Evolution of the estimation of the metallurgical balance

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The metallurgical balance is a tool usually applied in the mining industry. The final result is used for different objectives. All the existing software for the calculation of the metallurgical balance fits the numbers in such way that a logical correspondence between the input and output materials exist. Nevertheless, the accuracy of the metallurgical balance strongly depends on the quality of the input data.

Division El Teniente of Codelco Chile has been optimizing the metallurgical balance system the last 14 years. As well, it has participated in the development of corporate norms to optimize the operations of sampling and weighting systems. As a consequence, the precision and the accuracy of the metallurgical balance have been improved in a significant way. Also the understanding of process variability was enhanced. The improvements have allowed Codelco to discover and minimize hidden losses and to better support top management decisions.

The present paper describes the main aspect of the continuous improvement process.

Introduction

The metallurgical balance (BM) is an inheritance of the Kennecott American pre-nationalization administration. The calculation model of the BM in the Division Teniente was computerized in 1980 considering the process control elements existing at that time, see Figure 1.

With all the information, the difference between the concentrate tonnage sent by the concentrator and the tonnage of the concentrate received by the smelter was estimated. Then, the tonnages and grades were fitted in order obtain a zero closing difference. Later, the recoveries and official figures of production were estimated. As the measurements of almost all the control points were inaccurate and imprecise, the closing differences were also

Figure 1. Sampling and weight 1994

1. Mineral feeder Incorrect weight system
2. Mineral feeder Incorrect sampling system
3. Process concentrate Incorrect sampling system
4. Concentrator general tail Incorrect sampling system
5. Internal tail Correct sampling system
6. Internal tail Incorrect sampling system
7. Concentrate received in smelter (calculated) Incorrect sampling and weight system
8. Concentrate received in smelter (calculated) Incorrect sampling system
9. Secondary material Incorrect sampling system
10. Slag’s Incorrect sampling system
11. Final product (metallic copper) Correct weight system
biased and imprecise. As a consequence of the fitting process, the adjustment constantly harmed the concentrator and benefited the smelter (Figure 2).

In this scheme, the actual causes of problems were hidden by the MB process. As a consequence, bad decisions and unnecessary actions were taken along the mining value chain, from rock to anodes. Also, the tonnage of concentrates stockpiles was artificially inflated.

Development

The permanent bias of the BM and the appointment of independent economic production units of management made a significant change. The sampling and weighting systems were improved at the product transfer points and the BM was modified considering:

- Reduction of control points (border control)
- Concentrator and smelter process have independency in the adjustment system in the final data.
- Elimination of the adjustments to the concentrate tonnages.
- Concentrator and smelter converge to the same point (4) show in Figure 3.
- Creation of quality assurance and control standards

Figure 3 shows the new concept.

Improvements at the concentrator

The improvements conducted in the concentrator were the following ones:

Weighting systems

A high standard weighting system was installed to improve the accuracy and precision of the estimation of the concentrate tonnage at the transfer point.

Corporate Norm CNAM 014, ‘Weighting systems in Conveyor belts’11 was implemented. Back analysis proved that the application of this norm has been fundamental in the improvement process of the quality of the MB. It is in line with other international standards and is as well based on suggestions and recommendations of many manufacturers.9–13

A fundamental point of Norm CNAM 014 is calibration of the system by systematic tests of material of well-known weight in order to have a better estimation of the true weighting error.

The test of materials concept is explained in Figure 4.

After the first tests, the top management was surprised because tonnage biases were unacceptably high (shown in Table I).

After the improvement of the measurements the organization accepted the transfer point measurements as a reference for the MB. In other words, the values obtained at the transfer point are never modified. This decision made room for many improvements at the concentrator and the smelter. An example is shown in Figure 5.

A multidisciplinary work group was created. The objective of this group was to define the responsibilities related to the operation, maintenance, material tests, monitoring and analysis of the results.

Quality plans and technical audits were used to verify the correct use of the standards.

A specific group for the maintenance of the measurements equipments was created.

1. Mineral feeder
2. Concentrator general tail
3. Concentrator material
4. Transfer of concentrate
5. Slags
6. Secondary material
7. Smelter material
8. Final product

Figure 3. New concept of MB with control point in the border
Sampling systems

**Surpassing the cognitive blindness.**

The principles of the theory of sampling (TOS) were ignored by the organization. As a consequence, sampling errors generated by incorrect sampling systems were also ignored. Pedro Carrasco and Francis Pitard demonstrated to the organization the relevance of TOS to improve MB and chronostatistical process control. Top management understood the importance of correct sampling and was willing to invest in order to acquire new correct sampling stations for the head, concentrates and tails.

**Corporate Norm CNAM 007**

‘Conditions of Sampling Stations of Materials Flows and Product Transference’ was elaborated and implemented. It is considered that its application is indispensable to assure reliable results in the metallurgical balance, commercialization, process control and transference of involved materials.

The main objective of the standard is to minimize the following sampling errors when sampling flows:

- Fundamental error
- Delimitation error
- Grouping and segregation error
- Extraction error
- Weighing error.

### Table I

<table>
<thead>
<tr>
<th>Weighing points</th>
<th>Bias (%)</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sewell mill</td>
<td>+ 4.9</td>
<td>1997</td>
</tr>
<tr>
<td>Conventional mill</td>
<td>+ 4.1</td>
<td>1998</td>
</tr>
<tr>
<td>Unitary mill</td>
<td>- 37.8</td>
<td>2005</td>
</tr>
<tr>
<td>SAG 1 mill</td>
<td>+ 14.0</td>
<td>1999</td>
</tr>
<tr>
<td>SAG 2 mill</td>
<td>- 3.0</td>
<td>2005</td>
</tr>
<tr>
<td>Concentrate transference</td>
<td>+ 0.8</td>
<td>1995</td>
</tr>
</tbody>
</table>

**Figure 4. Materials test**

**Figure 5. Improvement of the tonnage estimation at conveyor belt**

**Figure 6. Sampling station for the final tail.** (A) Primary cutter; (B) secondary cutter
Figure 7. Primary cutter

Figure 8. Secondary Vezins
Installation of high standard sampling stations
Sampling stations of high standard were installed at the border control points. See Figure 6.

Determination of the sampling frequency
The sampling frequency was computed minimizing the estimation variance of the grades to an acceptable value by using geostatistics principles. Figure 9 shows an example.

Control of sampling correctness
The sampling correctness was monitored studying the behaviour of the nugget effect of the variogram function along time. The variograms were computed on a monthly basis. See Figure 10.

Creation of a multidisciplinary team and technical committee
The objective of these groups was to define the responsibilities related to the operation, maintenance, monitoring, and analysis of the results and implementation of improvements.

Some important contributions of this multidisciplinary team to the continuous improvement of the sampling systems are:
- Participation in the elaboration and application of Norm CNAM 007
- Experimentation for verification of the critical velocity of the Vezin reducer
- Design of a cutter with changeable edges for the Vezin reducer
- Definition of the frequency of sampling sustained in the variographic studies
- Introduction of the variogram function to control the correctness of sampling stations and to better understand process variability
- Identification of robust engines in reducing Vezin system
- Design of a double drawer for receiving samples from the primary cutter avoiding contamination
- Measurement of the variation of the speed of the primary cutter by means of electronic resources. Figure 11 shows an example.

Improvements at the smelter
The main sources of uncertainty in the MB at the smelter are related to the estimation of the tonnage and grade of the slag. As a consequence, the efforts have been focused on the improvement of this point.

Slag cleaning furnace
The research works to improve the control of the slag can be summarized in the following points:

Development of sampling experiments of cold and hot slag
The sampling of hot slag took place by means of traditional trowel. Fifteen increments were collected along the filling of the pot.

In order to carry out the sampling of the cold slag, the hot material of the pot was disposed of in a flat surface. A cold layer of an approximated thickness of 40 cm was created. After, a systematic sampling pattern took place. Forty centimetres drill holes were emulated. The drilling diameter was 10 cm.

The results of the comparison are shown in Table II (Test Number 2 was repeated 3 times).

The obtained results suggest:
- The copper grade of the cold slag is systematically
The examination of the sampling modes suggests:
- The traditional sampling with trowels is incorrect. Indeed this sampling mode generates extraction, delimitation, fundamental, grouping and segregation errors.
- The proposed sampling mode for the cold slag respects the principles of the theory of sampling. Unfortunately the mode is not very handy.
- The high nugget effect of the slag flows and the insufficient size of the trowel sample would explain the bias and its dependency of the copper grade.

Development of a method for the extraction of slag samples

On the basis of the experiment described before, it was decided to develop correct and more practical sampling modes. Figure 12 shows the result of the development.

All these advances in the sampling of the slag have improved the estimation of the copper grade. Also the weighting systems were improved, implementing the use of statics scales. Both improvements helped, in a substantial way, process control to minimize losses. The closing differences of the MB were also minimized.

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Table II
Slag copper grade sampling bias evaluation

<table>
<thead>
<tr>
<th>Test</th>
<th>Increments</th>
<th>% Cu liquid slag</th>
<th>% Cu slag cold</th>
<th>Absolute difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>356</td>
<td>0.68</td>
<td>0.76</td>
<td>+0.08</td>
</tr>
<tr>
<td>2</td>
<td>214</td>
<td>0.67</td>
<td>0.75</td>
<td>+0.08</td>
</tr>
<tr>
<td>3</td>
<td>214</td>
<td>-</td>
<td>0.73</td>
<td>+0.06</td>
</tr>
<tr>
<td>3</td>
<td>228</td>
<td>0.77</td>
<td>0.92</td>
<td>+0.15</td>
</tr>
<tr>
<td>4</td>
<td>211</td>
<td>1.17</td>
<td>4.47</td>
<td>+3.30</td>
</tr>
</tbody>
</table>

Figure 11. Variation of speed of primary cutter

Figure 12. Slag sampling with static ‘drill holes’
Improvements at the sample preparation laboratory

Elaboration of quality assurance standards
The following standards were elaborated at corporate level:
• Norm CNAM 008 ‘Heterogeneity Test to determine sampling constants and nomograph to design optimum sample preparation protocols’
• Norm CNAM 012 ‘Standard conditions for sample preparation’ It recommends correct equipment for sample preparation.
• Norm Codelco CNAM 013 ‘Quality assurance for sample preparation for chemical analysis purposes.’ It recommends the systems of quality control to estimate the sampling errors at the different selection stages of the sample preparation process.

Modernization of equipment
The following improvements were implemented in the sample preparation laboratories:
• Replacement of jaw and roll crushers by last generation equipment.
• Replacement of disc mill pulverisers by ring mill pulverisers
• Rotary splitter implementation (Figure 13)
• Elimination of incorrect homogenization practices
• Acquisition of digital drying ovens
• Acquisition of high sensitivity scales.

Creation of specialized maintenance group
This group is exclusively focused to maintain the sample preparation equipment.

Creation of technical sampling committee
The main duties of the committee are:
• Review of sample preparation protocols and nomograms
• Improvement of the design of sample preparation equipment
• Verification of the critical speed and determination of the optimal number of cuts in the rotary splitter
• Analysis of exactitude and precision of sampling procedures
• Technical audits
• Continuous improvement of sample preparation protocols.

Improvement at the chemical laboratory
In the case of the chemical assays, the analytical techniques have been previously validated by the R&D department. All the main steps and procedures are documented in a quality system to control the analytical process. Some relevant improvement actions are:
• Acquisition of last generation AA and ICP spectrometers (Figure 14)
• Preparation of standards assigned to an area of restricted access
• Precision scales with semester certification
• Daily verification of precision scales with secondary patterns
• Use of reference materials
• Internal controls for the chemical analyses
• Internal controls for the sample preparation
• Analysis in duplicate for samples of the metallurgical balance
• Qualified chemists.

Conclusions
The key factors in the improvement process of metallurgical balance at El Teniente have been:
• To accept and to understand our ignorance about sampling and weighting correctness. As a consequence, we begun to escape from our cognitive blindness.
• Correctly measuring the tonnages and grades
• Systematic validation of the weighting and sampling systems
• Creation and application of quality assurance norms
• Understanding of the variability of the processes (cronostatistics)
• Working in multidisciplinary way
• Unrestricted support of the top management
• Leadership, commitment and perseverance of the champion of quality of the Division
• Creation of expertise in the corporation
• Technical audits of quality
• Establishing aligned objectives of quality with the mining business
• Key consultancy work of Francis Pitard (consultant) and ongoing advice and support of Pedro Carrasco (Geosciences Technical Director, Technical Group, Project Corporate Cice-Presidency Codelco)

As the tonnage error is most important in the quality of the metallurgical balance, the material tests are fundamental to know the precision and exactitude of the tonnage error. As a result the quality of management decisions improved in a significant way.

A specific group must exist for the maintenance of the sampling stations and weighting systems that considers the availability of spare parts, plans, programmes and budget.

The technical committees in the laboratory had very successful results in the process of continuous improvement of the weighting systems, sampling, sample preparation and chemical analysis.

Nowadays the organization is conscious of the benefit of the investment previously described in this paper. As a matter of fact, the return is excellent, besides important
hidden losses have been discovered and minimized. A better estimation of the operational variables, has allowed unbiased metallurgical balance results and a better estimation of the metallurgical recovery. The best test of the success is Figures 15 to 17. They clearly show the minimization of the losses in the final tails and in the slag and the evolution of the closing differences. If we measure well we can control well and finally we can improve.

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Alfredo Wilke Vera, graduated as a Chemical Engineer from State Technical University. He has 37 years of experience working in the Quality Control Department Codelco Chile Corporation el Teniente División. Income in 1973 by chemical analysis and since 1985 is responsible for the Metallurgical Balance of the Company. Since 1995 is in charge of the entire Department, including the extraction, preparation, chemical analysis of different samples of all the company. He has participated in developing the rules of the Corporation CNAM and has led the improvement works on sampling and weighing systems.
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Pedro Carrasco graduated as a geologist from University of Chile and as a geostatistician from the Paris School of Mines. He has 35 years of experience in sampling, exploration, mining geology, geological and geostatistic modelling, resource estimation and valorisation of mining business in gold, silver, copper, iron, tin deposits and mineral sands located in Chile, Argentina, United States of America, Australia, Philippines, Indonesia, Papua New Guinea and Zambia. Visiting professor of Mining Geostatistics at Centre of Geosciences of the ENSMP and several universities in Chile and Argentine. Past President of the Chilean Geological Society.