THE APPLICATION OF CEET AND FLEET IN THE BASE METALS INDUSTRY: CURRENT STATUS AND FUTURE VISION
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ABSTRACT

In the design of mineral processing plants, a major challenge facing the project team is the identification and collection of a representative bulk sample for the metallurgical testwork program. Even when the bulk sample represents the overall ore body, it is costly to obtain. In addition, it often happens that ore characteristics changing during normal mining cycles create periods of significant variances in plant performance.

Traditionally, two solutions are used to cope with these variances in ore characteristics (hardness, feed size distribution, grade, mineralogy, etc.). The first is to incorporate large safety factors into the design or include additional unit operations, e.g. pebble crushing, to compensate for this unquantified variation. The second is to install blending facilities to eliminate the effect of short-term variations. In both of these instances capital and maintenance costs are increased in order to deal with the problem.

An alternative approach to these two traditional methods is presented. The paper covers the development of two powerful software tools: CEET (Comminution Economic Evaluation Tool) for Milling circuits and FLEET (Flotation Economic Evaluation Tool) for Flotation circuits. These are based on fundamental principles and a deep understanding of the breakage and flotation mechanisms.

Case-studies covering the application of CEET and FLEET in the mineral processing industry are included. The paper concludes with the vision for the future advances in this technology.

INTRODUCTION

Process modeling and equipment sizing procedures for mineral processing operations have advanced significantly over the past two decades. However, no matter how exact the bench-scale or pilot testwork, models and scale-up calculations, if the ore samples being used for design do not accurately represent the complete orebody then major design errors can be encountered.

In addition, many base metal operations experience wide swings in throughput and product quality, mainly attributed to variations in ore characteristics (hardness, feed size distribution, grade, mineralogy, etc.). These variations are almost always of a magnitude not anticipated in the plant design; consequently, they are detrimental to the expected return on investment for the mining companies.

It is widely acknowledged that these two factors pose some of the largest challenges in the design and operation of mineral processing plants. Traditional methods to accommodate these factors are capital, maintenance and labour-intensive:

- Large safety factors applied in the design and specification of equipment, leading to higher capital costs.
- Costly blending facilities installed to reduce the impact of short-term variability.
- The inclusion of additional equipment or operating steps to compensate for unquantified variations (for example, a pebble crushing step, optional steel addition to a primary AG mill, “spare” flotation cell(s), an additional or oversized concentrate filter, etc.)

Recognizing that this as a significant area for improvement in the mineral processing industry, MinnovEX Technologies Inc. - based in Toronto, Canada and with representation in Chile, Brazil, South Africa and Australia, has focused on these challenges over the past 9 years. This has led to the development of two leading technologies – CEET (Comminution Economic Evaluation Tool) for Milling circuits and FLEET (Flotation Economic Evaluation Tool) for Flotation circuits.
The CEET and FLEET technologies fundamentally differ from other design methods by their use of a data set that is a geostatistically significant population of grinding and flotation characteristics distributed across the mine block model.

The compression of 9 years of technology development into a single paper is impracticable. Instead, a summary of the fundamental make-up of the two technologies is given, together with an extensive list of other papers that can be referenced for more detail. The paper therefore focuses more on typical applications and case-studies which illustrate the relevance and power of the CEET and FLEET systems. The paper is concluded with a taste of the current focus, where CEET and FLEET are incorporated into a web interface called Process Access, and where the concepts will develop towards in the future.

**CEET TECHNOLOGY**

In 1993 MinnovEX Technologies undertook the research and development of the MinnovEX SPI (SAG Power Index) test using a 30 cm diameter SAG mill and a test procedure designed by John Starkey. The objective of the MinnovEX SPI test work was to provide design teams with an orebody profile of required SAG/AG power from hardness data.

The technical considerations and theory involved in the measurement of SAG hardness using the SPI Test are discussed in the paper by Starkey et al., 1994 (1).

The key parameters of the test are summarized below:

- **SAG Mill Size** - 30.5 cm (1 ft) diameter by 10.2 mm (4 inches) long
- **Steel Charge** - 2.5 cm (1 inch) diameter balls
- **Test Feed** - 2 kg of dry ore crushed to 80% passing 12.7 mm
- **Test Product Required** - 80% passing 10 mesh (1.7 mm)

The test procedure involves the dry grinding of the 2 kg of crushed ore (SAG feed or core sample) in a number of stages until the product is 80% passing 10 mesh (1.7 mm). The test is a batch test with the product returned to the mill after each stage. The test delivers the time (in minutes) required to achieve the specified size reduction.

The time determined in this test is, by analysis of first principles, a measure of the power used to create the constant size reduction. Field calibration data for the SPI Test proved that this time is directly proportional to plant SAG mill power when grinding to 10 mesh and that the relationship can be described by a straight line function.

The power of the MinnovEX SPI test is that a small sample of fist-sized ore or drill-core pieces (which represent primary crushed SAG feed) can be used to predict production scale SAG mill power requirements. The unique aspect, however, is that such a small, low-cost test is used. This immediately opens the opportunity to do multiple (in some cases, 100’s) of SPI tests on samples taken from across the orebody – giving an orebody profile of ore hardness and consequently, SAG power requirements.

A key reason for the scalability of the SPI Test to industrial scale SAG operations is that the breakage mechanisms that occur within the test mill include contributions from both abrasion and impact/nipping, as is the situation within industrial SAG mills. The test has been extensively calibrated to full scale mills through detailed benchmarking campaigns on large industrial mills; to date, more than 200 data sets have been generated at over 20 sites. The benchmarking calibration also has allowed for the quantification of the impact of in-circuit pebble crushing and finer feed size distributions. Calibration and verification of the test is provided in Starkey et al., 1996 (2) and in Benchmarking and Orebody Profiling – the Keys to Effective Production Forecasting and SAG Circuit Optimization, by Bennett et al., 2001 (3).

As mining companies started using and understanding the required power profiles it became clear that these profiles could be exploited to a much higher degree. Therefore, in 1998 the software tool CEET was jointly sponsored and developed by MinnovEX and 13 major mining companies for the purpose of designing and predicting the performance of grinding circuits.

The CEET software tool is composed of three primary components:

- A process model for the SAG circuit (the SPI energy relationship).
- A process model for the ball mill circuit (Bond’s relationship-modified).
- A data set of ore hardness.

CEET fundamentally differs from other design methods by its use of a data set that represents a geostatistically significant population of hardness data distributed across the mine block model.

In brief, CEET is used to:

- Select the optimum SAG - ball mill circuit for a given orebody – in Design Mode,
- Enable companies to carry out throughput production planning in a much more accurate manner than was done historically – in Production Planning Mode, and
- More accurately define ore reserve estimates by including throughput, grind size and comminution operating cost on each mining block – in Design and/or Production Planning Mode.

In addition to power selection, shell sizing, and costing for multiple circuit options, the program also outputs tons per hour, $P_{sp}$ and operating cost on every mining block for subsequent integration back into the block model.
The fundamental basis of the CEET and CEET2 systems is provided in operation along the processing route – flotation.

Across the whole resource, thereby accounting for variability across the orebody in the CEET philosophy – design of comminution circuits done on a block-by-block basis across the whole resource.

During the development of CEET, both MinnovEX and the partner companies identified areas in which the program could become an even stronger tool for comminution design and production forecasting. Three areas were identified, all focused on increasing information for individual mine blocks: (a) estimate of feed size distribution, (b) estimate of pebble crusher circulating load, and (c) improved estimate of size distribution of the SAG transfer material. The CEET2 programme, also sponsored by industrial partners, was therefore initiated to focus of these issues.

FLEET TECHNOLOGY

With the rapid acceptance and application within the mineral processing industry of the CEET philosophy – design of comminution circuits done on a block-by-block basis across the whole resource, thereby accounting for variability across the orebody in the design process – the subsequent step was to extend the philosophy to the next unit operation along the processing route – flotation.

It is well recognized that the flotation performance will vary significantly within a single mineral deposit. This is further pronounced through the wide application of SAG milling. Throughput and grind in SAG milling circuits is more susceptible to ore hardness changes than is the case with crushing-rod-ball circuits. The implication of this on laboratory flotation testing for prediction of design parameters and metallurgical performance is as follows: it is unlikely that either the milling circuit product grind (size distribution) feeding flotation or the flotation residence time will be known at the time of laboratory testing for a given block of ore. Hence, the grind used for the laboratory test is not likely to be that which actually occurs once the ore is processed, and the laboratory retention time may not represent the plant conditions.

Hence, the primary problems identified by MinnovEX and the FLEET industry partners, to be addressed by FLEET technology, were:

- Variability of metallurgical response within an orebody
- Scale-up from bench scale to full plant flotation results

Therefore, the objective of the process models within the FLEET software would be to provide its user with the ability to more accurately forecast the grade and recovery on a block-by-block basis within the mine block model (based on a tonnage and grind for that block).

The extended mine block model now becomes a more powerful repository of key metallurgical processing parameters – hardness, tonnage, grind, feed grade, concentrate grade and concentrate recovery, as illustrated in Figure 2. Incorporating fundamental models for various flotation unit operations (rougher and cleaner banks or unit cells, columns, contact cells) and “modifying units” (for example concentrate regrind steps),

Figure 1 – CEET in Design Mode

Figure 2 – The Extended Mine Block Model
different circuit configurations can be rapidly compared on a metallurgical and cost basis – leading to the identification of the most techno-economically effective flotation circuit configuration to achieve desired product grade and recovery.

Similarly to the CEET approach, a bench-scale laboratory test procedure is needed to provide key flotation parameters on a block-by-block basis. Therefore, the same criteria apply – the test must be simple to perform on a small sample size, rapid, and hence low cost. Figure 3 depicts the resultant MMFT (MinnovEX Modified Flotation Test) configuration.

The key features of the test are:
- A rougher recovery versus time float is conducted (usually referred to as a kinetic test or rate test).
- Sequential tailings are collected, weighed wet, dried, weighed and assayed.
- Water recovery to the concentrates is measured.
- A sample of feed and a sample of tailings are screened into four fractions, and these are also assayed.
- A cleaner stage(s) is generally not conducted (although it is recognized that it may be required for very complex ores).
- The grind for the test must fall within a typical range of size distribution required for appropriate liberation of that ore – it is not necessary to grind to a specific target size.

Hence, the test is uncomplicated and easy to replicate.

The objective of the laboratory test is to obtain average rate constants and maximum recoveries for the minerals and metals being considered. These are then translated into production scale plant performance by taking into consideration all the scale up methodologies that are necessary. When developing a greenfields flowsheet, it is important to recognize that flotation testwork within FLEET is conducted after the most appropriate reagent suite, conditioning time and operating conditions (% solids, pH) have already been established. When FLEET is used for production planning purposes, the

Figure 3 – MMFT Configuration

existing plant parameters/reagent suites are used.

Flotation parameters for each of the key minerals are established, for example, chalcopyrite, pyrite and non-sulphide gangue, such that the sum of the three mineral assays is 100%. In addition, trace quantity elements can be tracked; for this copper porphyry example, these might include gold and/or arsenic.

Analysis of the data from each test yields the following information:
- For each mineral or metal, the $k_{AVG}$ and $R_{MAX}$ at a specific grind;
- The effect of grind on $k_{AVG}$ and $R_{MAX}$; and
- A function to describe the distribution of rate constants that occur.

The flotation parameters are utilized in fundamental models for unit cells and columns. A comprehensive description

Figure 4 – Illustration of Rate Constant Distributions propagated from a hypothetical linear feed distribution.
of the flotation model – made up of three components – is provided in Dobby, Kosick and Amelunxen, 2002 (6).

The three model components – the collection process described by kinetics, froth recovery and particle entrainment – are combined to model particle recovery for each mineral/metal in each cell within a circuit. The rate constant distributions from the laboratory cell are applied to the first cell in the flowsheet, and the modeling of the cell produces a new set of rate constant distributions for the tailings of the cell (which will be fed to the second cell). As well, the rate constant distribution of the concentrate (the froth product) is also generated, to be applied to the next stage.

Thus, rate constant distributions are propagated through the flowsheet. An example of what these might look like for four rougher cells is shown in Figure 4.

THE APPLICATION OF CEET – ILLUSTRATED THROUGH A CASE STUDY

Since its availability as a design and production planning tool, CEET (and subsequently CEET(2)) has been used in the design of virtually every recent large milling installation, and by numerous operators for production planning. The list below lists just some of the recent applications for design of new mills, mill expansion and production planning:

- BHP-Billiton - Escondida Phase 4 expansion, Chile
- BHP-Billiton - Tintaya, Peru – Antapaccay project
- Barrick Gold – Goldstrike Mill, USA
- Barrick Gold – Pascua, Chile Il
- CVRD – Sossego Project, Brazil
- Phelps Dodge - Chino Mines, USA
- Phelps Dodge – Candelaria, Chile
- Phelps Dodge – Bagdad, USA Co
- Falconbridge/AngloAmerican – Collahuasi, Chile
- Falconbridge – Raglan, Canada
- Penoles – Francisco Madero, Mexico
- AngloGold – Navachab, Namibia
- Placer Dome – Porgera, PNG
- Outokumpu – Norilsk expansion, Russia
- Ivanhoe Mineral – Savage River, Australia

Although a gold application, the expansion of the Barrick Goldstrike grinding section is selected here as an ideal illustration of the application of CEET.

GRINDING CIRCUIT EXPANSION AT BARRICK GOLDSTRIKE

A comprehensive CEET evaluation program was conducted as part of Goldstrike’s planned expansion of one of its grinding circuits. The work included:

- Development of a hardness ‘model’ for the ore body, as described by SAG Power Index and Bond Work Index;
- Site benchmarking surveys to CEET; fine tune the SAG and ball mill calibrations within
- Conducting CEET studies to examine the process options;
- Comparing CEET results to standard grinding circuit design techniques.

SPI tests (66) and Bond Work Index tests (158) were conducted on samples of drill core selected by Goldstrike geological staff, and the data was distributed onto the mine block model to represent future ore types. Five benchmarking surveys were conducted around the ball mill and the SAG mill, with the primary objective of obtaining the site-specific ball mill and SAG adjustment factors.

The initial CEET runs showed that the current limitation on throughput was the two ball mills. Hence, the focus was on additional ball mill power.

Both the conventional Bond method and the CEET approach were employed in parallel and the results compared before final mill selection. In the conventional Bond method, an average Bond Work Index (BWI) of 21.5 kWh/mt was used. This figure was selected from the distribution of BWI values in the mine block model to accommodate approximately 80 percent of all ore blocks.

In parallel, CEET iterations were performed. Generally speaking, CEET provided less power requirement than the conventional method. However, this is not surprising, given the two differences in the calculation methods: (a) application of a hardness distribution across all blocks with CEET versus a single point for the conventional approach, and (b) application of an operating efficiency factor on the ball mill (CFq) with the CEET calculations. As one of it's most powerful factors, through its iterations, CEET allowed accounting for the times where the circuit was going to be SAG limited. It is also, however, possible to allow the transfer size to increase, which allows designing for more power in the ball milling circuit.

The effect of combining ores of different hardness was also investigated. Barrick measured the BWI of five composites made up from two or three ores of known hardness.

The component ores in the various mixtures had BWI values ranging from 8.8 to 23.4. The measured hardness on the five composites was always slightly higher than the weighted average BWI value. The average difference between actual and predicted BWI was 78 percent with a range from 2.4 percent to 12.9 percent. It was shown that a better estimate of the BWI for mixtures was obtained if a 2.5 power factor was used, i.e., BWI_{mixture} = \left(\sum (BWI_{components})^{2.5}\right)^{0.5}.

The impact of this effect can be illustrated by considering an equal blend of hard and soft ores with BWI of 20 and 10 respectively. A simple average would predict a combined BWI of 15, while the 2.5 exponent calculation would predict 16.2 or 8 percent higher than the simple prediction. The finding that the BWI of a mixture is slightly greater than the weighted average is important since it means that ore hardness will be higher than expected when simple weighting is used for hardness planning.

Through this comprehensive and considered approach, Barrick was in the position to confidently select the ball mill unit, which would satisfy their future production plans over the life of the studied orebody. This case-study is presented in more detail in Application of CEET at Barrick’s Goldstrike Operation, by Custer et al., 2001 (7).
THE APPLICATION OF FLEET: A COPPER PORPHYRY ORE CASE STUDY

A benchmarking campaign was conducted on a copper porphyry ore. Figure 5 shows the size distributions, as fitted to the Rosin-Rammler equation, for feed stream minerals. The "feed" in this case consists mostly of silicates. Two sets of data are shown; one for the plant flotation feed and the other for laboratory feed when processing raw ore, i.e. the feed to the batch cell was crushed and ground in the laboratory. The chalcopyrite P80 is considerably lower than for the ore as a whole (which is not unexpected). These results illustrate the need to address the size distributions of different minerals. In this case, the two sets of distributions are reasonably similar; however, it is not uncommon for a difference to exist, and this is a key issue for successful scale-up.

Laboratory flotation tests using the MMFT were conducted for each benchmarking campaign. The FLEET modeling tool and methodology was run for each bench marking campaign, using kinetics derived from the MMFT tests, and tonnages and feed grades occurring at the time of the surveys. In each case, the froth zone recovery was calculated as a reconciling factor between plant and laboratory scales. The following observations were noted:

- Chalcopyrite froth zone recovery for the roughers was approximately 25% - this is consistent with visual observation that the rougher froth was not moving rapidly.
- Gangue froth recoveries in the roughers were lower than for chalcopyrite.
- Chalcopyrite, pyrite and gangue showed reasonably similar froth zone recoveries in the cleaner stages.
- The low froth zone recovery of the 2nd cleaners was consistent with a very high circulating load back to the 1st cleaners.

This type of benchmarking (which has been described only briefly), in conjunction with bench scale flotation data, then allows the process engineer to create block model data sets and conduct circuit simulations on a block-by-block basis. (Further details can be found in Reference (6)).

IN CONCLUSION - TAKING THE CONCEPT INTO THE FUTURE

The concept of design and process optimization through the extended mine block model achieves its optimal value when the output of CEET is used as the input to FLEET. Although not scheduled for full completion until the end of 2002, commercial applications of FLEET have been carried out already. Figures 6 and 7 demonstrate how CEET and FLEET work together to manage risk associated with determining and controlling the cost/revenue components of comminution and flotation unit operations. This concept is expanded on in the paper Managing Company Risk by Incorporating the Mine Resource Model into Design and Optimization of Mineral Processing Plants, by Kosick, Bennett and Dobby, 2002 (8).
In conclusion - taking the concept into the future

The concept of design and process optimization through the extended mine block model achieves its optimal value when the output of CEET is used as the input to FLEET. Although not scheduled for full completion until the end of 2002, commercial applications of FLEET have been carried out already. Figures 6 and 7 demonstrate how CEET and FLEET work together to manage risk associated with determining and controlling the cost/revenue components of comminution and flotation unit operations. This concept is expanded on in the paper "Managing Company Risk by Incorporating the Mine Resource Model into Design and Optimization of Mineral Processing Plants," by Kosick, Bennett and Dobby, 2002 (8).

The current focus is now centered on employing the power of the Internet to facilitate access to – currently the CEET and FLEET tools, and in the future – a wide suite of process models, ranging from stockpile modeling through gravity separation, hydro, pyro, bioleach to thickening and acid mine drainage. The software tool which will provide this link is called Process Access. Process Access is a web interface and navigation tool for mineral processing engineers. It is designed to be the link between a mine-site's resource model and the best process models available, all through a single access point. This makes Process Access an unprecedented resource for the refinement of plant design, production planning, circuit optimization and, in the future, site economics.

And, as the mineral processing engineer becomes more familiar with the power of this approach, a new realm opens up – application of the extended mine block model concept within on-line expert control of mineral processing unit operations. This area holds great promise and forms the basis of the vision into the future for this technology.
REFERENCES


