and prompt gamma neutron activation techniques have been used successfully for borehole logging in the iron ore mining industry. The sampling radius of gamma-gamma and neutron-gamma are 150 mm and 300 mm respectively. For a 300 mm diameter blast hole, the masses of ore sampled by the gamma-gamma and neutron-gamma tools are approximately 12 and 32 t respectively. Consequently, the sample to ore-block ratios for these two techniques are about 1:467 and 1:175 which is much more favourable than for the conventional method.

Prompt gamma neutron activation logging has been used successfully for the determination of iron grade and silica content in iron ore (Eisler et al., 1977; Charbucinski, 1991; Charbucinski, 1993). Neutron-gamma is a 'specific' method; its response is characteristic to elemental composition of the ore. The neutron-gamma reactions produced by thermal neutrons produce gamma-rays specific to the chemical elements found in the ore. Both iron and silicon have relatively large neutron-capture cross-sections and produce easily identifiable gamma-rays used to determine their concentration in the ore. Figure 1 shows a neutron gamma spectrum recorded by the prompt gamma neutron activation probe with a BGO detector in an iron ore deposit. The iron and silica peaks are evident in the spectrum. The accuracy for the determination of iron in 280 mm blastholes was 0.54% Fe and for the determination of average silica content was 0.65% Si per blasthole.

The spectrometric gamma-gamma technique enabled the simultaneous measurement of iron grade, density and borehole diameter on a stratigraphic basis in wide (310 and 380 mm) dry blast holes in iron ore deposits (Eisler et al., 1987). The primary gamma-ray source used was  $^{60}\text{Co}$ . The accuracy for iron determination in 1.5 m split intervals was 1.6% Fe in ore bearing at least 55% Fe. For ore of

wider range in grade, the accuracy was 1.9% Fe, where ore grades ranged from 35 to 69% Fe, whilst the accuracy was 3% Fe where the minimum grade was 9% Fe. Total blast hole grade, over an average length of 15 m, was determined with the accuracy ranging from 0.9 to 1.3% Fe, depending on the quality and location of the ore. The accuracy for density measurements was 0.18 and 0.30 t/m<sup>3</sup> in blast holes of 380 and 310 mm diameter respectively. The accuracies for the hole diameter determinations were 10 and 5 mm for hole diameter ranging from 310 to 410 mm and from 390 to 500 mm respectively.

Natural-gamma is used for delineating the iron ore body based on the big difference in natural gamma radiation between the iron ore (low in natural gamma radiation) and the shaly rock. It can also provide a means for determining alumina contamination of iron ore based on the correlation between alumina and the kaolinitic material of the ore matrix (Charbucinski et al., 1991)

### **Manganese**

Both prompt neutron gamma activation and neutron activation techniques have been used for the determination of the manganese content of manganese ore (Aylmer et al., 1984). <sup>252</sup>Cf neutron sources were used for both techniques. The field trials were carried out in dry, shallow (15 m deep) boreholes of 150 mm diameter. In spite of the difficulties in sampling for calibration, both of the quantitative techniques performed accurately given the wide range of ore grades and ore types encountered in the deposits where the field trials took place. The root-mean-square (r.m.s.) deviation between manganese grade based on regression analysis of logging data and laboratory assays was approximately 3.4% Mn for ores ranging in grade from 10% to 50% Mn for both techniques. However, the prompt gamma neutron activation was less dependent than the neutron activation on chemical differences between the mineralised ores at the different deposits.

### **Nickel Logging**

Preliminary investigation on nickel logging by CSIRO showed that spectrometric logging could be beneficial to the nickel mining industry. Prompt gamma neutron activation was found to be the only quantitative technique to this application. On the other hand, although it was not possible to interpret the spectrometric gamma-gamma probe quantitatively, because the iron probe response is similar to the nickel response, the logs obtained using this probe delineated the mineralised zones intersected by the boreholes.

## **RECENT DEVELOPMENTS USING ULTRA-LOW RADIATION INTENSITY GAMMA-RAY SOURCES**

Although nuclear techniques are widely used in the mining industry, some mines are still reluctant to use them due to the extra care required when working with radioactive sources. Work has been carried out over the last years to develop environmentally friendly techniques for in-situ analysis using ultra-low radiation intensity gamma-ray sources. Equipment for in-situ analysis using low activity sources significantly simplifies safety procedures and reduces to a minimum the source radiation risk. Logging systems using very low activity sources are much more likely to be accepted by the mining industry.

Two source/detector configurations have been developed (Charbucinski et al., 1997). One configuration, used in the LOW ACTIVITY TOOL, comprises a 1.8 MBq  $^{137}\text{Cs}$  gamma-ray source placed along the axial centreline of the detector. The other configuration, used in the ZERO PROBE, comprises three 0.36 MBq  $^{137}\text{Cs}$  gamma-ray sources placed circumferentially around a cylindrical iron/lead shield.

### **Iron ore**

The Low Activity Tool was tested in an iron ore deposit (Borsaru et al., 1995). The probe proved suitable for delineation of the ore body and also for predicting its grade. The iron ore region can be delineated from the count rates recorded in different energy windows of the backscattered spectrum, or the ratio of counts recorded in two windows selected in the high and low energy regions of the spectrum ( $P_z$  ratio). The low energy region of the spectrum is sensitive to the average atomic number  $Z_{eq}$  of the matrix and it can therefore be used to delineate the iron ore (high  $Z_{eq}$ ) from the host rock (low  $Z_{eq}$ ). Figure 2 shows the delineation of a shale band, approx. 1 m thick, intersected by the borehole in an iron ore deposit.

### **Pb-Zn ores**

Both single source and three source configurations were tested for orebody delineation and grade control of Pb-Zn ore (Charbucinski et al., 1997; Almasoumi et al., 1998).

Lead grade is determined from the 80 keV K X-ray peak excited by the multiscattered gamma-rays. The probes were field tested in two cored holes in a Zn ore deposit, reamed later to a diameter of 142 mm. The holes were water-filled. Figure 3 shows spectra collected in a borehole over the intervals

93.95 – 95.45 and 106 – 107.2 m, with corresponding Pb assays of 6% and 0.04% Pb respectively. A strong Pb peak is visible at 80 keV energy for the interval containing high lead. The lead peak is absent in the other spectrum. The r.m.s. deviation given by the regression equation was 0.3% Pb for both probes and the standard deviation of the population was 1.7% Pb.

The gamma-gamma probe is not able to measure the concentration of zinc directly. The probe's response is related to the overall contributions given by the major components with high atomic number which are present in the Pb-Zn ore, eg Pb, Zn, Fe and Mn. Because Pb concentration can be measured directly, the determination of Zn is possible if the Fe and Mn concentrations in the ore are constant, or can be estimated in a different way. The concentrations of Fe and Mn were estimated in this work from statistical information obtained from a geological database. The r.m.s. deviation for the determination of %Zn was 2.4% Zn and the correlation coefficient was 0.85. The standard deviation of the population of 72 samples used was 4.55% Zn.

## CONCLUSIONS

Nuclear techniques are more widely used in the oil industry than in the mineral industry. One explanation to this fact is that nuclear logging provide vital information for the oil industry which can not be obtained by any other means. In the mineral mining industry, core recovery and subsequent chemical analysis can provide all the information required, although at a higher cost. Also, the cost of logging in the oil industry constitutes only a small fraction of the cost of drilling deep wells. This is not the case when drilling much shallower, cheaper holes common in the mineral industry. As a percentage of the cost of drilling, logging costs are much higher for the mineral industry.

There are important benefits from using nuclear logging: a. it samples a much larger volume of rock than the core samples, b. it provides results in real time and c. it saves money by providing information from open holes, which are cheaper to drill than the cored holes.

The spectrometric SIROLOG system for in-situ analysis developed by CSIRO has proved itself in the Australian mining industry. The new fully digitised, portable systems using ultra-low radiation intensity gamma-ray sources will make the system even more competitive.

It is very likely that nuclear techniques will contribute much more to the mineral industry in the future, especially at development and mine production stages.

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