ULTRA-LOW RADIATION INTENSITY SPECTROMETRIC PROBE FOR ORE BODY DELINEATION AND GRADE CONTROL OF PB-ZN ORE

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ABSTRACT

CSIRO Exploration and Mining has developed a fully spectrometric gamma-gamma probe, operable with only a quasi zero-activity gamma-ray source (i.e., below 2 MBq). The prototype low radiation intensity probe has been tested at one of the Zn-Pb deposits in Queensland. The probe showed an excellent capability for ore body delineation. Lithological profiles derived from logging data showed sharp anomalies both in selected spectral regions and in spectral ratios during probe transition from ore body to barren rock, or vice versa. The instrument has demonstrated good potential for quantitative determination of Pb and Zn content in ore. Delineation of non-lithological boundaries, through an application of a cut-off grade algorithms has been demonstrated as a practical stand-alone mine control test.

INTRODUCTION

The mineral exploration and mining industry has a need for safe, portable and manoeuvrable borehole logging equipment for deposit delineation and grade control during the final stages of exploration, mine development and ore production. Geophysical logging has become an integral part of modern exploration and mine development activities. Among the many physically different borehole logging techniques, nuclear borehole logging is practically the only technique which has the capacity for providing on-line, quantitative in situ grade control.

Most of the commercial logging companies use non-spectrometric gamma-gamma borehole logging technique (density gamma-gamma log). This technique is mostly used for coal or ore body delineation. When ore grade measurements are required it is assumed that ore grade and ore bulk density are correlated. While ore grade and density may be quite well correlated in some deposits, that correlation is often too weak to provide, with confidence, the ore grade or the chemical concentration of key impurities. The techniques which are essential for both identification of elemental constituents and for their quantitative estimation in the ore are those which are spectrometric. Spectrometric methods have a capability for detecting and recording, differentially, different probe-response events, e.g. those due to different gamma-ray energies or, alternatively, those events having different arrival time. This capability in respect of gamma-ray energies is important for identifying and estimating some elemental constituents of the ore (e.g., the PGNAA technique).

The commercial density gamma-gamma logging tools utilize radioactive sources having high activities (around 2000–6000 MBq). These levels of radioactivity present difficulties for managing the safety and security of mine personnel and the environmental impact caused by a probe being irretrievably jammed in a borehole. CSIRO-developed SIROLOG spectrometric borehole logging probes have achieved significant use and recognition in the mining industry because of their superior quantitative performance (Eisler *et al.*, 1990, Charbucinski, 1993, Borsaru *et al.*, 1994). However, many mining companies still consider that the risk associated with the irretrievable loss of even a standard SIROLOG probe is too high (despite its source activity of approximately 40 MBq being about 1/100th of a conventional commercial probe) and would prefer to have the source intensity brought down by an additional order of magnitude. The states of Victoria, New South Wales and Queensland defined 3.7 MBq as the minimum activity of a gamma-ray source requiring a Licence for Possession, Use and Transport of Radioactive Substances. Therefore, operations with logging equipment having radioactive source of activity lower than 3.7 MBq would significantly simplify required procedures and reduce to a minimum the risk associated with application of radioactive sources.

The development of the new SIROLOG instrumentation by CSIRO Exploration and Mining goes one step further towards introducing to the mining industry a spectrometric borehole logging system based on the application of quasi zero activity gamma-ray source (below 2 MBq). Tests of this new instrumentation have been reported for coal seam delineation and on-line quantitative ash in coal determination (Charbucinski, 1993a, Borsaru *et al.*, 1994a, Charbucinski *et al.*, 1996) and also for iron ore body delineation (Borsaru *et al.*, 1995).

The objective of the present work was to optimise probe design for Pb-Zn ore body logging and to demonstrate both the delineation and quantitative capabilities of the low radiation intensity spectrometric probe for in situ analysis of lead and zinc.

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TECHNIQUE OVERVIEW

Two different low activity probe configurations have been developed for the coal mining industry (Charbucinski, 1993a, Borsaru *et al.*, 1994). In one of them (Low Activity Tool) a single ^{137}Cs gamma-ray source of 1.8 MBq activity was positioned axially from the detector behind a very short (30 mm) shield of tungsten and iron. In the second configuration (ZERO PROBE) three ^{137}Cs microsources (each of 0.37 MBq) were placed around the detector at virtually zero distance from the crystal (measured along the borehole axis). This ultimately short distance had the effect of providing the probe with the best possible bed resolution.

For minerals applications these ultra-low activity probes required redesign of probe configurations and development of new calibration and inversion algorithms. This was necessary because the probes developed for the black coal industry were designed to perform optimally in low density–low equivalent atomic number environments, while the zinc ore has significantly higher equivalent atomic number and is associated with much higher density lithology. The higher densities required new optimisation of source-to-detector distances. Planned larger diameter holes (greater than 150 mm) allowed further optimisation of scintillator crystal volumes. However, the optimised geometry still featured a very small source-to-detector distance, resulting in the probe operating in the pre-inversion zone of the calibration curve. In that zone, the count rate of gamma quanta scattered in a high density medium (ore) is higher than the count rate recorded in a lower density scatterer (barren rock).

One needs to emphasise that the low radiation intensity probe is the low activity version of the SIROLOG spectrometric gamma-gamma probe. As such the probe is not able to measure the concentration of Zn directly. The gamma-gamma probe response is related to the overall contributions given by the major components with high atomic number present in the ore, e.g., Pb, Zn, Fe, Mn. Figure 1 shows spectra recorded in five large geophysical models. Four models contained Zn-Pb ore of various quality and the fifth model (W2) contained waste. The prominent features of the shown spectra are the 180° backscatter peak around channel 140 and the Pb characteristic x-ray peak around channel 58. The energy calibration was 1.5 keV per channel. Not shown in the figure is the photopeak of primary radiation from the probe's ^{137}Cs source which was utilized for hardware gain stabilization of the logging system.

The physical design of the probe is such that it uses single scattered gamma-rays (180°) to provide information about bulk density of logged formation, while multiscattered quanta of lower energies carry information on the average chemical composition of ore. The x-ray peak of Pb is utilized for %Pb determination.

The overall contribution of the major ore components to the value of a spectral ratio used for correlation with the average chemical composition can be expressed in % Zinc-Metal Equivalent (ZME) units. ZME units provide a useful measure of the response of the probe to the total composition of the material. It is defined from Equivalence Factors (EF) which are numerical values "translating" contents of other heavy elements (e.g., Pb, Fe, Mn) into Zn content. The EF is a multiplier such that

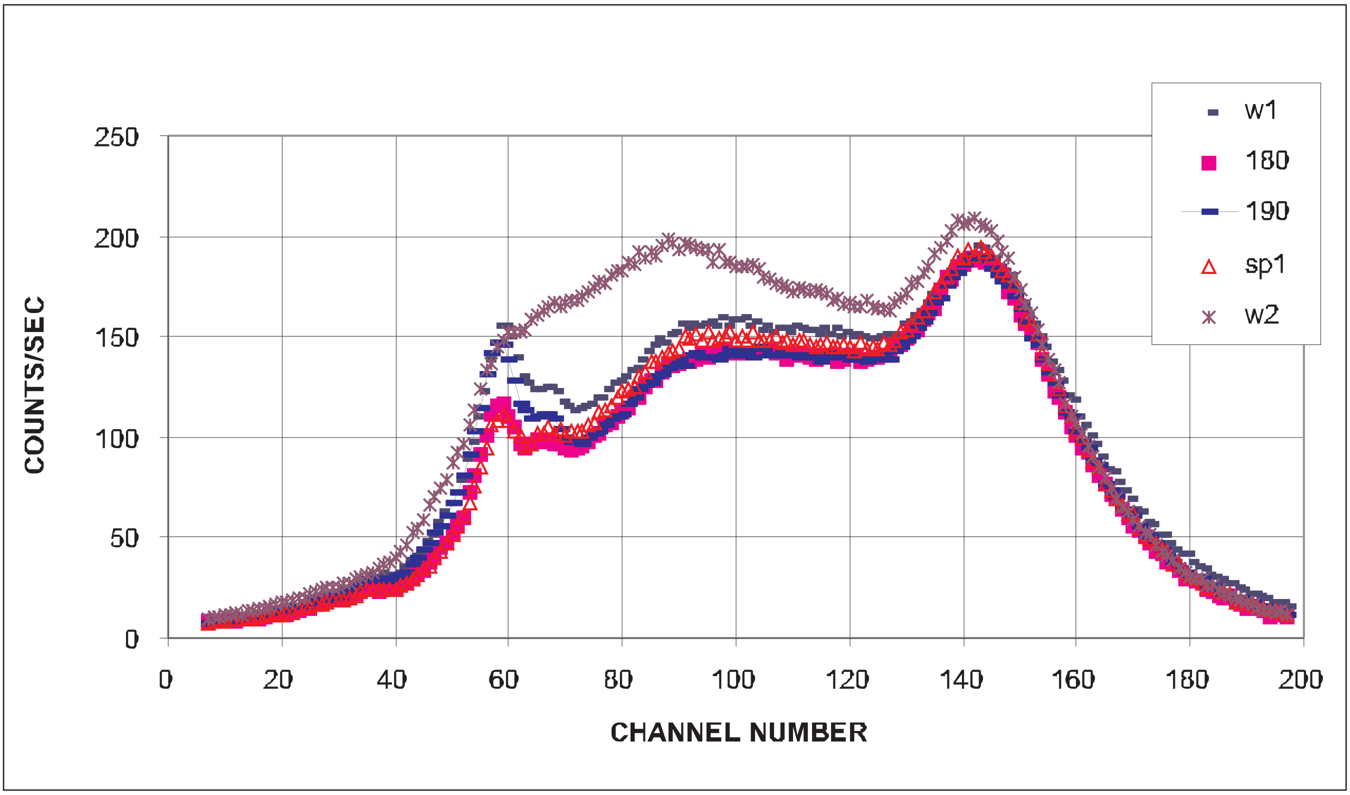

Figure 1: *Spectra recorded with a 76mm dia × 76 mm detector in large ore samples.*

gamma radiation scattered and/or absorbed by a compound of a multi-heavy element medium (and measured through a given spectral parameter) results in the same value as that of the spectral parameter being measured in a mono-heavy metal ore (e.g. Zn only). For zinc content (%Zn), the Zinc Metal Equivalent percent is equal to:

$$\%ZME = \%Zn + \%Pb * EF_{Pb/Zn} + \%(Fe{+}Mn) * EF_{(Fe+Mn)/Zn} \quad [1]$$

In other words, gamma-ray interaction with matter in a multi-heavy element medium should be the same as the interaction in a hypothetical mono-heavy element medium described by the same %ZME. Equivalence Factors are usually established in an empirical way, and of course have differing values for different spectral ratios or windows.

The quantitative determination of Zn content in ore, after correcting on Pb content from its spectral contribution (x-ray peak), is possible only if Fe and Mn contents are either relatively constant, at least within a given ore unit, or these contents can be measured by a complementary physical technique. The iron component requires use of an alternate measurement technique, preferably a magnetic susceptibility probe, which could be incorporated into the measurement system to provide a single pass logging operation.

INSTRUMENTATION

The large hole size (142 mm) permitted application of a higher volume crystals than the standard detectors of 60 mm SIROLOG probes. The probe, with an external diameter of 100 mm, has been designed and manufactured, using a 76 mm × 76 mm NaI crystal. The auxiliary equipment consisted of a portable single conductor cable and winch with a winch controller, the surface electronics unit SIROMCA and a dedicated PC computer. Due to the very weak gamma-ray source applied (under 2 MBq), there was no need for a source container/transporter. The SIROMCA unit combines the functions of pulse shaper, nuclear amplifier and digitally gain stabilized multichannel analyzer. In the new generation of SIROLOG instrumentation the SIROMCA surface electronics unit has been eliminated. All SIROMCA functions and also additional features have been incorporated directly into a logging probe.

The new system features a unified approach to the spectrometric logging hardware such that all SIROLOG spectrometric systems use essentially the same hardware. Recent microprocessor developments have allowed the design of a generic MCA system which can fulfill the needs of these low count rate and low power consumption systems, while coping with the higher count rates of logging (approximately 100 000 cps). A system was designed to fit inside a 60 mm probe barrel and use serial communications to transmit complete spectra up the cable in digital format to a PC.

FIELD TRIALS

To establish the "bed resolution" capability of the logging probe static measurements were performed in the two-layer model simulating barren rock and a good quality ore. The measurement points were established by moving the probe "up-hole" in 1 cm increments. Figure 2 presents the change of count-rate recorded in the spectral window ch 75–90 for the ore-to-rock transition. This figure provides a value of 150 mm as a distance for which a full transition from "ore-count-rate" to "barren rock-count-rate" takes place. This value should be understood as the distance from the barren rock/ore boundary at which the probe will record information from an isolated lithological unit.

Two cored holes, reamed later to a diameter of 142 mm, close to the anticipated diameter of future production holes, were available for the tests. Both holes were water-filled. Core obtained from those holes was subdivided according to the observed lithological differentiation. Over 80 sections of core were assayed and the results of laboratory analyses were used as reference points for the assessment of the probe potential for Pb and Zn determination.

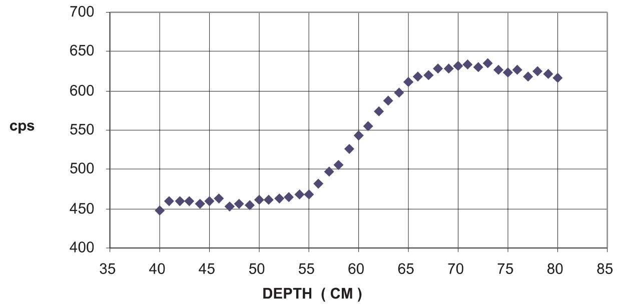

Figure 2: *Ore-to-rock transition response profile (static measurements, 10 mm increments).*

Delineation of ore body

The borehole tests were performed at logging speeds between 1.5 and 2.0 m/min, implying integration times of 1.5 seconds for a sampling interval of 5 cm. The spectral parameters which were applied as delineation indicators were the same as the best indicators found during laboratory tests, namely the spectral window 110–135 keV and spectral ratio 190–235 keV / 110–135 keV. Figure 3 shows a geophysical profile based on the above spectral ratio plotted against a Zn chemical chart. The measured values of this parameter change significantly with the transition from barren rock to zinc ore, from around 1.4–1.5 to 2.3–2.5, providing good means for ore body delineation. The profiles obtained with the SIROLOG low radiation intensity probe offer better boundary definition than even high gamma-source activity commercial logs of these holes.

Probe quantitative performance

The analysis of the spectrometric data was aimed at selecting a set of spectral ratios and/or spectral windows to be used for quantitative analysis of obtained data. Initially the windows and ratios used for the laboratory data analysis were applied. Then a number of new windows and ratios were evaluated and subjected to an analysis where step-by-step changes of Pb/Zn and (Fe+Mn)/Zn Equivalence Factors were investigated. The final stage of selecting the optimal spectral parameter for quantitative Zn-predictions (after fitting the right Equivalence Factors) was a fine tuning of the spectral boundaries of the best spectral ratio found in the preceding stage. Figure 4 shows correlation between values of %ZME derived from logging, applying the optimal spectral parameter for a linear calibration equation, and the values of %ZME based on chemical assays.

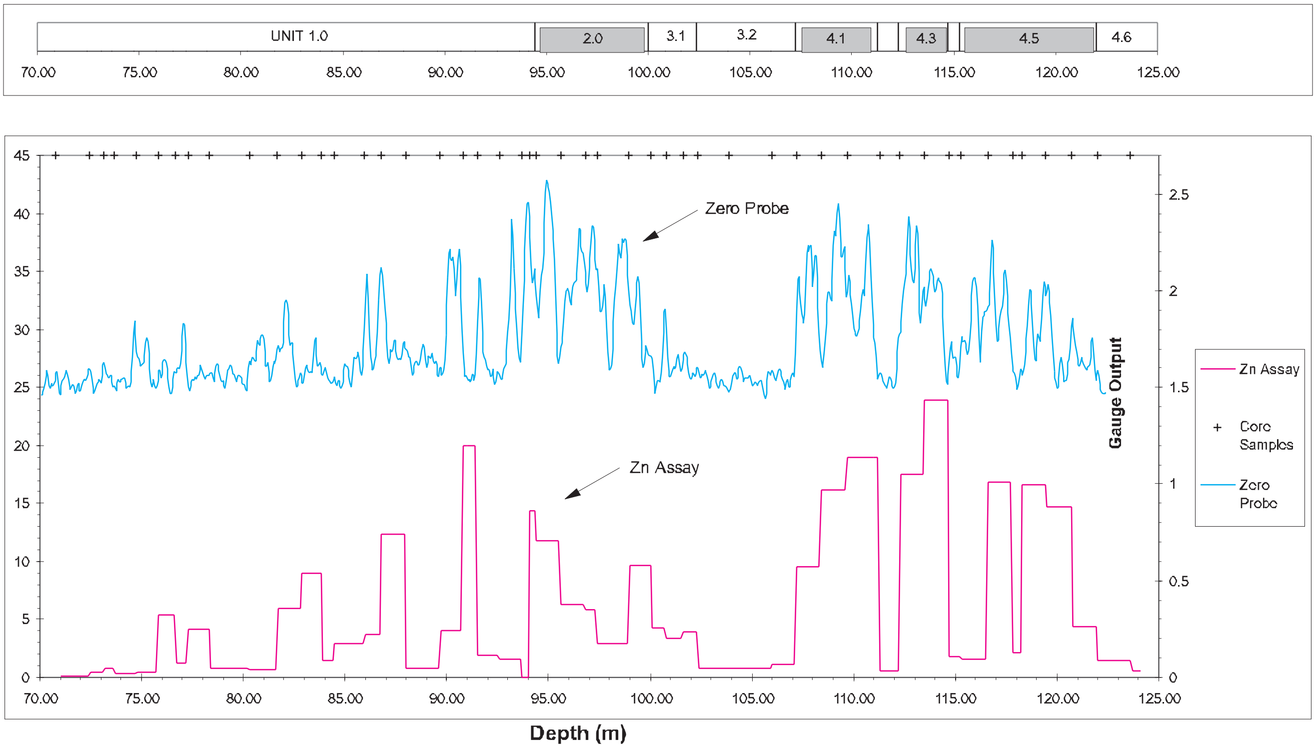

Figure 3: *Chemical assay for the test hole and the logging profile based on the spectral ratio: 140–235 keV / 110–135 keV, (Petrov, 1996).*

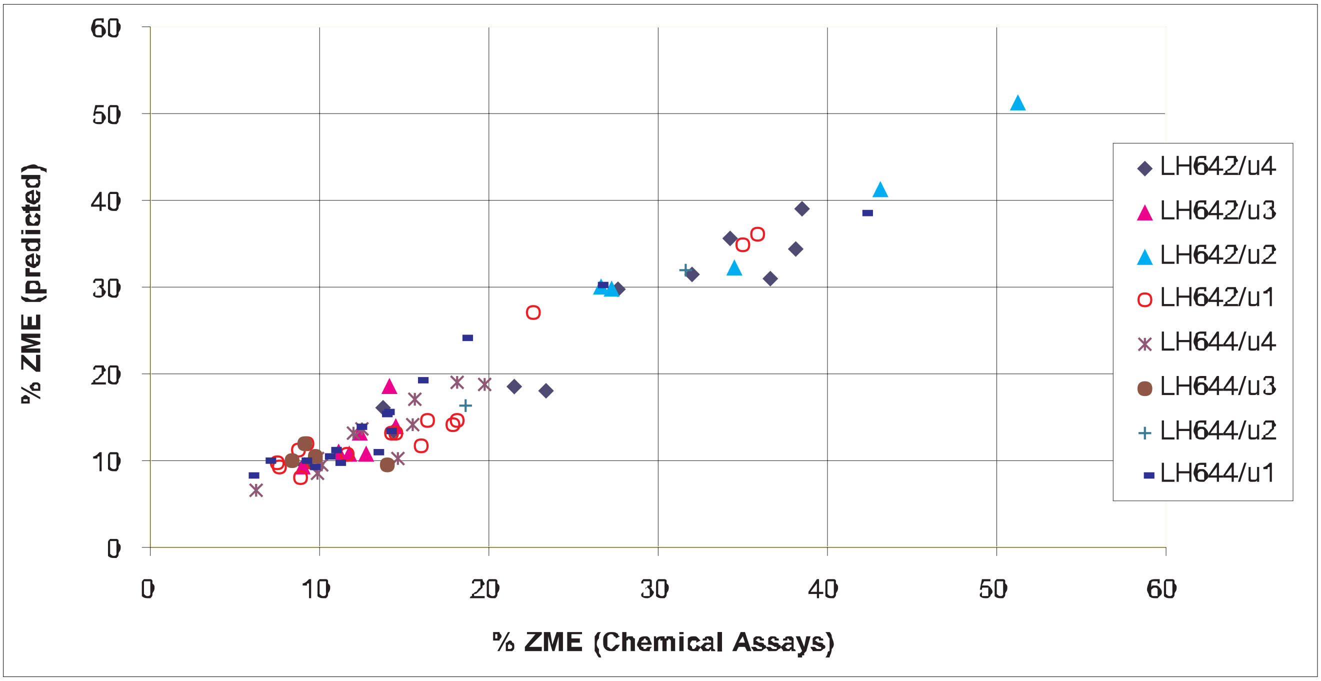

Figure 4: *Comparison of %ZME by laboratory analysis and by geophysical log.*

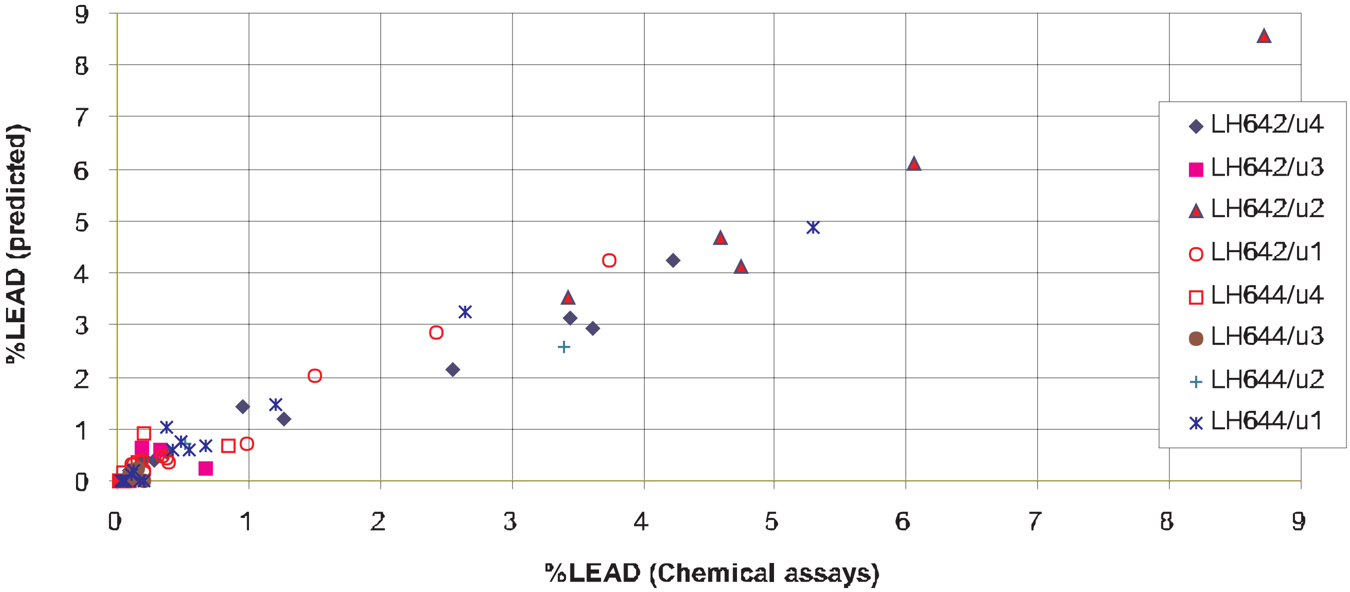

Figure 5: *Probe's %Pb determination performance.*

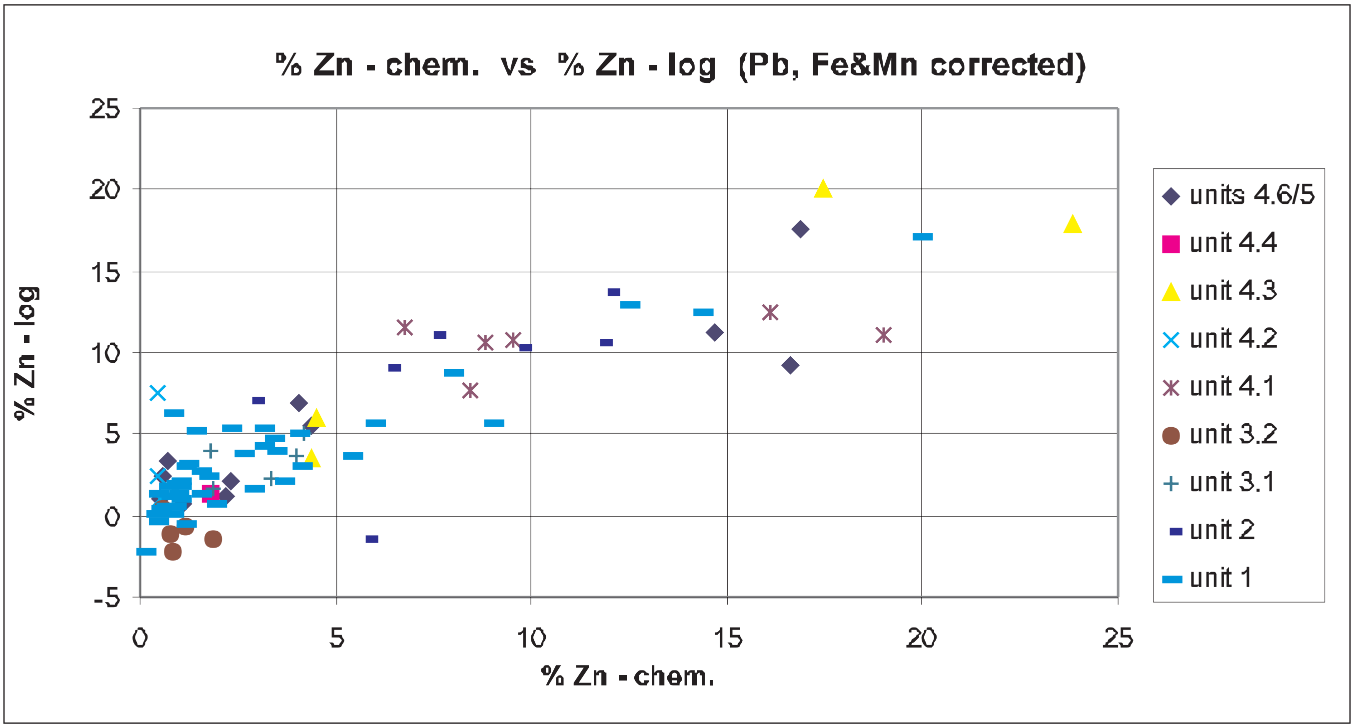

Figure 6: *Comparison between %Zn-chem and %Zn-log (Pb-corrected, and Pb, Fe, Mn-corrected).*

The r.m.s. deviation between laboratory assays and the tool's predictions was 2.4 %ZME. The standard deviation for the population, s, was 10.4 %ZME and the number of assays in the regression equation was 72. The correlation coefficient was 0.97. Only 72 samples were considered in the regression equation from a total number of over 80. The reason for not including all the samples was to have a more uniform distribution of samples in the regression. Therefore, a number of samples of low grade (ZME < 9) were (randomly) not included in the analysis. If all the samples were included in the equation the data points would have been clustered in the area of low ZME.

Determination of Pb content

The 87 keV characteristic x-ray peak showing prominently in the backscattered gamma-ray spectrum was used for the determination of Pb content. The results of the laboratory investigations of the potential of the SIROLOG low radiation intensity probe for Pb determination has been reported elsewhere (Almasoumi *et al.*, 1997). The spectral parameter based on a ratio of net Pb peak-area to gamma-ray intensity of energy just above the Pb-peak, provided a good measure of Pb content in ore. Figure 5 shows a cross plot of the predicted %Pb (obtained from a two-variables calibration equation) against the laboratory assays. The r.m.s. deviation between the field estimates and the laboratory assays was 0.3% Pb, the standard deviation of the population was 1.7% Pb. The correlation coefficient for the regressed data was 0.98.

Determination of Zn content

To assess the feasibility of Zn-grade predictions from log-derived values of %ZME the Pb and Fe and Mn contributions to %ZME predictions need to be estimated. Spectrometric logging data permit the application of an intrinsic correction of the lead-contribution, through measurement of the net area of the characteristic x-ray peak for lead. As the Fe and Mn contributions to the total value of %ZME cannot be measured from the spectrometric gamma-gamma log, the corrections for Fe and Mn applied were based on statistical information from the geological data base. Figure 6 shows the cross plot between values of Zn content derived from %ZME by subtracting both Pb-contributions (measured directly) and Fe and Mn contributions (average statistical values for each ore unit), and the chemical assays. The correlation coefficient for the data set was equal to 0.90 and the r.m.s. deviation was equal to 2.4% Zn. It is worth noting that when only the Pb contribution was taken into account the quoted values were 0.88 and 2.6% Zn, correspondingly. However, a noticeable improvement may be possible when %Fe (and %Mn) are measured directly by another physical technique.

Reproducibility tests

Each hole was logged at least twice with the aim of assessing how reproducible the obtained profiles and quantitative predictions were. Figure 7 shows profiles of duplicate runs in one of the holes. The logging

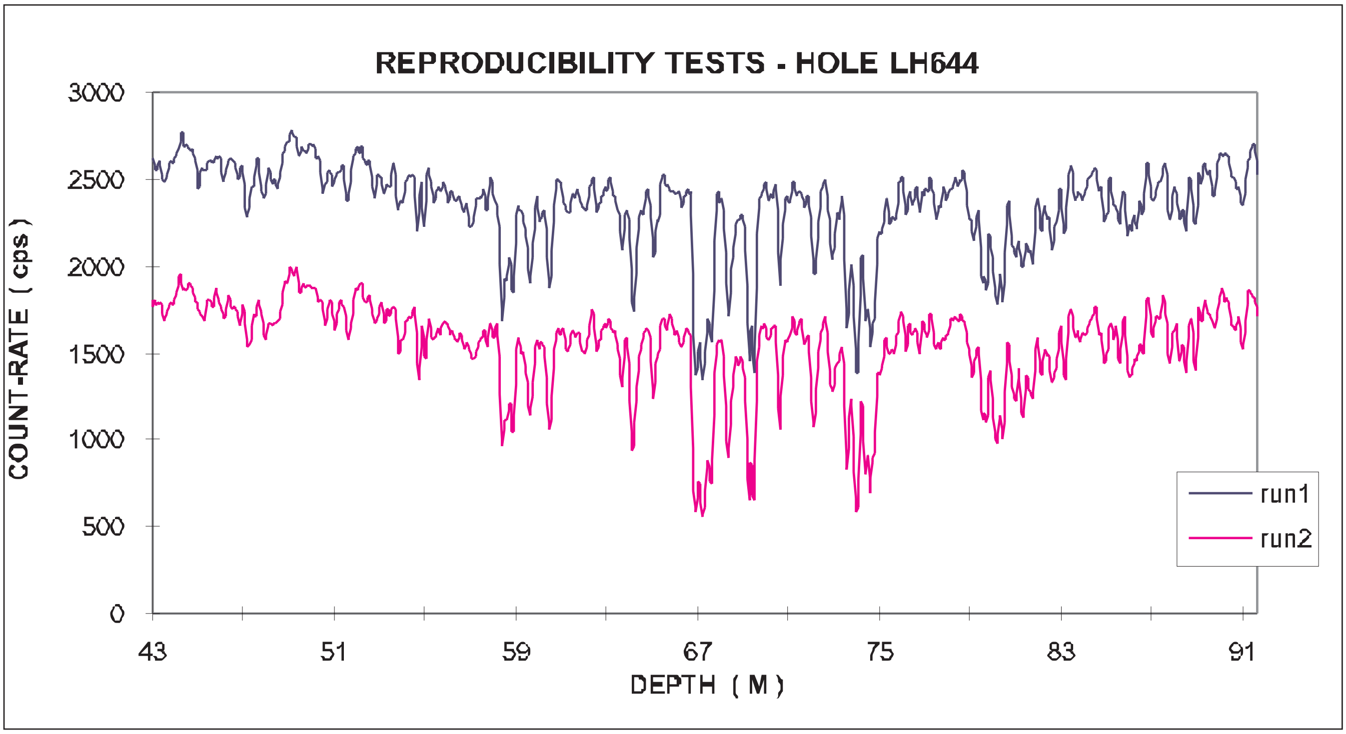

Figure 7: *Profiles of duplicate logs in one of the test holes (profile of run 2 has been shifted verically on the count rate axis).*

profiles show spectral intensity measured in Energy window 110–135 keV. For better clarity of comparison, the profile corresponding to run 2 has been shifted vertically along the y-axis. It can easily be seen that the original profile and the second run are almost identical, proving a high quality of delineation reproducibility.

Reproducibility of quantitative predictions was tested by comparing values of %ZME obtained from run 1 with the corresponding values obtained from run 2. The 83 logging splits, corresponding to the core samples taken for chemical analysis, were used for testing the reproducibility. Values of the spectral ratio used for analyses were derived from both logging runs and subsequently pairs of %ZME were calculated using the calibration equation. Finally, the values from run 2 were regressed against the values from run 1. The correlation coefficient for the data set was equal to 0.99 and the standard deviation (1 sigma) for the regression was equal to 0.85% ZME, indicating high reproducibility of the logging data.

Determination of cut-off boundary

The application of the SIROLOG low radiation intensity probe for predicting the cut-off boundaries of Zn ore was tested on one of the ore units. By definition, the cut-off boundary is the depth where the integrated zinc value from the top of the ore unit reaches the lowest economical acceptable value for the mined unit. The integrated values of %Zn were calculated from the top of ore unit for 5 cm depth increments. It was assumed that the concentrations of Zn, Pb, Fe and Mn are constant for all the 5 cm splits which belong to a chemically assayed sample interval. This assumption may not always be accurate. Figure 8 shows profiles of integrated, from the top of ore unit, values of %Zn-chem and two profiles of %Zn-log, one corrected on only %Pb, and the second also corrected by the average, for the entire unit, value of %Fe+%Mn. The figure indicates that the profiles of the %Zn-log match the profiles of %Zn-chem (when disregarding the top section of the ore unit, for which %Zn-log profiles show more structure than %Zn-chem profile which was taken as a single Zn-assay for one sample).

CONCLUSIONS

The spectrometric low radiation intensity probe has been shown to be effective in the Pb-Zn ore application. Non spectrometric probes would not be capable of equivalent performance standards. The probe utilizes a gamma-ray source of activity lower than 2 MBq and provides minimal risk to safety and environmental integrity.

- The probe showed excellent delineation characteristics, and indicated considerable variation in the log. Lithological profiles derived from logging data showed sharp anomalies both in selected spectral regions and in spectral ratios during probe transition from ore body to barren rock or vice versa. Having the source placed a very short distance from the detector has the effect of providing the probe with the best possible vertical resolution.

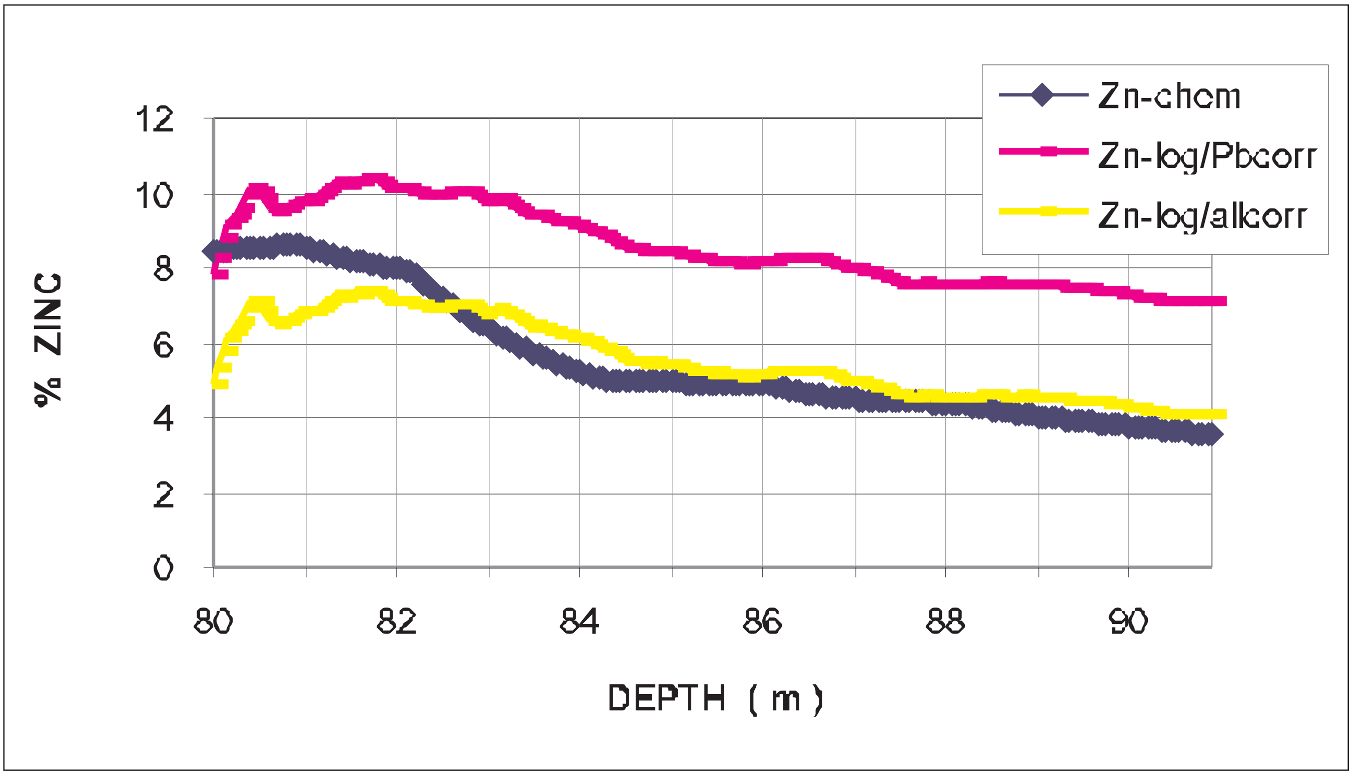

Figure 8: *Profiles of integrated values of %Zn from the top of the ore unit for chemical assays and log-derived values.*

- The quantitative performance of the probe has been satisfactorily demonstrated, providing determination of %Zn to within 2.4% r.m.s. and determination of %Pb within 0.3% r.m.s.
- Delineation of non-lithological boundaries, through an application of a cut-off grade boundary has been demonstrated as a practical stand alone mine control tool.

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