Pyrometallurgical Process Management *Research Summary*

Advanced Process Modeling at the BCL Smelter: Improving Economic and Environmental Performance

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Since 1973 Bamangwato Concessions Limited (BCL) has operated a nickel-copper smelter in Selebi-Phikwe, Botswana. The smelter treats concentrates from local mines and various custom feed concentrates. The nickel throughput capacity of this smelter is constrained by a low nickel feed grade in its primary BCL concentrate. BCL contracted Xstrata Process Support (XPS) to assist in identifying key economic drivers to maximize revenue-generating opportunities. After the disclosure of essential BCL plant performance data XPS developed and utilized advanced metallurgical modeling techniques to identify production bottlenecks, calculate Ni, Cu, and Co recoveries, manage the slag volumes, increase the custom feed capacity, and perform various feasibility analyses for key unit process operations in the BCL smelter. The methodology for developing the process model and its application in contributing to the economic bottom line are outlined in this paper.

INTRODUCTION

Prior to 1970, the economy of Botswana was limited and largely depended on farming and meat export to neighboring countries. The economy took a dramatic leap during the 1970s and 1980s with the major discovery of diamond deposits at Orapa and nickel/copper deposits at Selebi-Phikwe. To exploit the nickel/copper deposits, the mines at Selebi-Phikwe were established and the Bamangwato Concessions Limited (BCL) smelter was commissioned in November 1973. Currently, the smelter treats the ores from three underground mines situated within a 14–15 kilometers radius of the smelter: Phikwe, Selebi, and Selebi North. In addition, BCL operates an underground and open pit mine close to Francistown on behalf of Tati Nickel Mining Company Ltd. All the concentrates produced from Tati mines are also treated at the BCL smelter.

The BCL smelter employs the Outokumpu flash smelting process technology to produce Ni-Cu matte and exports matte to external parties for subsequent separation and refining; primarily at refineries in Norway and Zimbabwe. The first matte from the BCL smelter was cast in December 1973 and numerous operating problems were encountered and resolved during early days of operation. Since commissioning, the BCL smelter has gone through several modifications to increase the initial production capacity of the plant from 40,000 tonnes/year to the current level of 60,000 tonnes/year of matte. The historical details of various modifications at the smelter are presented elsewhere.[1,2]

How would you…

…describe the overall significance of this paper?

The predictive techno-economic process model described here is a combination of reliable thermo-chemical software tools and operational plant data. It documents the technical, environmental and economic performance of the Bamangwato Concessions Limited (BCL) operation and acts as a decision-making tool in striving for operational excellence.

…describe this work to a materials science and engineering professional with no experience in your technical specialty?

This work demonstrates through select examples the application of sound engineering principles for the development of a process model using multiple software packages. The process model has been used to quantify the technical and economic bottlenecks of the BCL smelter.

…describe this work to a layperson?

A successful attempt has been made to provide BCL management with a new management tool on the impact of feeding various concentrates into their nickel smelter. This tool is a process model which predicts metal recoveries, environmental performance and operating costs as a function of their business choices.

Given the complexity of the operation and its remote location from main industrial and commercial towns, the BCL smelter is largely self-sufficient in terms of all utilities such as electricity, water, and oxygen. This has resulted in BCL being one of the largest employers in the country. Since commissioning significant work has been carried out to improve the plant throughputs and production level.[1–4] Some key improvements at BCL smelter involve the following:

- Addition of three oxygen plants over an extended period of time to increase both concentrate throughput and the oxygen enrichment level
- Installation of a stand-alone flux drying facility
- Addition of a third Pierce-Smith converter
- Installation of Kvaerner multi-coil steam dryer for concentrates
- Upgrading of rougher and scavenger circuits in the concentrator
- Replacing the original cleaner bank cells with modern Outokumpu cleaner bank cells in the mill
- Introduction of sulfatizing air into the waste heat boiler in 2004
- Flash furnace tapping efficiency
- Improving the flash furnace integrity
- Converter aisle efficiency
- Modernization of flash furnace in

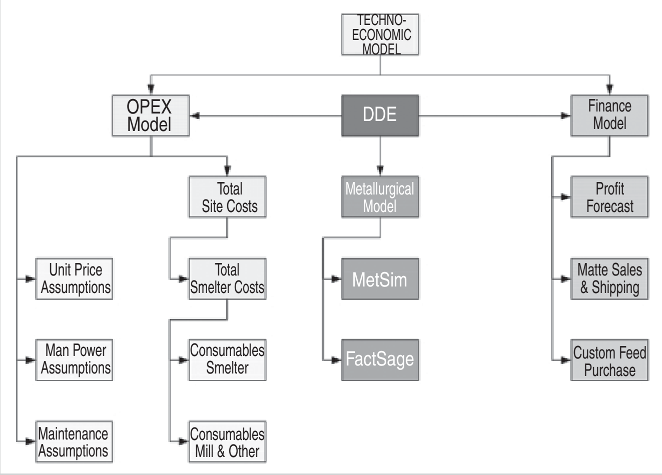

Figure 1. Pictorial overview of the predictive model.

2007 (replaced four burners with a single Outotec burner)

The aforementioned improvements have helped the BCL smelter to maintain sustainable production throughput (i.e., on-line time). But with time, as the ore grades from the local mines have started to decrease, the smelter has been focused on increasing its custom feed capacity. In 2009, BCL contracted XPS to assist in identifying the bottlenecks of increasing custom feed capacity through the development of a predictive process model based on engineering design practices. The present paper outlines the development of such a process model and discusses its application in improving metal recoveries.

SCOPE OF WORK

The predictive process model encompasses the entire BCL metallurgical complex. It addresses ore mineralogy, concentrate mineralogy, custom feeds, the concentrator, the concentrate drying plants, the flash smelting furnace with its off-gas handling system, the slag cleaning furnace, and the converter aisle. A primary (technical) model was created to predict the input, output, and recycle streams for all major unit process operations and plant sections. Typical deliverables were: stream mass flow rate, composition, temperature and pressure (if relevant); predict overall, plant section and individual unit operation metal recoveries; and define overall and individual unit process operation mass and heat balances.

A secondary (economic) model takes the outputs from the primary model in order to optimize net profitability. The secondary economically oriented model deliverables are:

- Calculate operating costs and net profitability based on toll refining terms
- Estimate metal recoveries and revenue streams from different feeds
- Optimize custom feed addition

GENERAL PROCESS DESCRIPTION

The simplified flow sheet of the BCL smelter is presented in Figure A.[3] Ore is mined by underground methods from the Selebi and Phikwe ore bodies containing about 0.55% Ni and 0.58% Cu. The major sulfide minerals in the ore are pentlandite, chalcopyrite, pyrrhotite, and pyrite. The BCL concentrator treats the ore body and produces the concentrate typically containing about 3.5% Ni, 4.5% Cu, 30% S, 45% Fe, and 8% Si along with some moisture content. The concentrate is then sent to feed preparation section. The feed preparation at BCL consists of a pair of Niro-dryer and a Kvaerner multi-coil steam dryer supplying the dried concentrate and the custom feed to the flash furnace.

The BCL smelter operates the largest flash smelting furnace in the world. The flash furnace matte grades 33 wt.% (wt.%.Ni + wt.%Cu) which is converted in Pierce-Smith converters to produce two different types of high grade mattes: low sulfur matte (contains 6% S and called RTZ matte) and high sulfur matte (contains 22% S and called FNA matte). The final mattes are solidified in matte granulation before being shipped to external customers for refining. The flash furnace at BCL employs gas handling system which recovers the heat from the off-gas in waste heat boiler to produce low pressure steam. The gases from the uptake shaft of the temperature 1,350°C pass into a waste heat boiler and are cooled down to 350°C. The cold gas then passes through two in-line electrostatic precipitators for dust recovery. The BCL smelter is equipped with the capacity of in-house oxygen supply from an oxygen plant to the flash furnace maintaining the oxygen enrichment around 35–36 vol.% in the blast air.

The converter slag is first treated in a slag cleaning vessel called "cobalt vessel" and then sent for final cleaning to two in-line 9-MVA Barnes Berlic electric furnaces. The flash furnace produces large amount of the slag which cascades to two electric furnaces through launders for cleaning. The slag from the electric furnaces is granulated before being discarded, while the matte from electric furnace is tapped and joins the flash furnace matte in the converter aisle for upgrading. The discard slag from electric furnace contains less than 0.20 wt.% Ni and 0.40 wt.% Cu.

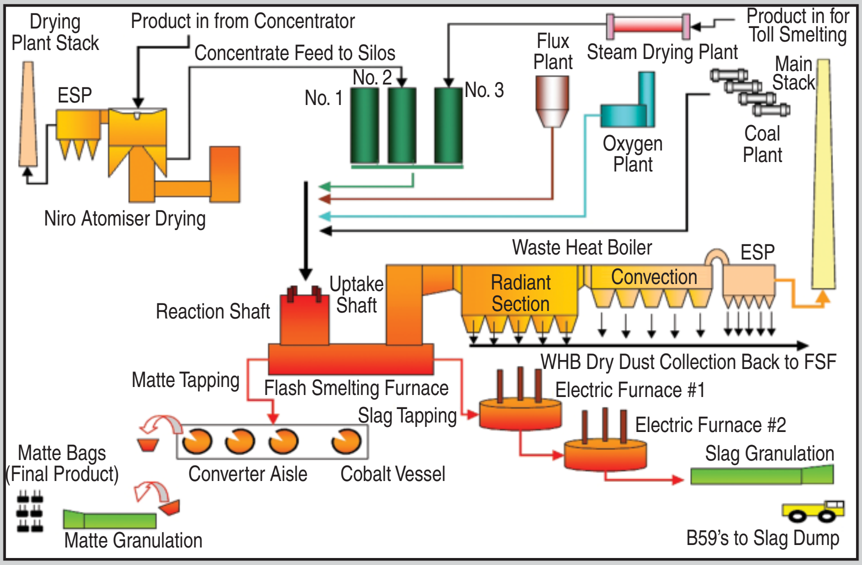

Figure A. Schematic flow sheet of the BCL smelter in Botswana.[3]

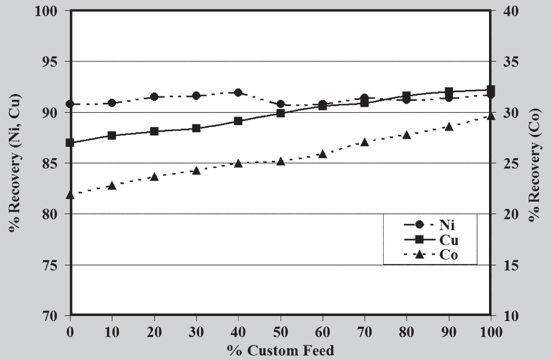

Figure 2. Metal recoveries as a function of custom feed ratio into the flash furnace for a constant concentrate feed rate of 116 tph.

to maximize smelter profitability while maintaining process stability, sustaining good slag and matte composition and a proper heat balance within the limits of supplementary oxygen or fossil fuel supply capacity.

As such the predictive model becomes a combination of a mass and heat balance with thermodynamic and some kinetic sub-models, primarily in the converter aisle. The structure of this model easily allows the addition of unit process operations. A customer friendly user interface was created and the technical and economic model can be operated independently from each other. Typical reports delivered are cost summaries, metal production and recoveries overview plus a commercial terms outline for custom feeds.

See the sidebar for a general process description.

DEVELOPMENT OF THE PRIMARY PROCESS MODEL

The process model for the BCL smelter was developed in two stages. In stage one, the thermo-chemical software “FACTSAGE®[5] was employed to map the liquidus temperatures of the slag for the various process parameters in all the metallurgical smelting vessels (i.e., flash furnace, electric furnace, cobalt recovery vessel, and Pierce-Smith converters). The %Fe/SiO_2 ratio, MgO wt.%, CaO wt.%, and Al_2O_3 wt.% were selected as the main process parameters for liquidus mappings. In the second stage of model development, a heat and mass balance model for the complete smelter flow sheet was developed using METSIM®[6] software. In developing the process model, the current plant data were used for calibration and validation. For proper heat and mass balance, the recycled streams were added and the model was run iteratively to convergence. Using the “dynamic data exchange” tool in METSIM, the calculated results were transferred into an excel worksheet, which served as an interface with the secondary economic model.

To model the complex phases like the matte and the slag, a simple “molecular theory”[7–9] was employed and the gas phase was assumed to follow the ideal behavior. According to molecular theory[7–9] the liquid phases, the matte and the slag, are assumed to consist of molecules. This approach is a simplistic way of modeling complex phases which contain ionic species, however, from a heat balance point of view the adopted approach adequately takes into account its nearest neighbor interaction in the liquid phase through proper selection of pseudo-components. In this simplified approach, especially when many complex anions and cations are present in solution, the entropy may not be calculated accurately; hence the model would not give exact results for the calculation of the chemical activity of a single oxide or a sulfide in the solution. Nevertheless, with an adequate selection of “pseudo-components” in solution such as FeS, Fe_2SiO_4, Ca_2SiO_4, Mg_2SiO_4, $CaSiO_3$, $MgSiO_3$, etc., the enthalpy of the solutions and the resulting heat balances are considered sufficiently accurate for industrial applications. A similar approach to model the slag and the matte was adopted in previous work.[10,11]

Since the entropy and activity of the chemical species in the solution cannot be accurately calculated, the feature of the Free Energy Minimizer in the METSIM software was not used while calculating the equilibrium assemblage of different phases. Instead, in order to model each unit process operation, a series of chemical reactions were listed, and the extent of reaction was based on measured distribution coefficients and plant data. To verify the assumptions regarding the selection of pseudo-components in modeling, the specific heat capacity of slag and matte phases were verified with FACTSAGE. It needs to be pointed out that FACTSAGE employs an advanced quasi-chemical modeling approach to account for nearest neighbor interactions in complex phases.[12,13]

SECONDARY ECONOMIC MODEL

With the previously outlined objective to evaluate the profitability of different feed and operating scenarios a secondary, economical model was developed on the Excel platform. The input to the economical model was supplied from the METSIM process model using “dynamic data exchange” tool. In the economical model, the fixed and variable costs are defined. The variable costs are related to the plant performance in terms of reagent consumptions and metal recoveries. An example of typical cost centers employed at the smelter is presented in Table I.

The pictorial overview of the structure of the predictive techno-economic model is presented in Figure 1. The figure highlights the method of data trans-

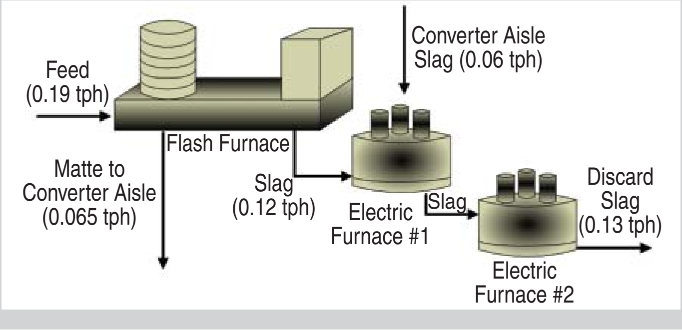

Figure 3. Mass balance of Co around flash and electric furnaces.

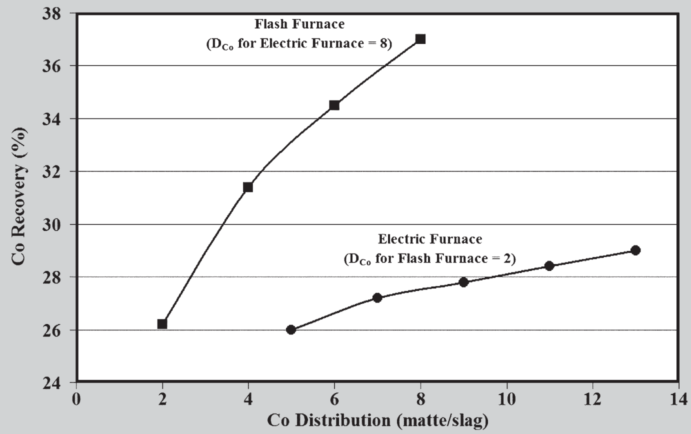

Figure 4. Calculated values of overall Co recovery as a function of increasing values of the distribution coefficients in the flash or electric furnace.

Table I. Typical Cost Center Structure at BCL

Level 1 Cost Centers	Level 2 Cost Centers
Concentrator	Crushing and Grinding Flotation
Feed Preparation	Niro Dryers Spray Dryers Flux Drying Plant Pulverized Fuel Plant
Smelter (=Hot Metals)	Flash Furnace Electric Furnaces Converter Aisle
Waste Heat Boiler	Waste Heat Boiler Operations & Maintenance (including water treatment plant)

fer from the excel sheet to the OPEX and finance model.

APPLICATIONS OF THE PREDICTIVE MODEL

The BCL flash furnace treats about 116 tonnes/hour of the Ni/Cu sulfide feed material of which 55% is low grade BCL concentrate and the remainder is higher grade custom feed material. The average concentrate grade from BCL ore is approximately 3.0 wt.% Ni, 4.5 wt.% Cu, and 0.15 wt.% Co, while the custom feed material typically grades approximately 5.7 wt.% Ni, 3.4 wt.% Cu, and 0.2 wt.% Co. Currently, the custom feed material is only treated in the flash furnace and its impact on overall smelter performance was examined. The metal recoveries of the smelter were calculated as a function of varying the proportion of custom feed material versus BCL concentrate for a constant throughput of 116 tph. The results are presented in Figure 2, where the "X" axis represents the percentage of custom feed to the flash furnace and the "Y" axis represents the recovery values for Ni, Cu and Co, respectively. In these calculations, the other process conditions such as temperature, oxygen enrichment, %Fe/SiO_2 of the slag, etc. were all kept constant. The figure shows that the addition of higher grade custom feed material to the smelter alone does not improve Ni and Cu recoveries very much. The operation of a plant with 100% of the higher grade custom feed material marginally improves cobalt recovery from 22% to 30%.

The results indicate that the certain vessels at the smelter may not operate at their optimum level, especially when it comes to cobalt recovery. A number of plant trials have been conducted in the past in the electric slag cleaning furnaces and cobalt vessel to enhance the slag cleaning efficiencies. It was reported that only marginal improvements in Co recovery were noticed by adding more reductants to both the electric furnaces and cobalt vessel. The process model illustrated that most of the cobalt in the feed material never reaches the converter aisle and reports to the slag in the flash furnace. The calculated mass balance for Co around the flash furnace and the electric furnaces is presented in Figure 3.

Figure 3 indicates that the cobalt vessel in the converter aisle is not a bottleneck for improving Co recovery. In order to demonstrate the real bottleneck for Co recovery, the distribution coefficient of Co was changed stepwise in both the electric and flash furnace. The results of these calculations are plotted in Figure 4. It shows that the flash furnace distribution coefficient has much bigger impact on cobalt recovery than the electric furnace. This can be partially explained by the fact that the flash furnace has larger amounts of the matte than the electric furnaces, where the matte is only produced through settling. The high matte volume at lower grades in a vessel enhances the slag cleaning via chemical interaction between FeS in matte with the dissolved base metal oxides (NiO and Cu_2O) in the slag phase. The flash furnace is the metallurgical unit where the first chemical separation of the metals between matte and slag phases takes place. The process improvements such as reducing the slag viscosity, lowering oxygen potential in settler atmosphere, etc. can significantly improve the Co recovery of the plant in addition to Ni and Cu.

Another improvement target that has great potential impact on metal recoveries is the reduction of total amount of the slag produced from each vessel, which is directly linked to the concentrate grade. A reduced slag volume not only provides physically more room for higher grade custom feed treatment in a vessel, but also facilitates the available energy in melting the cold charge. In this regard the process model was employed to calculate the amount of the

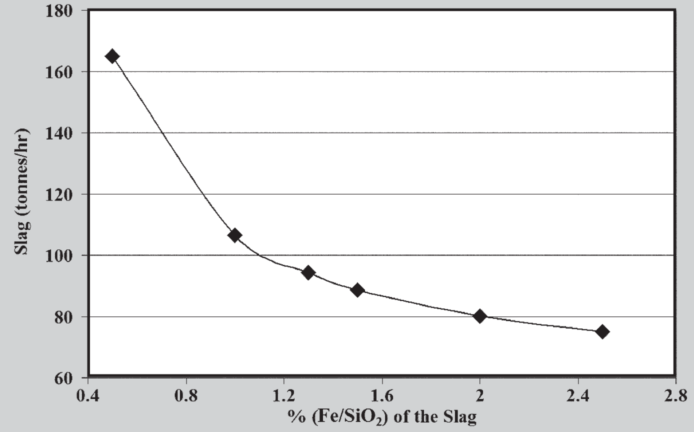

Figure 5. Calculated slag tonnage as a function of % Fe/SiO_2 of the slag.

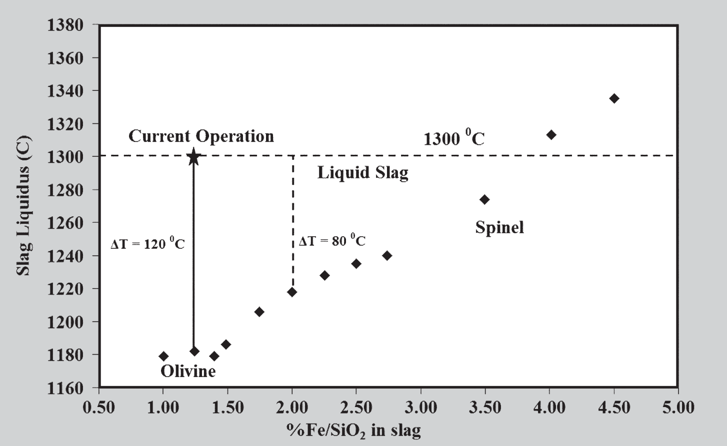

Figure 6. Slag liquidus temperature as a function of %Fe/SiO_2.

slag produced in the flash furnace with increasing %Fe/SiO_2 ratios. The results are presented in Figure 5. Naturally increasing the %Fe/SiO_2 ratio in the slag decreases the slag volume. However, increasing %Fe/SiO_2 ratio also impacts the liquidus temperature of the slag and therefore the available superheat.

To study the impact of changing %Fe/SiO_2 ratio of the slag upon liquidus temperature, some thermo-chemical calculations were performed using FACTSAGE. In these calculations all the degrees of freedom for this industrial slag system were fixed based on plant operating data. The thermodynamic principles employed are described elsewhere.[14–16] The liquidus mapping results, shown in Figure 6, reveal that raising the %Fe/SiO_2 ratio will increase the slag liquidus thereby reducing the available superheat to the slag. Based on current plant data it was determined that the temperature of the slag in the settler of the flash furnace is currently about 1,300°C. The level of %Fe/SiO_2 ratio in the slag is about 1.2. Thus, flash furnace slag has a slag liquidus close to 1,180°C and available superheat of ~120°C. It also indicates that BCL has the possibility of increasing the %Fe/SiO_2 ratio by 65% from its current level to roughly 2 and still operate with a superheat of 80°C. This will yield an estimated slag volume reduction of 17%.

It should be noted that reducing the amount of flux, thereby the raising the %Fe/SiO_2 ratio in the slag, would increase the activity of FeO in the slag leading to more dissolved metal oxides in the slag phase via the following reactions:

$$\text{NiS (matte)} + \text{FeO (slag)} = \text{NiO (slag)} + \text{FeS (matte)} \quad (1)$$

$$Cu_2S\text{ (matte)} + \text{FeO (slag)} = Cu_2O\text{ (slag)} + \text{FeS (matte)} \quad (2)$$

$$\text{Co (matte)} + \text{FeO (slag)} = \text{CoO (slag)} + \text{Fe (matte)} \quad (3)$$

However, this does not necessarily mean that the total amount of pay metals going to the slag phase will rise. The reduced amount of slag multiplied by higher metals concentration in the slag usually produces similar or lower metal losses (in tons), but more importantly improves the furnace heat balance significantly. For cleaning in the electric furnaces, it is better to feed a lower amount of slag at higher pay metal load, if the tons of pay metals are the same. A similar thermo-chemical study on slag chemistry for converter aisle was also performed. The study revealed that there is enough room for increasing the %Fe/SiO_2 ratio in converters thereby decreasing the total slag volume.

CONCLUSIONS

The METSIM process model was employed to calculate the pay metal recoveries for different feed scenarios, and was useful in identifying the bottlenecks for metal recoveries at the smelter. The process model shows that a coordinated effort toward reducing the total slag volume, optimizing the slag chemistry, and reducing the slag viscosity will significantly improve the metal recoveries at the smelter and also the custom feed handling capacity.

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