

Spectrometric Nuclear Logging as a tool for real-time, downhole assay – Case Studies using SIROLOG PGNAA

K Trofimczyk¹, S Saraswatibhatla¹, C Smith²

1. Geosciences Resources Group, Anglo Technical Division, South Africa
ktrofimczyk@angloamerican.co.za, ssrinivas@angloamerican.co.za
2. Australian Commonwealth Scientific and Research Organisation (CSIRO), Australia
Craig.Smith@csiro.au

ABSTRACT

The SIROLOG Prompt Gamma Neutron Activation Analysis probe is a spectrometric borehole logging tool developed by the CSIRO in Australia. The principle of the technique is the measurement of the characteristic intensity and energy of gamma (γ) rays that result from nuclear interactions when fast neutrons bombard the formation. The intensity and energy of the emitted γ rays is related to the elemental composition of the rock, thus the volumetric occurrence of the elements in a bulk rock mass intersected by a borehole, can be directly estimated. Downhole nuclear logging has certain benefits over conventional core and drill-chip assaying. A much larger volume of the material surrounding the borehole is sampled than the sample taken for laboratory analysis, thus providing better sampling statistics. Provided a suitable calibration exists, data processing can be automated for quick turnaround of results (near real-time processing). Since a continuous log is measured *in situ*, the data is not limited by zones of core loss or breakage or potential sample contamination.

The SIROLOG PGNAA probe was demonstrated on four Anglo American mines in 2004. At Namakwa sands heavy mineral sands mine in South Africa, the technique indicated the potential to deliver quantitative estimates of whole rock geochemistry, including heavy mineral concentrations. At Sishen Iron Ore mine in South Africa, quantitative *in situ* determination of Fe (iron) grade was demonstrated. This is in line with published results from studies done at other iron ore mines. Encouraging results were obtained for P (phosphorous), one of the important penalty elements, although low concentrations and a limited range of grade values in the small data sample, affected the outcome. At Skorpion mine in Namibia, a good estimate of Zn (zinc) grade, the primary ore mined, was obtained in blast boreholes; however the penalty element, Ca (calcium), could not be accurately predicted due to the low abundance of this element intersected by the test boreholes. Similarly, low abundance of Cu (copper) returned poor calibrations in a study on waste dumps at Mantos Blancos mine in Chile.

The results demonstrate that the PGNAA technique can quantitatively predict the abundance of certain elements *in situ*, although site-specific calibrations are required for best results. However, calibrations are difficult to establish where the abundance and the range of grade values of the target element are low, or the typical signature of the target element overlaps that of another element. The development of higher resolution LaBr₃ γ -ray detectors can potentially alleviate these limitations. Another drawback of downhole nuclear logging is the hazard associated with the use of chemical radioactive sources. Alternative, safe sources, such as neutron activation systems, are currently being developed. These systems use non-isotopic, switchable sources such as D-T neutron generators that can be switched off when not being used.

Key words: Wireline logging, PGNAA, SIROLOG, borehole, spectrometric nuclear logging, nuclear, assay

INTRODUCTION

Throughout the mining life cycle, from exploration to mining production, chemical properties of the ore deposit are obtained from the cuttings and core from boreholes. The sampling component (sample weight obtained from the borehole) and the analytical component (the amount of sample sent for analysis)

affects the final reading and may bias the values obtained from laboratory assays. In contrast, borehole logging methods collect information *in situ* about the rock formations surrounding the borehole and can provide rock properties independent of core or sample recovery. A benefit of geophysical logging is that it allows detailed interpretation of non-cored boreholes, permitting either substitution of diamond drilling or

extension of drilling programs on the same budget since non-cored boreholes are cheaper to drill (Borsaru *et al*, 2006; Charbucinski and Nichols, 2003). A natural extension of this argument is application in blast holes.

Nuclear borehole logging techniques have been used in the mineral industry for long time. A neutron log utilising a downhole neutron source and measuring the gamma rays emitted upon capture of the neutrons, was described in 1941. Logs depending on other nuclear reactions (e.g. gamma-gamma density logging) followed in the 1950s (Telford *et al*, 1990). A bulk response of the formations is obtained due to the penetration of neutrons and gamma rays into the formation (Rider, 1996).

The SIROLOG PGNAA (Prompt Gamma Neutron Activation Analysis) developed by the CSIRO in Australia, is an extension of standard total count nuclear techniques, whereby the volumetric occurrence of certain elements in a bulk rock mass, intersected by boreholes, can be directly estimated (CSIRO, web). Depending on rock density and moisture content, the SIROLOG PGNAA probe samples the rock mass adjacent to the borehole out to ~50 cm in all directions (Charbucinski *et al*, 2004a) and thus investigates a substantially greater volume of rock compared to that obtained from the borehole core or blast hole chips. Because neutrons are deeply penetrating, the technique is not as sensitive to the rugosity and condition of the borehole as other techniques (e.g. the gamma-gamma density log). The data is digital and thus amenable to automated processing for quick turnaround of results.

Applications of PGNAA logging in exploration and evaluation include the estimation of *in situ* rock mass density as well as estimates of elemental compositions. Industry demonstrated success includes Si and Fe in coal ash and iron ore, Mn in manganese ore and metalliferous applications (Cu, Ni, S, Fe) (Borsaru *et al*, 2004; Charbucinski and Nichols, 2003; Charbucinski *et al*, 2004a, Borsaru *et al*, 2006). Supporting this base of studies, this paper presents the results of field trials undertaken in 2004 on a number of Anglo American mine sites. Data acquired at Namakwa Sands heavy mineral sands mine and Sishen iron ore mine in South Africa, Skorpion zinc mine in Namibia, and Mantos Blancos copper mine in Chile (waste dumps application) are shown. The potential advantages of PGNAA are illustrated as well as some of the challenges and possible limitations of the method.

METHODOLOGY

The measurement of gamma radiation emissions resulting from the interaction of an introduced neutron source with the rock mass in a borehole is known as prompt gamma neutron activation analysis or PGNAA (Charbucinski, 1993; Borsaru *et al*, 2002; Smith and Berry, 2005 a,b,c). In a borehole logging configuration,

both a neutron source and a gamma (γ) ray detector is present in the tool.

When fast neutrons emitted by a neutron source enter the formation, they undergo collisions with the nuclei present in the matrix and lose energy. If they are not absorbed during this slowing down process, they will ultimately reach the thermal energy of 0.025 eV. These thermal neutrons continue to diffuse through the medium until terminated by some other process, like neutron capture. In the capture process, the thermal neutron enters the nucleus, and produces an unstable compound nucleus, which decays by emission of one or more γ -rays of energies specific to the target nucleus and the type of nuclear reaction. In principle, if the intensity and energy of the gamma rays are measured by means of a suitable spectrometric detector, the type and amount of an element present can be determined (Charbucinski, 1993; Charbucinski *et al*, 2003). Provided that an appropriate calibration exists, the concentration of the element can be determined from the neutron-gamma (n- γ) spectrum.

The energy of emission is measured in mega-Electronvolts (MeV). A number of elements generate characteristic γ radiation signatures during interaction with neutrons. Table 1 lists neutron capture data for a number of major rock forming and metallic elements.

Table 1: Neutron capture data for a number of rock-forming and metallic elements (from Charbucinski *et al*, 2003)

Element (atomic mass)	Thermal neutron capture cross-section (barns)	Major gamma-rays (MeV)	Gamma-ray intensity (per 100 neutron radiative captures)
Copper (63.55)	3.79	0.28	32.7
		7.64	15.7
		7.91	30.8
Iron (55.85)	2.55	5.92	9
		6.02	9
		7.63	24.1
Silicon (28.09)	0.16	7.65	28.5
		1.16	19.9
		2.09	21.5
		3.54	68.0
Aluminium (26.98)	0.23	4.93	62.7
		6.38	12.4
		7.72	27.4
Calcium (40.08)	0.43	1.94	72.6
		4.42	15.0
		6.42	38.9
Sulphur (32.06)	3.32	0.84	75.6
		2.38	44.5
		2.93	22.3
		3.22	27.1
		5.42	59.1

A typical PGNAA n- γ spectrum recorded in iron ore is shown in Figure 1. At the point of emission the energy spectrum of γ rays, generated by the neutron capture,

consists of a series of isolated narrow lines whose energies are accurately known. The derivation of elemental concentrations is based on their relative intensities. In passing through the rock mass, the isolated γ rays undergo some changes to their relative intensities and a continuum develops (Figure 1) that forms a background to the isolated lines and the emitted lines tend to become broad peaks when recorded (Charbucinski, 1993, Charbucinski *et al.*, 2003). The broadening of the peaks depends on the type of detector employed.

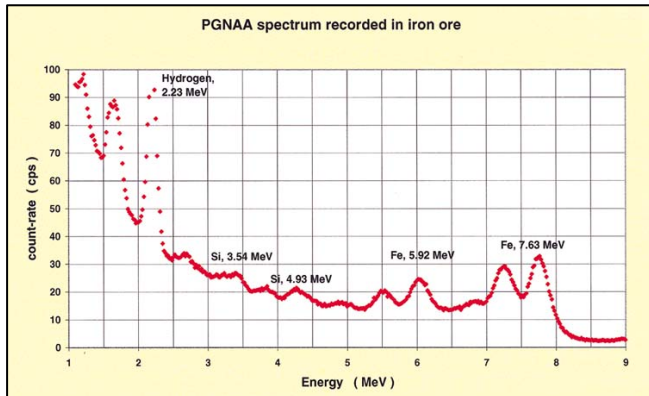


Figure 1: A typical PGNAA spectrum obtained from iron ore logging

The SIROLOG PGNAA sonde used in the Anglo American test surveys, employed a 75 mm x 62 mm diameter bismuth germanate ($\text{Bi}_4\text{Ge}_3\text{O}_{12}$) scintillation detector (commonly referred to as BGO). BGO, due to its high density (7.1 g/cm^3) and high effective atomic number ($Z_{\text{eq}} = 70$), has greater γ -ray stopping power than either NaI or CsI scintillators, especially for high energy γ rays, thus providing a high efficiency of detection of γ rays. BGO is non-hygroscopic and is mechanically rugged, which are useful characteristics for borehole applications. An advantage of the BGO detector for PGNAA logging is that the crystal is less sensitive to activation and capture than either NaI or CsI. However, the energy resolution of the BGO detector is lower than NaI or CsI due to its low light output, which affects the resolution (Charbucinski *et al.*, 2003).

The trade-off in resolution introduces certain limitations. It is apparent from Table 1, for example, that the high-energy γ rays released by the Al nuclei following neutron capture have practically the same energy as the γ rays released by Fe nuclei. Since the cross-section for neutron capture for Fe is an order of magnitude greater than for Al, the γ rays of energy ~ 7.6 MeV are generated mostly by Fe. (This also depends on the relative concentration of the elements in the formation being surveyed). For iron ore surveys, the accuracy of the Fe determination based on the 7.6 MeV γ rays will be affected by γ rays generated by Al (Borsaru *et al.*, 2002). The 6.02 MeV and 5.92 MeV γ rays released by Fe can also be used for measurement of

%Fe. However, determination of %Al will be problematic as the γ rays released by Al nuclei will be either too weak or swamped by the γ rays from Fe.

Another effect that must be considered when analysing n- γ spectra is inelastic scattering that takes place above the threshold energy (normally about 1 MeV) (Borsaru *et al.*, 2002). The neutrons produced by the neutron source have energies up to 8 MeV. Hence, when logging dry boreholes (e.g. blast holes), a large number of fast neutrons impact on the rock mass because there are few hydrogen nuclei (borehole fluid) to slow them. During the slowing process, some of the fast neutrons interact by inelastic scattering. The energy of γ rays produced by neutron inelastic scattering is much less than that produced by neutron capture, but is not insignificant (e.g. inelastic scattering energies for Fe are of the order of 0.85 to 1.24 MeV; versus around 7 MeV for neutron capture – Table 1).

PGNAA borehole logging can be performed in both dry and wet boreholes. The presence of water does affect the neutron / rock mass interaction process; more so if there is a large difference between the borehole diameter and probe diameter. It is usually necessary to have separate calibrations for dry and wet boreholes. In addition, it is usually necessary to generate separate calibrations for boreholes of different diameter.

The BGO detector and neutron source are separated by a combined lead shield and polyethylene thermaliser. As the neutron capture reactions are originated by thermal neutrons, there is a need to thermalise fast neutrons emitted by ^{252}Cf . The polyethylene, due to its high content of hydrogen nuclei, contributes significantly to the thermalisation of neutrons. The 2.23 MeV hydrogen capture peak is used for gain stabilisation of the logging system as well as for normalisation of the γ -ray count rates recorded in the spectral windows. Gain stabilisation is important with BGO detectors, because of their high sensitivity to temperature variations (Charbucinski, 1993).

RESULTS AND DISCUSSION

Field demonstrations were undertaken at four Anglo American mines. At Namakwa Sands heavy minerals sands mine and Sishen Iron ore mine in South Africa, PGNAA data was acquired in reverse circulation (RC) percussion evaluation boreholes. The study at Skorpion zinc mine in Namibia focussed on blast hole logging. An innovative application of the PGNAA technique for Cu grade estimation in waste dumps was investigated at Mantos Blancos mine in Chile.

The SIROLOG PGNAA tool used in the Anglo American surveys had a diameter of 100 mm. The tool employed a ^{252}Cf neutron source of $\sim 6.5 \mu\text{g}$ activity. The full logging system (Figure 2) consisted of the logging sonde, a winch with single conductor cable, a

single wire interface supply system (SWISS), a logging tripod, a radioactive course-container / source-charger with a 120 MBq ^{252}Cf source, a laptop computer and an extreme-duty 12V battery that is designated non-spillable for shipping by air transport if required.



Figure 2: Components of the SIROLOG PGNAA portable logging system

Boreholes were logged at a speed of around 2.0 meters / minute. Data was recorded in 480 energy channels for each 10 cm interval (split) of the borehole during the upward movement of the tool.

Namakwa Sands Mine

The Namakwa Sands heavy mineral sands mine is located on the west coast of South Africa. Heavy minerals, including ilmenite, rutile, zircon and leucosene, are extracted from palaeo-beach sands. Formation of thick heavy mineral enriched sequences occurred due to prolonged concentration by wave action in a confined area. During the accumulation of sand units, pedogenic processes were active resulting in hard layer formation as consolidated, silicified and calcretised strata. The SIROLOG demonstration was designed to assess the potential for using PGNAA to estimate heavy mineral concentrations and to define hard material in the mine sequence.

Eighteen reverse circulation (RC) percussion boreholes were logged. A typical plot of one of the borehole datasets is shown in Figure 3. Borehole depth is on the vertical scale and the respective gamma ray energy channels on the horizontal scale (480 channels). The vertical trace corresponding to channel 110 represents the hydrogen peak which is used to stabilise the instrument. The light blue colour zones at channel 180 and 250 correspond with strong Si peaks. There is considerable variation in the spectral PGNAA response down the hole and this variation corresponds with changing lithology (chemistry) (Smith and Berry, 2005a).

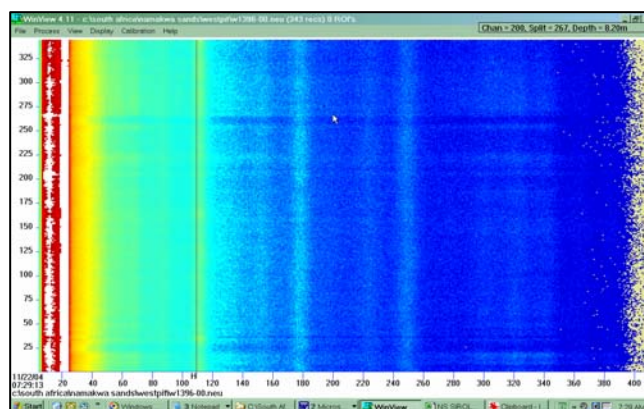


Figure 3: Raw PGNAA spectral plot borehole 1396.

The assay data provided by the mine ranged mostly from 2 m to 3 m interval samples. The sample preparation and analysis procedure used at site involved the removal of a slimes and oversize component from all drill samples. The remaining sub-sample emulates the plant feed and is assayed for SiO_2 , Fe_2O_3 , MgO , Al_2O_3 , TiO_2 and ZrO_2 . For the samples from the test boreholes, the plant feed component of the sample varied from 45% to 99% of the total sample. The SIROLOG technique measures the geophysical response from the total rock mass. It cannot be reliably assumed that the elemental distribution within the plant feed sub-sample is the same as that for the discarded slime and oversize, so only plant feed sub-samples with mass greater than 90% of the total sample were used for the development of calibrations for the study. This reduced the sample dataset from the 18 boreholes by around 75%, but ensured that any correlations represented are derived from comparing like for like.

Calibrations were generated for each of the grade parameters above and are shown in Figure 4 (in the appendix). The PGNAA response for each parameter is modelled from regions of interest (ROI) on the spectral response, based on the characteristic γ -ray emissions of the parameter. The correlation coefficient (R^2) for all the calibrations, except Al_2O_3 are better than 0.8 (80%). When combined, the cumulative total of the six sample grade parameters is >92%, meaning that these six components make up the majority of the sample composition. The SIROLOG results suggest that PGNAA may thus be able to deliver quantitative estimation of whole rock geochemistry, including the heavy mineral concentrations based on the TiO_2 and ZrO_2 content (Smith and Berry, 2005a).

A link between higher density and the occurrence of hard layers at Namakwa Sand has been reported for a downhole gamma-gamma density survey at Namakwa Sands (Trofimczyk *et al*, 2005). For comparison, the SIROLOG tool was surveyed in a number of boreholes also surveyed with a Weatherford (formerly Reeves) gamma-gamma density tool. A linear regression correlation of 0.85 was achieved for merged 1 m

composites of the independent density datasets as illustrated in Figure 5 and shows the potential of obtaining an estimate of bulk density from PGNAA.

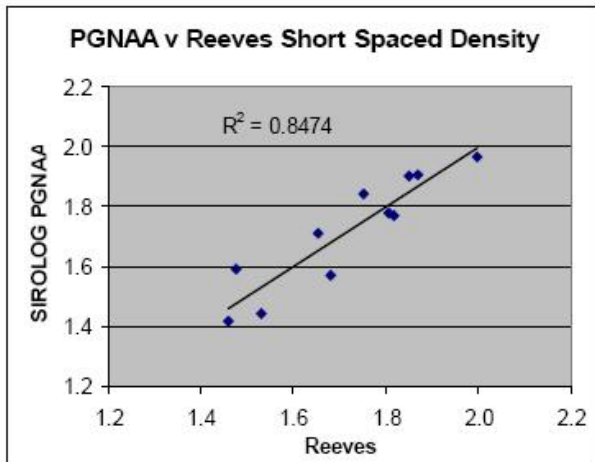


Figure 5: Comparison of the SIROLOG PGNAA-derived density with gamma-gamma density data (unit of g/cm³) for borehole 1179 (Smith and Berry, 2005a).

Although it is accepted that the gamma-gamma technique delivers higher accuracy estimates of density, the application of PGNAA means that other elemental information can be provided simultaneously with density, avoiding the use of a second log run (Smith and Berry, 2005a).

Sishen Iron Ore Mine

There are a number of case studies on Australian mines on the application of PGNAA for quantitative *in situ* determination of iron (Fe) grade (Borsaru *et al*, 2002; Charbucinski, 1993). A test of the SIROLOG PGNAA tool was undertaken in two, 125 mm diameter, RC percussion boreholes at Sishen Iron Ore mine in South Africa's Northern Cape Province, in November 2004. The boreholes were designed to illustrate different ore types and grade ranges for the elements of interest. A total of 49 m of borehole intersection was obtained from the two boreholes. The boreholes were dry throughout.

The deposit mined at Sishen is a high-grade hematite iron ore, which occurs in the Kuruman Formation (Asbestos Hills Subgroup), a banded iron formation succession in the lower portion of the Griqualand West Supergroup, which is preserved along the western margin of the Kaapvaal craton (Eriksson *et al*, 2006). The objectives of the SIROLOG demonstration were to develop indicative calibrations and estimate the content of Fe, Al₂O₃, Ba, K₂O, P, S and SiO₂ in the test boreholes and to assess the accuracy of these derived estimates of grade in the light of mine-site requirements for production control and scheduling. In particular, an *in situ* assay technique that can provide timeous and accurate estimates of the so-called penalty elements, potassium (K) and phosphorous (P) would be of value.

The occurrence of these elements in the mined iron ore concentrate, have a detrimental effect on the steel-making process.

Calibrations were generated for each of the grade parameters above and results for Fe, Al₂O₃, P and K₂O are shown in Figure 6 (in the appendix). The geophysical data was composited to match the depth intervals of the assay data (generally 2m). Very good correlations (linear regression) between laboratory assay and PGNAA-derived grade were obtained for Fe and SiO₂ (R²>0.95). This is in line with previous published results from other sites (e.g. Borsaru *et al*, 2002; Charbucinski, 1993). The regression for Al₂O₃ is also very good (R² of 0.94). However, one of the spectral regions selected corresponds with the Fe-Al peak and therefore the calibration may be directly sensitive to Al. Without further work, the Al₂O₃ cannot be considered quantitative due to the uncertainty of the relationship between the spectral response and Al₂O₃ grade (Smith and Berry, 2005b).

The result for the important penalty elements is mixed. The regression for P (R²=0.77) is reasonable considering the relatively low concentration of this element and limited grade range in the test boreholes. This calibration could be improved with better constraints on the sampling and analysis procedure, as well as a larger and possibly more representative PGNAA dataset for calibration. The result from the test is considered semi-quantitative (Smith and Berry, 2005b). The calibration for K is poor (R²=0.477). The typical spectral response for K could not be matched with definite responses on the logged gamma ray spectrum (Smith and Berry, 2005b). Good correlation between assay and PGNAA grade was also observed for Ba and S (R²>0.74), although the low concentrations of these elements and limited grade ranges represented in the data affected the outcome.

Considering the relatively small test sample, the results obtained at Sishen mine are encouraging. Quantitative *in situ* determination of Fe grade and at least one of the important penalty elements is indicated.

Skorpion mine

Skorpion mine, located ~40 km north of the Orange River, the border between Namibia and South Africa, mines a zinc oxide ore body, the main ore minerals being sauconite (clay mineral), hemimorphite (silicate mineral) and smithsonite (carbonate mineral). The host rock is folded, metamorphosed arkose, interbedded with tuff and underlain by a non-mineralised limestone (Borg *et al*, 2003). The ore is accessed via an opencast pit.

A SIROLOG PGNAA trial was undertaken in November 2004. A total of 70 blast holes within the pit were surveyed using a 100 mm diameter PGNAA probe. The percussion-drilled blast holes were dry

throughout, nominally 152 mm in diameter and 11 m deep on average. The drill chips are sampled at 2.5 m intervals. The objective of the survey at Skorpion mine was to demonstrate the feasibility of the PGNAA technique for production control, in particular the ability to estimate the concentration of the Zn, Fe, Mn, Cu and Ca. The penalty element at Skorpion is Ca, which consumes acid in the treatment process to recover the Zn ore. Ca occurs in the limestone formations within the stratigraphy. Innovatively, the mine makes use of limestone to neutralize processed materials prior to disposal or storage.

Calibrations were generated for each of the grade parameters. Results for Zn, Fe and Ca are shown in Figure 7 (in the appendix). The calibrations were prepared for the entire length of the blast holes surveyed by the geophysicists. The 2.5 m assay data was composited and used to generate PGNAA-derived grade predictions for each blast hole. Very good correlations (linear regression) between assay and PGNAA-derived grade were obtained for Zn, Fe, Cu and Mn ($R^2 > 0.85$) and indicate the potential of the technology for grade control monitoring in blast holes at Skorpion. Typically, Ca may range from 0.1% to 30%. Unfortunately, the boreholes logged in the test contained very low percentages of Ca (<2%), which resulted in a poor Ca correlation (R^2 of 0.6), possibly due to the low range of grade values. Subsequently, an additional 7 blast holes in a high-Ca (10%-20%) part of the pit were surveyed. An R^2 of 0.94 was obtained for the linear regression of assay versus PGNAA grade, however the data sample is small (Smith and Berry 2005c). Further test work is required to establish the prediction of Ca content from PGNAA definitively, although the results for the test are encouraging.

Mantos Blancos

Mantos Blancos mine is located in Region II, 45 km from the city of Antofagasta, in Chile, and at 800 m above sea level. Successful SIROLOG field trials were undertaken at a number of Anglo American copper mines in Chile in December 2002, including work in production blast holes at Mantos Blancos (Charbucinski *et al*, 2004b). This work prompted the acquisition of a SIROLOG unit for these mines.

Figure 8 shows the Anglo American logging operation in a production blast hole and illustrates a number of important design features with regards safety and efficiency of operation. A portable winch, neutron source container, probe box and mechanically operated boom are mounted on the back of a standard utility vehicle commonly used on the mines. Movement of the winch and boom is remotely controlled and operated from a distance. There is no manual handling of the logging tool, except engaging and disengaging the neutron source, significantly improving radiological safety of the logging operation. This system also

reduces the amount of time necessary to commence and complete logging operations in short blast holes and one person can efficiently conduct the logging.



Figure 8: Design of SIROLOG logging system for on-mine operations, Chile

Building on the success of the PGNAA logging in production boreholes, a test was commissioned at Mantos Blancos to investigate the ability of the technique to deliver *in situ* Cu grade in the waste dumps (Smith *et al*, 2005). Forty-three waste dump boreholes were logged, which was considered sufficient to develop a calibration for Cu grade, if this is possible. Calibrations were generated at two waste dump sites, Canchas and Mercedes and are shown in Figure 9 (in the appendix). The calibrations were prepared for the entire length of the blast holes surveyed by the SIROLOG probe. Although a trend is indicated, the correlations between assay and PGNAA Cu grade are poor ($R^2 < 0.8$). This testifies to a limitation of currently available PGNAA technology for applications where the concentration of the target element is low and the range of grade values limited, as might be expected for waste dumps.

SUMMARY AND CONCLUSIONS

Due to the relatively deep penetration of neutrons and γ -rays, nuclear techniques offer certain benefits over conventional core and drill-cutting assay methods namely:

1. A much larger volume of the material surrounding the borehole is sampled than the sample taken for laboratory analysis, thus providing better sampling statistics.
2. The results are available in real time (provided a suitable calibration is established).

The SIROLOG Prompt Gamma Neutron Activation Analysis (or PGNAA) technique, developed by the CSIRO in Australia, allows the volumetric occurrence of certain elements in a bulk rock mass intersected by a borehole, to be directly estimated from the characteristic

energy of γ -rays for each element that result from the nuclear interactions of fast neutrons bombarding the formation. The PGNAA technique was tested on four Anglo American mining operations in diverse geological settings. The tests were designed to assess the potential for using PGNAA to estimate the concentrations of key ore minerals mined as well as so-called penalty elements that may influence down stream profitability during treatment and processing of the ore. A secondary objective was to obtain an estimate of the bulk *in situ* density of the formations.

The results demonstrate that the PGNAA technique can quantitatively predict the abundance of certain elements *in situ*. However, calibrations are difficult to establish where the abundance of the target element and the range of grade values are low, or the typical signature of the element overlaps that of another element. These problems can potentially be alleviated with higher resolution γ -ray detectors. New LaBr₃ (lanthanum bromide) detectors from Saint-Gobain (Saint-Gobain Crystals, off web) offer performance in a range approaching high purity germanium, without the necessity for complex support electronics and cooling. LaBr₃ detectors have superior resolution (<3%) compared with NaI (~6%) and BGO (~12%) at 662 keV and have the ability to operate up to the energy range of BGO (>10 MeV). The improvement in spectral separation over the equivalent BGO crystals is illustrated in Figure 10 (appendix). Better resolution means that the energy spectrum can be sampled more tightly (1024 channels instead of 480 channels), thereby also improving the discrimination of element responses.

A further drawback of downhole nuclear logging techniques is the hazard associated with the use of chemical radioactive sources in the borehole, in particular the risk of getting the probe and source stuck or lost down a borehole. While technical studies are able to indicate the potential of the methodology, the practical application will rest with the acceptance and management of the attendant risks, or the development of alternative, safe sources, such as neutron activation systems, currently being developed. Neutron activation systems use non-isotopic, switchable sources such as D-T neutron generators that can be switched off when not being used or if the probe is lost in a borehole. Other advantages of these systems include:

1. Measurement of other elements and parameters that are not easily available using Cf or Am-Be sources;
2. Measurement of the γ -rays resulting from inelastic scattering as well as delayed activation γ -rays, which will assist in resolving elements such as Al, as well as previously hard to get elements such as O and C.

Appropriate design of the Anglo American logging system in Chile demonstrates the practical and safe application of this downhole logging technique in a production environment on mines.

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REFERENCES

- Borg, G., Karner, K., Buxton, M., Armstrong, R., Van der Merwe, W., 2003, Geology of the Skorpion supergene zinc deposit, southern Namibia: *Economic Geology*, 98, 749-771.
- Borsaru, M., Rojc, A., Ronaszeki, J., Smith, C., 2002, The determination of Fe, Si, and Al content in Iron Ore Blast Holes by Nuclear Logging: Proceedings of the Iron Ore 2002 Conference, Perth, Australia.
- Borsaru, M., Berry, M., Bigg, M. and Rojc, A., 2004, In situ determination of sulphur in coal seams and overburden rock by PGNAA: *Nuclear Instruments and Methods in Physics Research B* 213 (2004), 530-534.
- Borsaru, M., Zhou, B., Aizawa, T., Karashima, H., Hashimoto, T., 2006, Automated lithology prediction from PGNAA and other geophysical logs: *Applied Radiation and Isotopes*, 64, 272-282.
- Eriksson, P.G., Altermann, W., Hartzler, F.J., 2006, The Transvaal Supergroup and its Precursors. In: *The Geology of South Africa* (Editors: M.R. Johnson, C.R. Anhaeusser and R.J. Thomas). Geological Society of South Africa, Johannesburg / Council for Geoscience, Pretoria, 237-259.
- Charbucinski, J., 1993, Comparison of spectrometric neutron-gamma and gamma-gamma techniques for in situ assaying for iron grade in large diameter production holes, *Nuclear Geophysics*, 7, 133-141
- Charbucinski, J., Malos, J., Rojc, A., Smith, C., 2003, Prompt gamma neutron activation analysis method and instrumentation for copper grade estimation in large diameter blast holes: *Applied Radiation and Isotopes*, 59, 197-203.
- Charbucinski, J., and Nichols, W., 2003, Application of spectrometric nuclear borehole logging for reserves estimation and mine planning at Callide coalfields open-cut mine: *Applied Energy*, 74, 313-322.
- Charbucinski, J., Duran, O., Freraut, R., Heresi, N., Pineyro, I., 2004a, The application of PGNAA borehole logging for copper grade estimation at Chuquicamata mine: *Applied Radiation and Isotopes*, 60, 771-777.
- Charbucinski, J., Webb, A., Berry, M., Rojc, A., Smith, C., 2004b, The application of Prompt Gamma Neutron Activation Analysis (PGNAA) Borehole Logging for Copper Grade estimation at Anglo American Copper Mines in Chile: Pacific Basin Nuclear Conference and Technology Exhibit, March 21-25, 2004, Honolulu, Hawaii.
- Rider, M., 1996, *The geological interpretation of well logs: 2nd edition*, Whittles Publishing, ISBN 1-870325-36-2.

- Smith, C.P. and Berry, M., 2005a, The Application of Spectrometric Borehole Logging for Exploration and Mining at Namakwa Sands Mine, South Africa, Final Report, February 2005 (Exploration and Mining Report No. P2004/69).
- Smith, C.P. and Berry, M., 2005b, The Application of Spectrometric Borehole Logging For Mining at Sishen Iron Mine, South Africa, Final Report, January 2005 (Exploration and Mining Report No. P2004/68).
- Smith, C. and Berry, M., 2005c, The Application of Spectrometric Borehole Logging For Mining at Skorpion Mine, Namibia, Final Report, February 2005 (Exploration and Mining Report No. P2004/70).
- Smith, C.P., Charbucinski, J., Borsaru, M. and Rojc, A., 2005, The calibration of Prompt Gamma Neutron Activation Analysis (PGNAA) Spectrometric Borehole Logging for Copper Grade Estimation in Waste Dumps at Mantos Blancos Mine, Chile, Final Report, December 2005, (Exploration and Mining Report P2005/450).
- Telford, W.M., Geldart, L.P., Sheriff, R.E., 1990, Applied Geophysics: 2nd Edition, Cambridge University Press.
- Trofimczyk, K.K., Du Plessis, S.J., Button, M., Esterhutte, J., 2005, Hard Layer Investigation at Namakwa Sands: In Proceedings of the 9th Biennial South African Geophysical Association Conference and Exhibition, September 2005, Cape Town, South Africa.

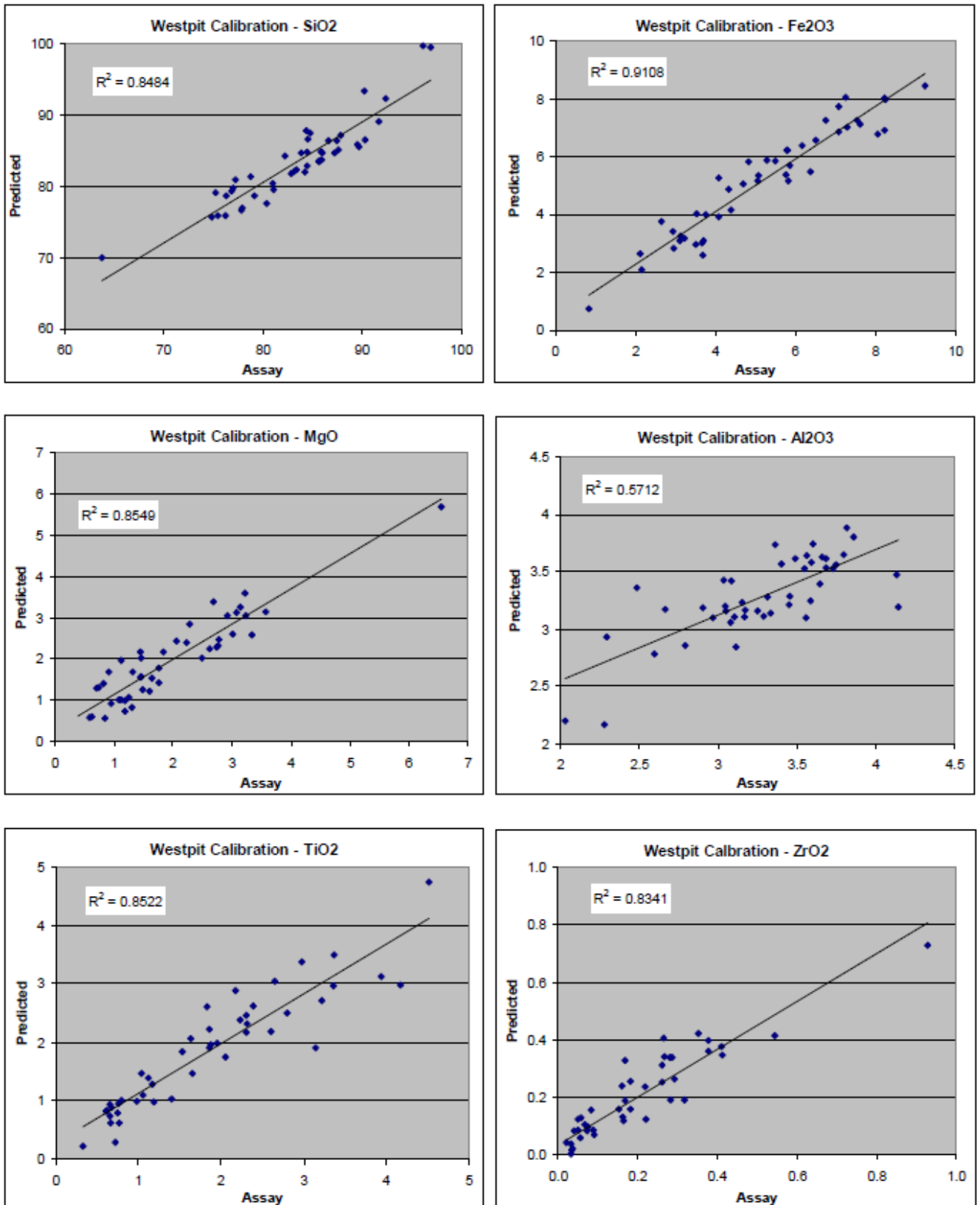


Figure 4: Correlation (linear regression) of SIROLOG PGNAA-predicted grade and assay (XRF) grade for SiO₂, Fe₂O₃, MgO, Al₂O₃, TiO₂ and ZrO₂, Namakwa Sands mine (from Smith and Berry, 2005a).

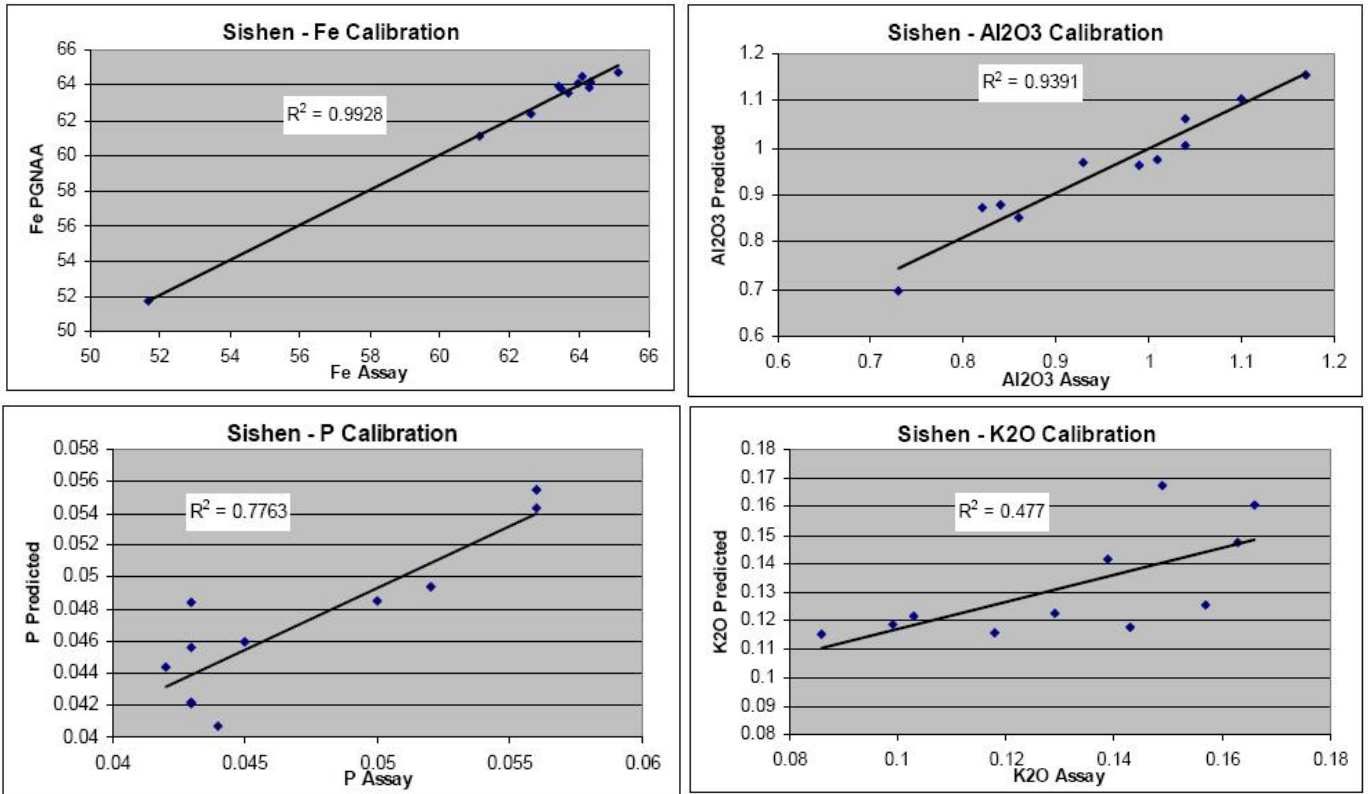


Figure 6: Correlation (linear regression) of SIROLOG PGNAA-predicted grade and assay grade for Fe, Al₂O₃, K₂O, and P, Sishen Iron Ore mine (from Smith and Berry, 2005b)

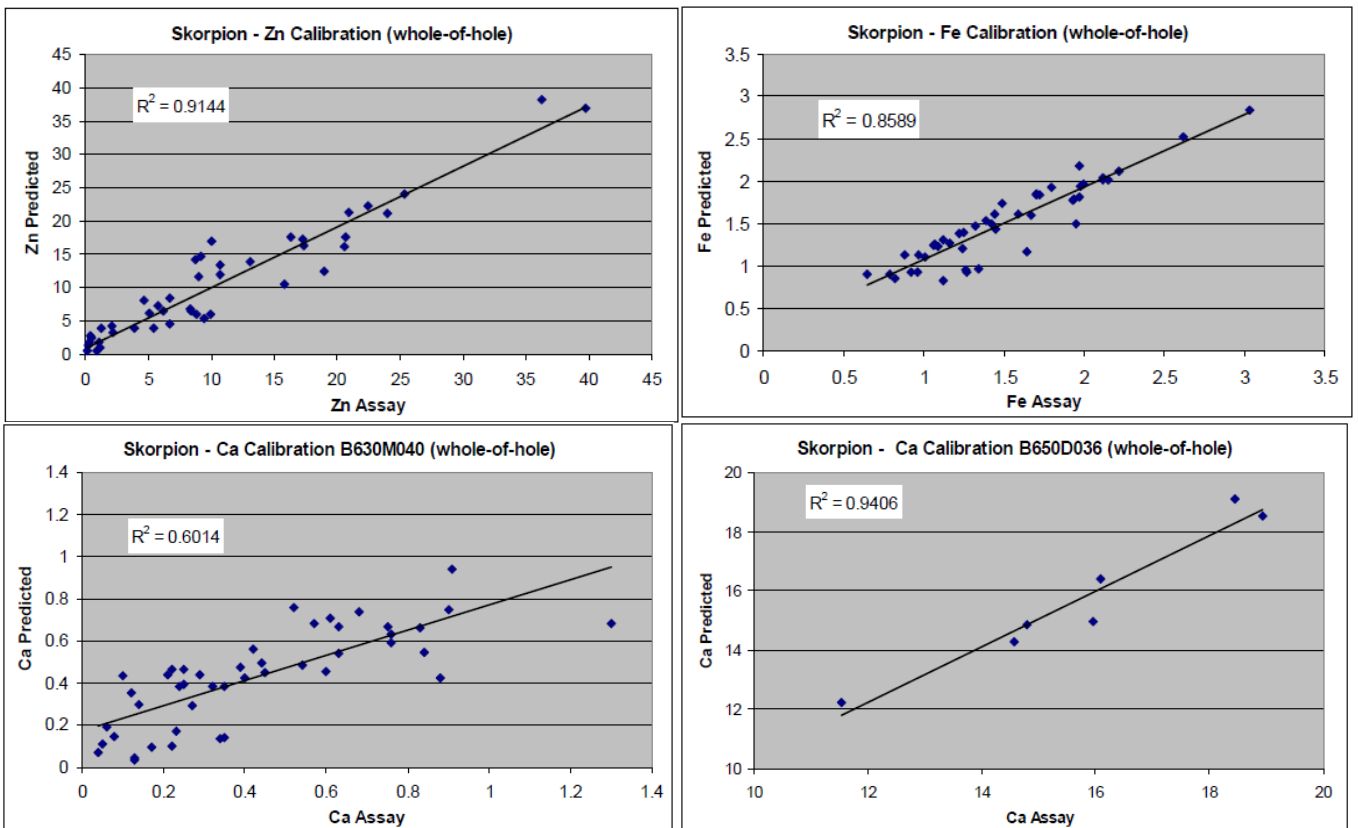


Figure 7: Correlation (linear regression) of SIROLOG PGNAA-predicted grade and assay grade for Zn, Fe, and Ca, Skorpion Zinc mine (from Smith and Berry, 2005c)

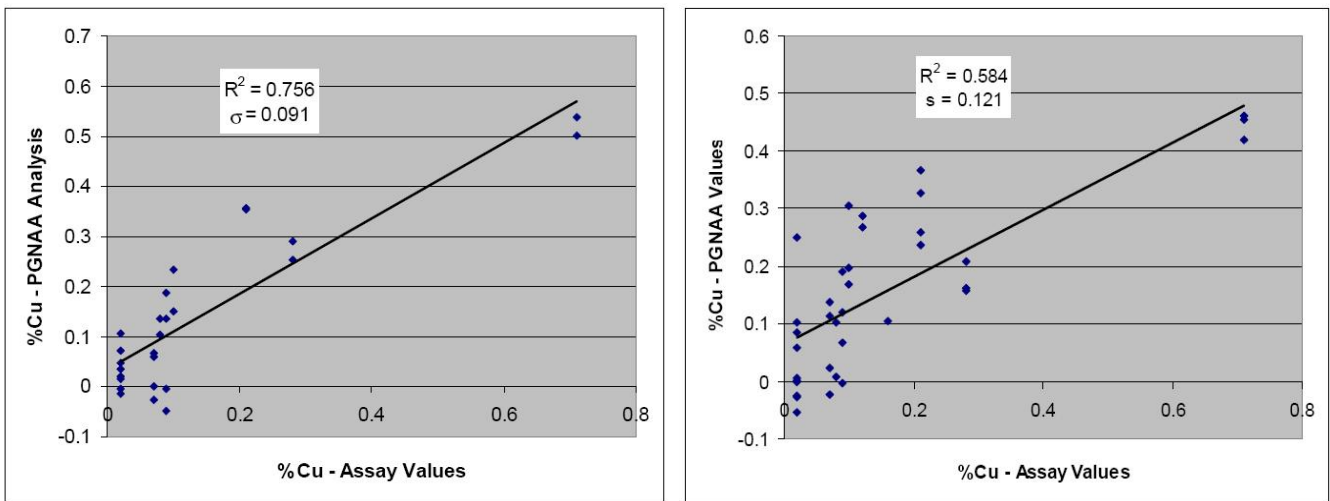


Figure 9: Correlation (linear regression) of SIROLOG PGNAA-predicted grade and assay grade for Cu from waste dump boreholes at Canchas (left) and Mercedes (right) sites, Mantos Blancos mine (from Smith *et al*, 2005)

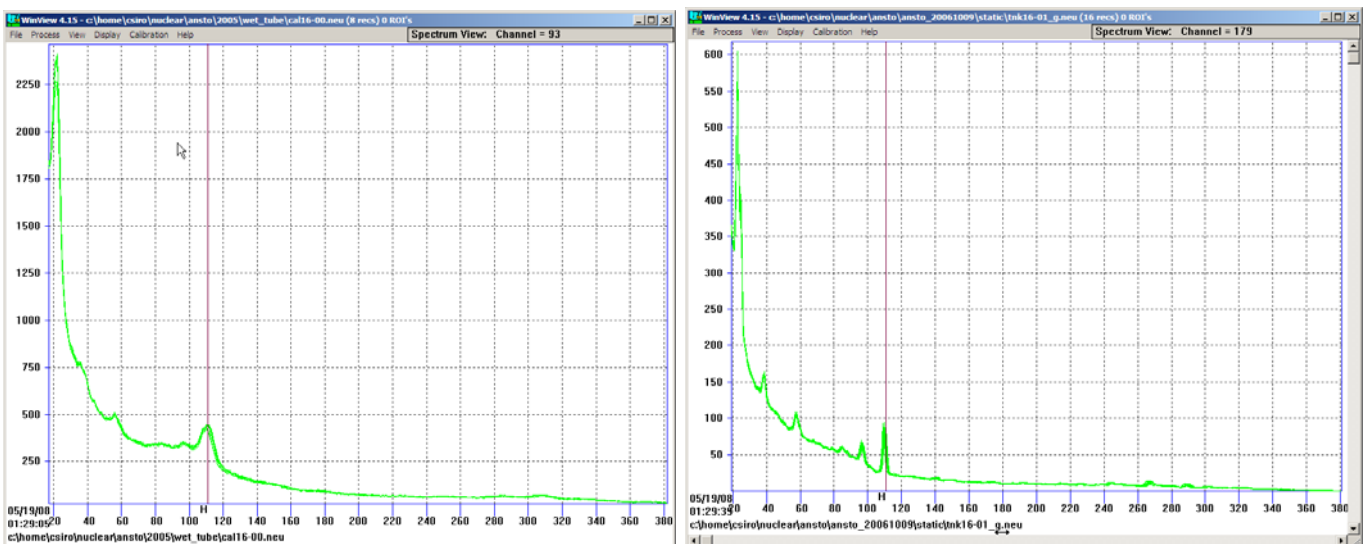


Figure 10: Comparison of spectral resolution between BGO detectors (left) and new LaBr3 detectors (right); the vertical axis is count rate (cps) and the horizontal axis is energy (represented by the channel number).