EXTENDING THE APPLICATION OF THE AMIRA P754 CODE OF PRACTICE FOR METAL ACCOUNTING

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Abstract

The primary objective of the AMIRA P754 project, 'Metal Accounting and Reconciliation', was to improve the auditability and transparency of Metal Accounting from mine to product and thus to assist in good corporate governance. The project was supported by five sponsoring companies in South Africa and Australia and involved three academic supervisors and seven students. Project areas had broad coverage from precious metals to commodities and from mine to product.

One of the major deliverables of the Project was the development of a Code of Practice for Metal Accounting for the Mining and Metallurgical Industry. The aim of the Code was to provide standard generic procedures and guidelines for obtaining credible figures of metal quantities processed and produced, and methods for obtaining a Metal Balance, and to be recognised and accepted as the Industry standard for best practice in this area.

Developing a code of practice has traditionally been the responsibility of professional bodies associated with particular industries – often on a voluntary basis. Given today's industry pressures, it was felt that funding key input might accelerate the development process as well as offer opportunities to research some of the problems and to train some post graduate students in a difficult discipline.

Since Release 2 of the Code and Guidelines was distributed in December 2005, followed by Release 3 in February 2007, the Code has been promoted through presentations and the publication of papers at a variety of conferences in South Africa, Australia and in the USA. Workshops to inform metal accounting practitioners about the application of the principles in the Code have been presented to most of the sponsoring companies as well as at a conference in Australia. Requests for copies of the Code have been received from mining companies, and from people providing services to these companies, in a wide range of countries on every continent. In addition, various members of the Code Development Team have been asked to conduct audits of various aspects of metal

accounting at a variety of operations ranging from base metals concentrators and smelting plants to precious metals refineries.

These audits have focussed, in particular, on the areas of sampling and analysis; mass measurement and stock takes; as well as data collection and handling and the preparation of metal accounting reports and the manner in which these feed into the operation's financial accounting reports. The experience gained during these audits has shown that the mining industry is becoming increasingly aware of the need for a Code of Practice to improve corporate governance, but that many operations are uninformed about the accuracy and precision of their metal production data, used to compile the financial reports, and of the need to ensure that mass measurement and sampling systems are correctly installed and maintained, and that sample management and analysis is well controlled. In this paper, some examples of successes and failures in the application of the Code are presented and briefly discussed.

1. Introduction

The 'AMIRA Metal Accounting Project' had its origin in a workshop held in Cape Town on 1 August 2001, with the title "Challenges in Metal Accounting and Information Management", which was organised by the Western Cape Branch of the South African Institute of Mining and Metallurgy. This workshop identified the lack of an accepted set of standard procedures for metallurgical accounting as an industry-wide problem. Discussions which followed this workshop led to the initiation of the AMIRA Project P754, "Metal Accounting and Reconciliation", in 2003.

The primary objective of the project was to provide tools for improving the auditability and transparency of metal accounting from mine to product, and to facilitate good corporate governance. The planned deliverables of the project were a series of research projects into aspects of metal balancing in different types of metallurgical operations, a Code of Practice for Metal Accounting, and a textbook on the subject which could serve as a guide for metal accounting practitioners and students studying the topic. An additional planned deliverable was the training of a new variety of professional experts in metal accounting, through successful completion of the research projects. Researchers were engaged at the Universities of Cape Town, Queensland and Stellenbosch, under the leadership of Dr Rob Morrison of the Julius Kruttschnitt Minerals Research Centre (JKMRC) at the University of Queensland, and the project was sponsored by five mining companies, including three of the largest global mining groups. Three of the university research projects have already been completed. Three students have been awarded masters degrees, and two have been awarded doctorates. The remaining projects should be completed during 2009.

The intention of the text book is to encapsulate the outcomes of the various research projects, as well as relevant portions of the Code of Practice, for use by plant level and specialist metal accounting metallurgists, consultants and academics. The book, edited by Dr Rob Morrison, has been written with funding from the sponsor companies, who placed bulk advance orders for copies, and underwritten by the JKMRC, where the book was published during the first half of 2009 and is available from the JKMRC and the SAIMM.

2. The Code of Practice

2.1 Development of the Code of Practice

In parallel with the research program, AMIRA established a team to compile the Code of Practice as a further deliverable in terms of the Metal Accounting Project. The team assembled in September 2004 and throughout the next 15 months, met regularly, usually twice per month, and held report-back meetings with the project sponsors and the members of the research team every three months. These report-back meetings were periodically preceded by a review meeting with members of the South African Accounting Profession who provided valuable insights into the problems they face in auditing metallurgical accounting figures for client mining companies. The team was also represented at monthly project steering committee meetings attended by representatives of the sponsor companies and of AMIRA.

Contributions to the Code were provided by the sponsor companies as well as by a number of companies who had not sponsored the Metal Accounting Project but who, nevertheless, were interested in the development of a code of practice as an industry standard. Contributions were also provided by the researchers and by specialist equipment suppliers, particularly in the mass measurement field.

With all the input and contributions to the Code, it expanded in size from the originally expected 30 pages to more than 100 pages within the first six months of the development program. The sponsors requested that the document being developed should be split into a brief 'Code of Practice' and a set of Guidelines to serve as a back-up to the Code. This was done and the first release of the draft Code and Guidelines was made to project sponsors in October 2005. This release was extensively and critically reviewed by an expert in sampling theory and, on the basis of his review, sections of the Guidelines were modified before Release 2 of the Code and Guidelines was issued in December 2005, to project sponsor companies and other interested parties, including experts in the field of sampling and a number of companies in the mining industry. During 2006, the Code and Guidelines were subjected to a professional editing process and were modified to incorporate comments received from companies using the Code and from a number of international experts in the fields of sampling and statistics. Following this process, Release 3 of the Code and Guidelines was issued during February 2007. Copies of this release have been distributed to a large number of companies and individuals on every continent around the world and feedback on the Code, received from some of these recipients, will be incorporated into Release 4, due to be circulated in mid-2009.

2.2 Principles of Metal Accounting

There are common problems experienced by all those involved with the metal accounting process, including the lack of a standard metal accounting procedure; the fact that it is often seen as ancillary to satisfactory plant operation and is, therefore, handled by junior, inexperienced technical graduates, or by clerical staff with no technical background; a lack of awareness of and attention to the precision of mass measurement, sampling and analysis; the use of inconsistent methods for the calculation of metal recoveries and the measurement and reporting of metal lock-up figures. There is also the potential for the manipulation of accounting figures and the possibility that members of the company's board and senior management may be uninformed about the accuracy and reliability of figures reported to them, and then used to generate the financial accounts and ultimately reported to the company's shareholders.

To address these problems, the Code is based on a set of 10 Principles of Metal Accounting which were agreed by the development team in consultation with the Accounting Profession and the sponsors of the project and which are summarised below.

1. The metal accounting system must be based on accurate measurements of mass and metal content. It must be based on a full Check in-Check out system using the Best Practices as defined in the Code, to produce an on-going metal/commodity balance for the operation. The system must be integrated with management information systems, providing a one-way transfer of information to these systems as required.

2. The system must be consistent and transparent and the source of all input data to the system must be clear and understood by all users of the system. The design and specification of the system must incorporate the outcomes of a risk assessment of all aspects of the metal accounting process.

3. The accounting procedures must be well documented and user friendly for easy application by plant personnel, to avoid the system becoming dependent on one person, and must incorporate clear controls and audit trails. Calculation procedures must be in line with the requirements set out in the Code and consistent at all times with clear rules for handling the data.

4. The system must be subject to regular internal and external audits and reviews as specified in the relevant sections of the Code to ensure compliance with all aspects of the defined procedures. These reviews must include assessments of the associated risks and recommendations for their mitigation, when the agreed risk is exceeded.

5. Accounting results must be made available timeously, to meet operational reporting needs, including the provision of information for other management information systems, and to facilitate corrective action or investigation. A detailed report must be issued on each investigation, together with management's response to rectify the problem. When completed, the plan and resulting action must be signed-off by the Competent Person.

6. Where provisional data has to be used to meet reporting deadlines, such as at month ends when analytical turn-around times could prevent the prompt issuing of the monthly report, clear procedures and levels of authorisation for the subsequent replacement of the provisional data with actual data must be defined. Where rogue data is detected, such as incorrect data transfer or identified malfunction of equipment, the procedures to be followed, together with the levels of authorisation must be in place.

7. The system must generate sufficient data to allow for data verification, the handling of metal/commodity transfers, the reconciliation of metal/commodity balances, and the measurement of accuracies and error detection, which should not show any consistent bias. Measurement and computational procedures must be free of a defined critical level of bias.

8. Target accuracies for the mass measurements and the sampling and analyses must be identified for each input and output stream used for accounting purposes. The actual accuracies for metal recoveries, based on the actual accuracies, as determined by statistical analysis, of the raw data, achieved over a company's reporting period must be stated in the report to the Company's Audit Committee. Should these show a bias that the Company considers material to its results, the fact must be reported to shareholders.

9. In-process inventory figures must be verified by physical stock-takes at prescribed intervals, at least annually, and procedures and authority levels for stock adjustments and the treatment of unaccounted losses or gains must be clearly defined.

10. The metal accounting system must ensure that every effort is made to identify any bias that may occur, as rapidly as possible, and eliminate or reduce to an acceptable level the source of bias from all measurement, sampling and analytical procedures, when the source is identified.

2.3 Code Philosophy

The basic philosophy behind the Code is that it prescribes standards and best practices for mass measurement, sampling, sample preparation, analysis, data management and metal balancing to enable compliance with the basic principles. However, where an operation cannot comply with these prescribed standards an exception report must be prepared, setting out the reasons for non-compliance (cost, risk, etc). The exception report must be signed off by a competent person and submitted to the Company's Audit Committee for approval. In this way, decisions related to metal accounting, which could have a significant impact on the company's reported results and on its metallurgical efficiencies, are brought to the attention of senior management and, where appropriate, to the board of directors. Such decisions are therefore handled in a transparent manner, subject to review by the company's financial auditors, and incorporate a formal review of the risks associated with non-compliance with the Code.

2.4 Competent Person

The Code makes provision for a 'Competent Person', who must be a member of the relevant local professional registration authority, or any other statutory local or international body that is recognised by the relevant Code administrators, and the person should have a minimum of five years experience relevant to the type of metal or mineral under consideration and to the type of operation involved.

The specific requirements for the work performed by the Competent Person are that he must:

- be formally appointed by the management of the company or the operation concerned, to recommend standards for the setting-up and auditing of Metal Accounting reporting systems
- accept responsibility for the final approval of the design of the Metal Accounting systems
- be responsible for auditing the system once it has been installed, to assess compliance with the design specifications
- conduct periodic reviews and audits of the system, at pre-determined intervals, to ensure continued compliance and, as required, to investigate problems which may occur

- submit reports to management in regard to the compliance of the system and monitor the action plans periodically produced to remedy faults

The Competent Person must be independent from the operation concerned and for large and/or complex operations, the Competent Person is likely to lead a small team of experts. However, only the Competent Person will have sign off responsibility.

The structure of the Code is best illustrated by the diagram in Figure 1 which shows the Metal Accounting Guidelines Document which informs the Code of Practice and which is supported by

the 10 principles of metal accounting, data collection and management systems and the use of the exception report and the competent person.

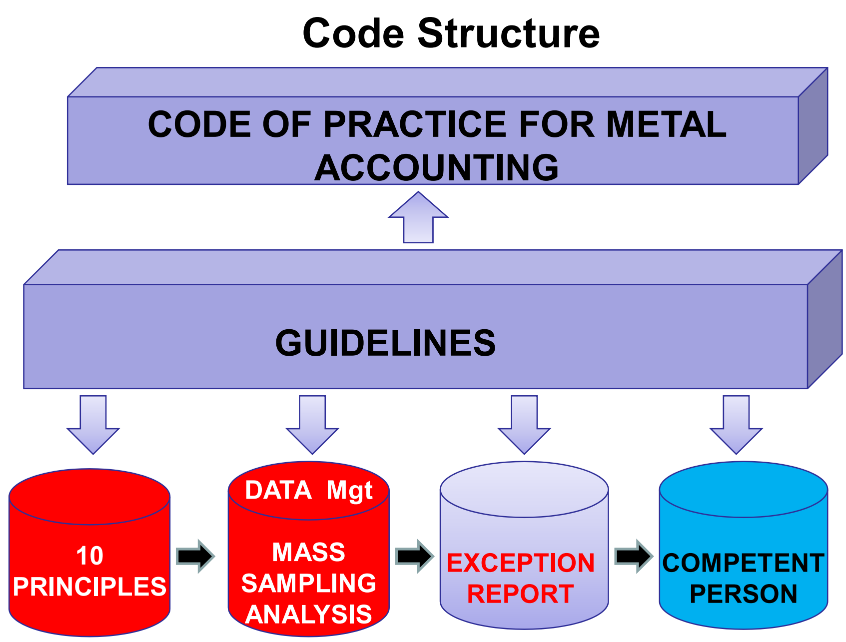

Figure 1: Code Structure

2.5 Outline of Code Contents

The Code contains an introductory section which covers safety and health, the principles referred to above, standards, traceability, accuracy and precision, error types, metal accounting risk and training. Subsequent sections deal with data management; mass measurement; sampling, including the statistical basis of sampling theory and sampling system accuracy; sample preparation and analysis; stock-takes, metal balancing, reporting, selection and use of the competent person, the design of metal accounting systems and metal accounting auditing rules.

The largest single section in the Code and Guidelines is Section 7, covering Metal Balancing. Topics in this section include an introduction, a discussion of the metal accounting process, and metal balancing, including definitions of 'recovery' and 'accountability' and suggested strategies for metal balancing, and reconciliation of metal balances, including sub-sections on detecting random error, bias, and flow rate accuracy. Metal balancing and accounting applications in concentrators, coal treatment plants, pyrometallurgical plants, and hydrometallurgical plants are discussed, as well as in heap leaching operations and in bench scale and pilot and demonstration plants. The section concludes with a discussion of metal balancing for environmental and health monitoring.

The Guidelines also contain a glossary of terms used in mass measurement, sampling, analysis and in other aspects of metal accounting. These are followed by lists of applicable references and standards, by a series of check lists for various operations related to metal accounting, and by copies of several technical papers describing mass balancing techniques, the determination of the sampling constant, and error and variance propagation in smelting operations.

2.6 Current status of the Code

One of the aims of the sponsor companies in promoting the development of the Code was that it should become recognised internationally as an industry standard, in a similar manner to other codes, such as the SAMREC and JORC Codes, for ore reserve estimation and reporting. To this end, the sponsors have asked AMIRA International to set up an international steering committee to administer the Code and Guidelines and maintain them as living documents and a standard practice for metal accounting in the global mining industry. It is envisaged that the international steering committee will be supported by regional committees, established with the assistance of the appropriate professional societies in countries where the Code is used.

Since Release 2 of the Code and Guidelines was distributed in December 2005, followed by Release 3 in February 2007, the Code has been promoted through presentations and the publication of papers at a variety of conferences in South Africa, Australia and in the USA. Workshops to inform metal accounting practitioners about the application of the principles in the Code have been presented to most of the sponsoring companies as well as at a conference in Australia. Requests for copies of the Code have been received from mining companies, and from people providing services to these companies, in a wide range of countries on every continent. In addition, various members of the Code Development Team have been asked to conduct audits of various aspects of metal accounting at a variety of operations ranging from base metals concentrators and smelting plants to precious metals refineries. The ensuing sections of this paper discuss some of the more significant learning points identified during these audits.

3. Mass Measurement

The overriding objective of mass measurement for Metal Accounting purposes is to establish the mass of the particular material or component present at a specific time, or the mass flow of that component over a defined time period, to a defined accuracy suitable for metal balancing.

Materials often contain moisture the proportion of which must also be established in order to obtain the dry mass. They may also have to be measured as a volume or mass/mass flow of slurry in tanks or conduits, or in stockpiles or storage areas, in which case the relative density must be measured. Both the density and moisture measurement often introduce significant errors in the calculation of the mass of dry solids.

Primary Accounting is defined as accounting for the Metal Balance across an entire plant. Thus the plant is treated as a black box with Primary Accounting applying to only the entry and exit streams. In the case of a concentrator, therefore, assuming that there is no process step such as gravity separation and that all intermediates or products such as crusher fines, belt washings, spillage etc. are recycled internally to the plant, the Primary Accounting streams will be the feed from the mines or other sources, concentrate product(s) and tailings. These streams, being the most critical, have the most stringent requirements such as certified (assized) weighing equipment, if possible, and the ability to establish the distribution of the random errors associated with the measurements.

Based on the ten principles detailed above and the Best Practice outlined in the Code and Guidelines, the essentials for any mass measurement system to achieve reliable results for Primary metal accounting are:

- Selection of the most suitable stream and location for measurement (Principle1)
- Correct specifications and selection of the method and equipment to suit the application (Principle 1)
- Optimum design, location and installation to permit measurement and calibration by recognised techniques (Principles 1 and 2)

- Regular calibration by approved techniques and procedures and certification in the case of custody transfer applications (Principles 3 and 4)
- Record keeping and logging of all calibration results, corrections and readings, to facilitate error detection and statistical analysis to enable the accuracy/precision of the measurement to be calculated (Principles 7, 8 and 10)
- Cleanliness, good housekeeping and maintenance

Whereas certain requirements of the Code with respect to mass measurement, such as Check-in Check-out, may be difficult or expensive to achieve and present practical problems (for example the measurement of tailings mass flow), especially with older plants, there are many areas which are totally under the control of day to day plant management where improvements can be easily implemented, and where controls and procedures have been found to be lacking.

In most cases, in metallurgical plants, the mass measurements for metal accounting are carried out using:

- Platform Scales and Weighbridges
- Conveyor Belt Weighers
- Weigh Tanks, Bins or Hoppers
- Magnetic Flow Meters in conjunction with Density Meters

The sections below highlight the most common problem areas and learning points that have been observed during the surveys/audits of various plants applicable to the mass measurement methods listed above. Most of these plants were aware of the Code and had, in principle, agreed to implement it, however in no cases were the Principles and Best Practice fully applied.

The problems have been classified into the following headings:

- Design and Equipment Selection
- Certification and Calibration
- Record keeping
- Plant Management and Housekeeping

Whereas, rectifying problems for items under the first heading in existing plants will probably require modifications to adhere to the Code and the second will be more difficult or require changes, if the facilities do not permit calibration by the approved techniques, the third and fourth areas are totally in the control of plant management and can easily be remedied. It is thus very disappointing to observe cases where the equipment is adequate and yet procedures are faulty or are not followed.

3.1 Design and Equipment Selection

The most common problem observed was in the design, layout and location of the conveyor belt weighers used to measure the ore delivered to the plant. Invariably the belt weighers, which in themselves may be capable of an accuracy suitable for metal accounting, are located on a long steeply inclined conveyor belt often with intermittent and highly variable feed and moisture content and with no facilities (such as weigh bins or diversion chutes) to conduct dynamic material run calibrations or even dynamic chain calibration, as required by Best Practice. The same applies to a slightly lesser extent to the measurement of the ore feed to the mills, although if there are crushing stages, the ore mass flow and size distribution is more uniform and thus more suitable for accurate mass measurement. It is apparent that very little thought went into the design of the mass measurement during the initial plant construction and belt weighers often appear to be added as an afterthought. Whilst this may be understandable in older plants, the same has been observed in plants built in the last few years. Considering that these measurements provide the metal accounting mass input, sometimes from multiple sources including toll material, it is most disappointing that only in a few cases was the Primary Accounting mass measurement system adequate and that some of these were then compromised by poor calibration procedures or maintenance.

Similar comments apply in cases where mass flow and density meters are used to measure slurry flows. In some cases, basic installation requirements were not adhered to and in none of the observed applications were there facilities (such as weigh tanks) to calibrate the meters utilizing the material being measured. Thus values obtained could be 10-20% in error.

3.2 Certification and Calibration

In the audits conducted to date, no applications have yet been observed where the belt weighers have been certified (although this is practiced in the coal and iron ore industries) and very few material run (bulk) tests are carried out. This is hardly surprising because, if the design does not facilitate this, the conduct of such tests is time consuming and requires very careful supervision to obtain any meaningful results. The same is true of mass flow and density meters. None of the plants audited to date had weigh bins or calibration tanks in order to perform the material tests. In some cases all calibrations and checks were conducted in-house and outside independent organizations were not utilized periodically, as required by Best Practice.

Calibration techniques for belt weighers that have been observed are highly variable and unfortunately their results and use for determining the accuracy of metal accounting mass measurements are often compromised by some or all of the following factors:

- Correcting on every occasion for as-found errors with or without recording these, even if these are random and within the accuracy of the system

- Calibrating at an insufficient frequency or with incorrect or non standard procedures or for an insufficient operating duration
- Not checking the belt speed adequately
- Calibrating with spillage on the weighbridge or platform or with water on the belt
- Poor belt condition or belt tracking
- Jammed, eccentric or misaligned weigh idlers
- Utilising dirty, corroded, or unchecked and uncertified test weights
- Utilising static calibrations only
- Utilising electronic calibrations only

With the modern electronic integrators utilized on belt weighers, calibration utilizing the software supplied, by simply pressing a series of buttons, is sometimes the only method used for calibration, in some cases with little understanding of the fundamentals.

In the case of platform scales or weighbridges the situation is much better as these are usually certified by outside officially recognised bodies using traceable certified weights at annual or biannual intervals. However, the checks conducted internally between these external audits are often infrequent, not conducted in terms of standard procedures and utilize weights which have not been checked for many years. Weigh hoppers, bin or tanks are seldom calibrated using test weights and if the measured material is a slurry the calculation of the dry mass is suspect, as the relative density of the components is not checked.

3.3 Record Keeping

The Code requires that all calibrations and checks are fully transparent. In many cases, the records are not readily available, the as-found values are not recorded, and corrections are carried out without being recorded. Results are not trended in order to check for problems and detect bias and in very few cases is there any assessment of the applicable tolerance to be applied to the mass measurement.

3.4 Plant Management and Housekeeping

In most cases, the calibration and certification is the responsibility of the Instrument Department, the operation and day to day readings that of the Process Department and the results of the mass measurement are utilized by the metal accountants. This split of duties is obviously not ideal as no one person has the overall responsibly. Thus, factors such as spillage on the weighbridge or scale platform, poor belt conditions, damaged weigh idlers, dirty or corroded test weights, inadequate maintenance and non adherence to operating and calibration procedures were frequently observed.

3.5 Moisture Measurement

Meaningful moisture measurements are seldom taken, as the moisture samples are often taken at a point separate from the location of the mass measurement, and are not representative of the material, especially on a conveyor belt or from a bin or stockpile. In some cases "historical" values are assumed. This can easily introduce errors of 1-2% in the dry mass, even for relatively dry material on conveyor belts and much higher values in the case of stockpiles.

3.6 Density Measurement

Where volume is measured, such as by electromagnetic flow meters or the volume in stocks or tanks, the density of the material must be determined to calculate the mass of the solid component. Experience from plant audits shows this to be a significant source of error as a result of the following factors:

- Bulk densities utilised are assumed, and constant, independent of the particle size, degree of compression or age of the material
- Densities of the solid and liquid components of a slurry are assumed (with that of the water, which is usually recycled process water, assumed as 1,00)
- Density meters are not calibrated on the material being measured

3.7 Measurement of Stocks

As highlighted in the Code, the mass measurement of stockpiles, bins etc are impossible with any level of accuracy because of the variations in moisture content and bulk density. It is common to assume the latter two figures, often based on some long standing values, the sources of which are usually not available.

4. Sampling, Sampling Management and Analysis

4.1 Sampling

As indicated in the Code, the major requirements to ensure unbiased sampling with an acceptable level of precision are that the sampling systems must be correctly designed, installed and maintained. Recent audits of metallurgical plants have shown that it is rare for any of these requirements to be met.

The two most common faults in terms of correct design are: -

- Rotary samplers being fitted with non-radial cutter blades. In most instances the blades are parallel, but there has been one example where the blades were radial in the wrong direction i.e. from the outside of the circle inwards rather than from the centre out

- The maximum speed of a cross stream sampler of 0,6m/s is often exceeded, sometimes by factors of over 3

In terms of installation, it is in the lack of thought given to the presentation of the plant stream to the sample cutter: -

- With cross stream cutters, no allowance is made for the interaction of the cutter head with the process stream. This results in the stream being partially diverted below the cutter and, therefore, not all of it being sampled; or there have been instances when a large part of the stream was diverted into the sample launder

- Often with rotary samplers, the end of the input pipe is too far from the cutter blades and the invariable flaring of the process stream as it leaves the pipe results in a portion of the stream not being sampled

In terms of maintenance, it is absolutely vital that samplers be inspected and cleaned on at least a shift basis. This of course means that it must be possible for staff to safely inspect all plant samplers, which is often not the case, and facilities must be available to easily clean the samplers.

A further common fault of sampling installations is the distance between the sample bucket and the sample preparation facility. The possibility that a portion of the sample will be discarded at the sampling point is directly proportional to the square of the distance the bucket must be carried, especially at 02:00 and if the bucket is not at ground level.

Many mining companies are transporting filtered flotation concentrates, and other plant products, between their own operations or to third parties, by road and rail trucks. The possibility of manually sampling these, with tube samplers or taking a grab sample, and obtaining a representative sample is zero. Yet these are exactly the sampling systems a lot of companies have in place. A minimum requirement is a mechanical auger system that is designed to take representative samples across the surface area of the material and through its entire depth.

4.2 Sample Management

Samples must always be labeled with an unambiguous ID, bar-coding is recommended, and stored in a container from which none of the sample, including moisture, can be lost. This is often not the case and there are examples where material, on which moisture is an important measurement, is stored in open containers for 8 hours in ambient temperatures above 40^0C. The moisture analysis on such a sample will be biased low, resulting in a high bias on the dry tonnes determination. Poor packaging often results in cross-contamination between samples. In addition, loss of sample, especially fines which invariably have a different grade from the bulk of the sample, will bias the analysis.

Samples must be dried under controlled conditions at temperatures of <105^{0}C to avoid chemical changes to the material e.g. oxidation of sulphides. Coal samples are usually dried at ambient temperatures.

The use of vertical spindle pulverisers in the sample preparation of materials is tending to be phased out in favour of closed mill systems such as LM2 mills. This is due to the tendency of spindle pulverisers to have uncontrolled loss of sample and the potential of cross-contamination due to smearing of malleable material on the pulveriser plates.

4.3 Analysis

There must be a detailed Analytical Protocol covering all samples received by the Laboratory. This must include: -

- Clearly defined custody transfer points
- Analysis required
- Analytical Methods
- Full calibration details
- QA procedures
- Turn around time

On-mine laboratories rarely have such protocols available. Few laboratories follow best practice in terms of their calibration of analytical instruments. The recommended minimum number of standards is 7, including a Blank, and this number is rarely met. The standards must be closely matrix matched to the samples and the concentration of the samples should be around the centre of the calibration range. These requirements are again often ignored.

5. Mass Balancing and Reconciliation

5.1 Introduction

It is worth making clear at the outset that mass balancing for metal accounting is not the same as mass balancing of – say - a flotation circuit survey even though similar mathematical tools may be used. Blindly applying a standard mass balancing package is an effective way of concealing bias. Bias is the enemy of balancing and reconciliation for metal accounting.

5.2 Objectives

As noted in Section 2, the Code recommends a full Check in, Check out methodology at each transfer of custody. Therefore, any mass balancing technique must be compatible with Check in Check out (CI/CO). Perhaps the most valuable aspect of a sound mass balance is that it can be used as a go/no go test for each CI/CO transfer.

This satisfies the first objective. Another way to phrase this objective is "Is there a significant discrepancy or are the variations within expected measurement error at some agreed level of confidence?"

The second objective is to pinpoint any measurement problems or biases as quickly as possible. These problems should be rectified as quickly as possible – not allegedly "corrected" by the balancing process.

5.3 Formulating the problem

To set up the mass balancing problem to suit metal accounting and reconciliation, we require a sound knowledge of error distributions in data measurement. All measurement processes - be they instrument readings, sampling and assay measurements or any other kind - are subject to statistical error. We also need to define two useful concepts:

- A measurement is "accurate" if it is sufficiently close to an accepted standard. A good example is the process of certifying a weighbridge or scale for commercial use – a classical example of a custody transfer. A certified mass measurement device usually provides a key input to a CI/CO transfer of value

- A measurement is "precise" if it gives very similar results when repeated. If a precise measurement is not close to the result which is accepted as accurate then we have a bias. A small bias is not a problem in a short term experiment such as a flotation survey. However, where key results are accumulated over many measurement periods a small bias will accumulate and cause problems with reconciliation and achieving fair CI/CO transfers Figure 2 summarises these concepts

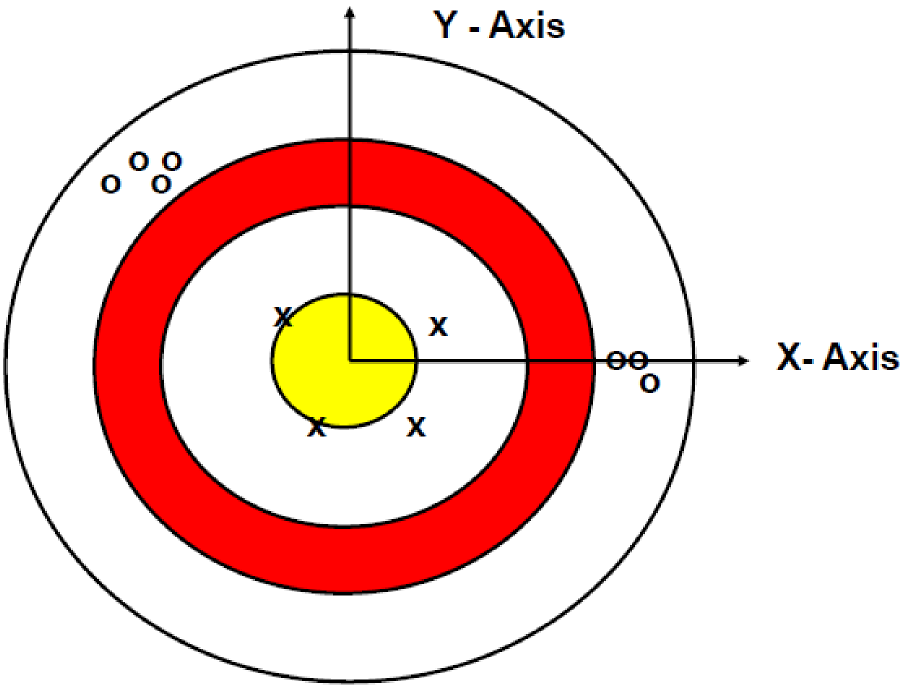

Figure 2: Accuracy and bias – the x's are accurate but not very precise! The small circles are less accurate and more precise but exhibit bias in X alone or in both X and Y

One way to state the problem mathematically is to define an adjustment between each measured and balanced value. For n measurements, each of which has a counter value of i, an adjustment Delta can be defined as:

$$\Delta_i = x_i - \overline{x}_i \qquad (1)$$

where x_i is each measured value and $\overline{x}_i$ is an adjusted value of x_i

Each adjustment can be scaled by its measurement accuracy, estimated by its standard deviation σ_i or some other measure of dispersion. Note that the standard deviation in this case should include all of the measurement errors – including sampling, sample preparation and analysis, where appropriate.

Now we can define a mathematical criterion – the weighted sum of squares WSSQ – which can be minimised to estimate a "best" set of data adjustments.

$$WSSQ = \sum_i [\Delta_i / \sigma_i]^2 \text{ subject to } C[x_i] = 0 \quad (2)$$

where C is a matrix of constraints which must be satisfied to be consistent with the complete flowsheet. Note that the flowsheet in this case includes variations in holdup in bins, stockpiles or in the process circuit itself.

If the required adjustment delta i is small compared with the measured variable, then intuitively the required adjustment is not a "discrepancy" in CI/CO terms. For normally distributed measurement variation, we expect the required adjustment to be within plus or minus one sigma for about two thirds of the measurement and within plus or minus two sigma for about 95% of them. Hence adjustments of more than twice the standard deviation need to be carefully examined.

Bias is easy to include in this model but not so easy to detect.

$$\Delta_i = (x'_i + b_i) - \overline{x}_i \quad (3)$$

where b_i is a bias associated with measurement i and x'_i is the unbiased measurement. If b_i is small compared with the measurement, it is not detectable in a single data set. However, as each mass and metal content increment is accumulated, the expected relative error of each accumulated sum reduces by the inverse of the square root of the number of increments.

Hence, the bias becomes easier to detect and in many cases, impossible to ignore. A maximum of one bias at a time can be tested for as part of the least squares approach. Practical approaches to bias detection are considered in Section 5.6

5.4 Solving the problem

Equations 1 and 2 are a standard problem for constrained minimisation of the weighted sum of squares, provided reasonably accurate initial estimates are available. Mass balancing provides a reasonably linear problem and many simplifications are possible. The two product formula is the most venerable of these, but provides no information at all about self consistency. Standard techniques for error propagation can be used (Cutler and Eksteen, 2006). Where multiple components are measured the standard deviation of the mass split can be estimated. There are two ways to attack the general mass balancing problem. The first is to estimate mass splits based on assay differences. Appendix E of the Code of Practice provides an example. This is the traditional mass balancing approach. Although it can be extended to include process hold ups (Morrison and Richardson, 1991), it is not generally useful beyond the processing plant.

Most custody transfers occur into or out of separation plants rather than within them. The traditional approach was very attractive for hand calculation as it is very computationally efficient.

With computational power available from modern PCs, the second approach utilizing simulation has much to recommend it. The simulation approach is well suited to stream splitters which provide undefined mass splits as they should not generate assay differences. For the simulation approach each stream is considered in terms of volumetric flows, as well as of each metal and gangue of interest. Each process block (or node) is modelled as a set of splitters.

If each splitter is modelled in flowsheet order (with iterations as required for recycle streams), the constraints of Equation 2 become implicit i.e. they are automatically included. Hence, we only need to adjust the split factors and input flows. Constraining split factors between zero and one is also recommended. For a detailed description of both techniques see Chapters 6 and 7 of the monograph produced at the end of P754. (Morrison et al, 2008)

5.5 Reconciliation

The simulation approach is also well suited to reconciliation. The objective of reconciliation of metal accounts is to develop a set of data which is numerically consistent with the CI/CO values at its boundaries (for which the operation paid and/or was paid for) and the measured values within that scope.

This can be carried out in two steps:

> Step 1 – Carry out the balance and check that all values are within the expected ranges of error
>
> Step 2 – If step 1 is satisfied "fix" the CI/CO values and rerun the balance.

If the measured values are still within the expected ranges, we now have a fully consistent and statistically validated set of data suitable for generation of KPIs and reports. Note that a few values beyond plus or minus two standard deviations are expected.

5.6 Detecting bias

The traditional approach is to use cumulative sums (or "cusums") of the difference between metal flows (at any point in process chain) where they can be estimated by two more or less independent methods. Over time the differences should fluctuate about zero due to random error. A bias will cause a positive (or negative) accumulation and should be easy to detect.

For the mass balancing approach, it should be clear that any bias will become part of the data adjustments. If there is no bias, we expect the weighted adjustment to have an equal chance of being positive or negative. Even though, the bias will be distributed to some degree, the adjustments will tend to be predominantly positive (or negative) if a bias develops. Hence both cusums and weighted adjustments should be trended for early detection of bias.

5.7 Conclusions

Metal balancing and reconciliation techniques can be combined with the CI/CO approach – provided they are adapted to suit the special requirements of aligning commercial and technical estimation.

Simulation techniques are recommended for both metal balancing and reconciliation. However, at least some knowledge of the errors associated with each measurement (including sampling and assaying) is essential.

6 Data Handling and Reporting

An essential component of the entire metal accounting system is the generation of reports showing the outcomes of the metal accounting function and the performance of the operations in which the accounting took place. These reports provide information to all levels of operational management, from the operators and supervisors controlling the daily plant throughput to the senior management directing the planning and operation of the entire mineral extraction and recovery undertaking. The reports also provide vital information to the company's marketing organisation, facilitating the scheduling of dispatches of products and the negotiation of long and short-term sales contracts, and to the company's financial accounting department in the preparation of financial accounts for the reporting period concerned.

There are a number of ways of acquiring or entering information for use in a Metal Accounting System. Data may be acquired from various plant systems such as SCADA, Plant Historians, LIMS systems, etc. Manual entry of data to operator log sheets and transposition to spreadsheets is common practice on some plants, because of the ease with which spreadsheets can be used and adapted to specific process requirements. However, spreadsheets do not allow for controlled data entry and they are easily corrupted. It is easy to inadvertently type over data, lose track of records, or duplicate and improperly enter data in a spreadsheet. Further to this, the justification of formulae in spreadsheets often lacks clarity, and is not always recorded with the spreadsheet. Because of this, the justification can get lost, especially if the developer of the spreadsheet moves on, thereby making spreadsheets vulnerable to error and unjustified computations. For these reasons spreadsheets must be avoided as a method of data entry.

7 Typical Auditing Procedures

The auditing of a metallurgical operation to assess its compliance with the requirements of the AMIRA Code of Practice (Release 3) is not a trivial matter and will require hundreds of man-hours by a multi-disciplined team to achieve an acceptable result.

The scope of the various audits conducted to date, by the authors, has varied according to the requirements of the operation concerned. In several audits, only the mass measurement, sampling and analytical procedures have been reviewed.

However, in an audit of a base metals operation comprising a concentrator, a smelter and a base metal refinery, the audit team was asked to audit the metal accounting function over the entire operation. The 4-person audit team found that they needed two weeks on site to complete the physical audit, including an introductory session at which the scope of the audit was defined, a plant induction session and a meeting at the end of the site visit to provide immediate feedback to the senior management of the operation.

In this instance, one member of the audit team checked every mass measurement used for metal accounting purposes, on each of the separate plants, including inspections of the actual measurement procedures and the equipment used, as well as checking all the calibration procedures, both internal and external, and records of each item of mass measurement equipment.

A second team member checked every accounting sample taken on each plant, by inspecting the sampling equipment and schedules and the sample management procedures for delivering the accounting sample to the analytical laboratory, storing it on receipt at the laboratory and preparing the analytical sample. The existing analytical procedures were also reviewed against the prescribed procedures and compared with accepted best practice, while the laboratory as a whole was inspected and its records, calibration standards and procedures for preparing, storing and using them, were compared with prescribed and best practice. One team member was dedicated to an audit of the smelter plant, where metal accounting often presents a challenge. This part of the audit included a comparison of the physical stockpiles of concentrate, reverts, cast metal and furnace inventories against the book stocks. In addition, a complete review was conducted of the metal accounting records for the plant for each accounting period in the current year as well as the figures for several previous years.

The fourth member of the audit team audited the metal accounting records of all the individual plants and the way in which these individual accounting reports were used to compile the overall metal accounting report for the entire operation. Particular attention was paid to the handling of errors and correction of interim assay results, as well as the reconciliation of accounting figures at custody transfer points, the measurement of inventory figures, and the authority levels required for signing off the various reports. The way in which the overall accounting report informed the operation's financial accounting reports was also audited.

Following completion of the physical audit, the compilation of the audit report required a further week's work from each team member. The final audit report was approximately 100 pages in length, but this was condensed into a 10-page summary which identified and classified the risks associated with each area of non-compliance identified during the audit. This summary report was used by the management of the operation to monitor responses to the audit findings and served as a basis for a follow-up audit conducted one year later.

8 Conclusions

The AMIRA Code of Practice for Metal Accounting was developed in response to a need identified by the companies sponsoring the AMIRA P754 Metal Accounting Project. The favourable response received from people who have applied the Code to their own operations indicates that it does address a real need in the minerals industry.

In effect, the Code prescribes a metal accounting system based on the employment of a competent person to ensure that input data is correctly measured and prescribes the way in which the input data is handled and utilized. It also provides for an exception report to cover instances where, for whatever reason, the requirements of the Code cannot be met. The exception report has to be signed off by the competent person and submitted to the audit committee or board of the company concerned, so that they may be kept fully informed of any deviations from the requirements of the Code. Thus prescribed metal accounting system is illustrated in Figure 3 below which shows the structure of the system.

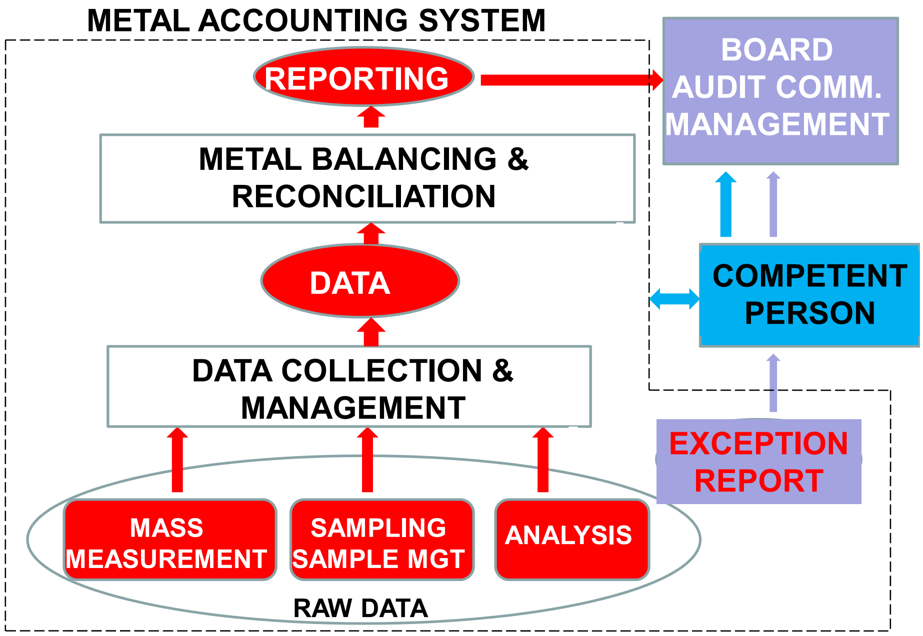

Figure 3: Metal Accounting System Structure

However, the Code can only be successfully applied if the input data to a metal accounting system is based on accurate measurements of mass and analysis of correctly taken and managed accounting samples. The input data, in turn, must be managed in a system which eliminates the possibility of data manipulation or alteration without appropriate authorization, ideally through automated data handling, which avoids possible transcription errors, to provide information to the senior management of an operation which is both consistent and reliable.

From initial experience gained in auditing operations to assess their compliance with the Code, compliance has generally been found to be poor, usually because of inadequate mass measurement and sampling, as a result of poor equipment specification, incorrect installation or deficient equipment maintenance. Data handling and control has also been found wanting in most operations visited. No operation audited to date has embraced the concept of the competent person to take responsibility for the entire metal accounting function, as envisaged in the Code. The engagement of such a person should do much to solve the problems identified in this paper and also to avoid wasted expenditure on poorly specified or installed equipment and on investigations into accounting problems which can be all too frequent in operations which have not adopted the basic principles of metal accounting.

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