Plant-Wide Control of a Base Metal Refinery: Top-Down Analysis

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Abstract: A top-down control structure is presented for the optimal steady-state operation of a base metal refinery. The economic cost function for the plant is derived in terms of the production rate of primary and secondary products, the losses of primary product to the secondary product streams, and the fixed and variable costs of the plant. The economic performance of the plant is largely defined by the operation of an exothermic pressure leach circuit. The leach efficiency of this circuit determines the potential production rate for the plant, its operation affects costs, and it is the source of all primary product losses. Given market prices for the primary and secondary products, and reagent and utility costs, the proposed control structure can be used to define the optimal operating region for the pressure leach circuit so as to maximize the profitability of the plant.

Keywords: refining, hydrometallurgy, plant-wide control

1. INTRODUCTION

Lonmin's base metal refinery (BMR) produces a platinum group metals (PGMs) concentrate, copper, and nickel sulphate. An overview of the BMR is presented in Fig. 1. It treats converter matte that it receives from Lonmin's Smelter complex and that contain approximately 30% Cu, 50% Ni, and less than 1% PGMs. This matte is processed in a series of atmospheric and pressure leaches to upgrade the converter matte into a high grade PGM concentrate.

The converter matte is processed in a milling circuit to increase its surface area. This improves leach efficiencies throughout the plant. Converter matte is received at approximately 2mm in diameter and the target particle size for the milling circuit's product is 80% passing $75\mu m$.

The continuous leach section comprises the atmospheric leach and the pressure leach. The atmospheric leach targets nickel for extraction and the pressure leach copper. Downstream from the BMR, the capacity and processing costs require that the PGM concentrate contains less than a specified amount of copper and nickel. Consequently, the continuous leach section cannot be operated at throughput rates that will result in retention times that are too low for sufficient base metal extraction. Furthermore, the atmospheric leach's capacity exceeds that of the pressure leach, and as a consequence the pressure leach determines the production rate of the plant.

In the crystalliser section nickel sulphate solution is crystallised for bagging and transportation. The crystalliser section's capacity is significantly larger than that of the continuous leach circuit and it has little impact on the potential production rate of the plant. Consequently, the crystalliser remains off line until it has accumulated sufficient feed inventory to allow sustained operation for a reasonable period of time.

In the electrowinning section copper is removed from the continuous leach solution stream. The solution is circulated through electrowinning back to the continuous leach section as spent electrolyte where it serves as a source for the leach reagents. As with the crystalliser section, electrowinning's capacity exceeds that of the continuous leach and it too has no impact on the potential production rate of the plant.

The primary, PGM bearing, product ideally remains in a solid phase throughout the plant, however, leaching of PGMs occur. After passing through the continuous leach section the volume of the primary product is significantly reduced allowing for batch treatment. The series of batch leaches following base metal removal are grouped together in the batch leach section, where selenium, tellurium, osmium, and any remaining nickel and iron oxides are targeted for extraction.

The work presented here follows the plant-wide design procedure outlined in Larsson and Skogestad (2000) and Skogestad (2004) to formulate a top-down control strategy for the Lonmin BMR. le Roux et al. (2016) followed the same procedure to formulate a generic top-down control strategy for grinding mill circuits. This design procedure for steady-state operation consists of the following steps:

(1) Define the operational economic objective.
(2) Determine the optimal steady-state operation.
(3) Select the primary controlled variables influencing the economic cost function.
(4) Select the throughput manipulator.

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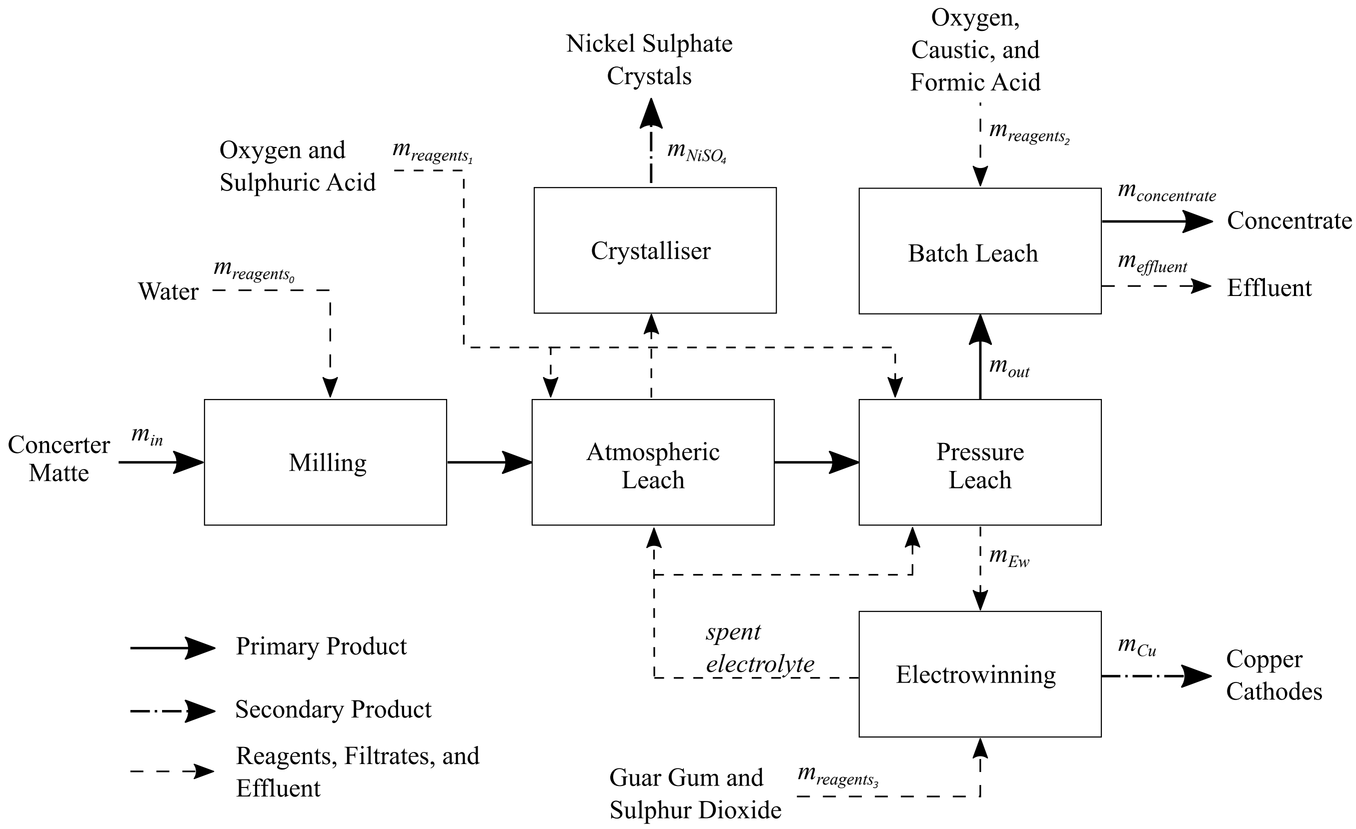

Fig. 1. An overview of the Lonmin Platinum base metal refinery.

2. CONTINUOUS LEACH SECTION

2.1 Atmospheric leach

The primary objective of the atmospheric leach circuit is nickel extraction. An important secondary objective is the precipitation of copper and PGMs in the spent electrolyte. PGMs that are not recovered through precipitation here will be lost with the nickel sulphate product, and the copper that is not precipitated will contaminate the nickel sulphate product resulting in a lower premium.

The atmospheric leach consists of a five reactor leach train followed by a thickener. Nickel sulphate solution from the thickener overflow is filtered before passing to the crystalliser section. This filtration circuit ensures that any solids remaining in the thickener overflow is recovered, repulped, and returned to the thickener underflow, i.e. back to the primary product stream.

Oxygen is sparged into the atmospheric leach reactors and spent electrolyte is added as the primary source of leach reagents, namely sulphuric acid and copper sulphate. Nickel is leached by dissolution with sulphuric acid and by metathesis with copper (Steenekamp and Dunn, 1999):

$$\mathrm{Ni_3S_{2(s)} + H_2SO_{4(aq)} + 0.5\,O_{2(g)} \longrightarrow NiSO_{4(aq)} + 2\,NiS_{(s)} + H_2O_{(aq)}} \quad (1a)$$

$$\mathrm{Ni_3S_{2(s)} + 2\,CuSO_{4(aq)} \longrightarrow 2\,NiSO_{4(aq)} + Cu_{2(s)} + NiS}(s) \quad (1b)$$

The control of this circuit requires the correct balance of matte, spent, and oxygen addition to ensure efficient nickel extraction while not allowing any copper or PGMs to remain in solution.

2.2 Pressure leach

This pressure leach circuit targets the copper and any remaining nickel for extraction. The section consists of a number of autoclaves in parallel, a thickener, and a filtration circuit. More than one autoclave can be brought on line to increase plant-wide throughput. The work presented here discusses only single autoclave operation.

The sulphide reactions in the continuous leach section are exothermic and hence releases a significant amount of heat. The reaction for the leaching of chalcocite in the pressure leach circuit, for example, is given by

$$\mathrm{Cu_2S_{(s)} + 2.5\,O_{2(aq)} + H_2SO_{4(aq)} \longrightarrow 2\,CuSO_{4(aq)} + H_2O_{(aq)}}, \quad (2)$$

and has a heat of reaction of 6MJ/kg.

A bulk leach is performed in the first three compartments of the autoclave to extract the majority of the copper. The third compartment product is discharged to a thickener, where the overflows is pumped to the electrowinning section, and the underflow is forwarded to the final, fourth compartment. The fourth compartment provides a polishing duty, allowing for finer control of the copper leach and an increase in the PGM grade of the leach product (Steenekamp and Turner-Jones, 2012).

The fourth compartment of the autoclave is discharged through a filtration circuit. Solids are accumulated in this filtration circuit for batch operation and the filtrate is pumped to the electrowinning section.

3. BASE METAL REFINERY REVENUE

The filtration circuit, through which the fourth compartment of the pressure leach discharges, represents the interface between the continuous- and batch leach sections. This filtration circuit has, by design, sufficient capacity and redundancy to allow for uninterrupted batch accumulation. As such the batch leach section has no influence on the throughput of the continuous leach section. Furthermore, any PGMs lost to the batch leach section's effluent stream occurs so independently from operations in the continuous leach section. The two portions of the plant are essentially independent.

At steady state, with reference to Fig. 1, the mass balance of the BMR, excluding the batch leach section, is given by

$$m_{in} + \sum_{i=0}^{3} m^i_{reagents} = m_{out} + m_{Cu} + m_{NiSO_4}. \quad (3)$$

Here m_{in} and $m^i_{reagents}$ represent the mass flow of converter matte and reagents to the BMR. The mass flow of concentrate to the batch leach section is represented by m_{out}, and m_{Cu} and m_{NiSO_4} the mass flow of the copper and nickel sulphate products from the BMR.

By introducing a coefficient ω_x that represents the mass fraction of PGMs in each of these streams the BMR's PGM balance is given by

$$\omega_{in} m_{in} = \omega_{out} m_{out} + \omega_{Cu} m_{Cu} + \omega_{NiSO_4} m_{NiSO_4}. \quad (4)$$

Note that the nickel and copper terms, $\omega_{Cu} m_{Cu}$ and $\omega_{NiSO_4} m_{NiSO_4}$receptively, represent the PGM losses with the nickel sulphate and copper streams.

The BMRs revenue can be expressed as

$$Revenue = Sales - Costs. \quad (5)$$

Here $Sales$ is determined by the mass flow of primary and secondary products, and their market prices

$$Sales = \alpha \omega_{out} m_{out} P_{\$PGM} + m_{Cu} P_{\$Cu} + m_{NiSO_4} P_{\$NiSO_4}. \quad (6)$$

The recovery of the batch leach section is accounted for by α, taken as a constant value that can be derived from historical performance, $\$PGM$ represents the basket price the BMR receives for its PGM product, which takes into account the market price for the individual platinum group elements, transportation, and subsequent processing costs. The price the BMR receives for its copper is represented by $P_{\$Cu}$, which depends on the achieved copper grade and market price. Similarly $P_{\$NiSO_4}$ represents the price the BMR receives for its nickel sulphate crystals, again, dependent on achieved grade and market price.

The BMRs costs are divided into fixed and variable components. Fixed costs include, for example labour, insurance, and software licenses. Variable costs include processing costs such as reagents and electricity. Variable costs are tied to the production rate, i.e. the tons of converter matte processed by the plant. For example, at higher production rates more copper will enter the circuit requiring more electricity for copper plating in the electrowinning circuit, and more oxygen and sulphuric acid for copper extraction in the pressure leach circuit. The BMR's costs can therefore be expressed as a function of production rate

$$Costs = f_{costs}(m_{in}). \quad (7)$$

This relationship can be fitted to historical data.

Using (4) to (7) the BMR revenue can be expressed as

$$Revenue = \alpha P_{\$PGM}(\omega_{in} m_{in} - \omega_{Cu} m_{Cu} - \omega_{NiSO_4} m_{NiSO_4}) + m_{Cu} P_{\$Cu} + m_{NiSO_4} P_{\$NiSO_4} - f_{costs}(m_{in}). \quad (8)$$

4. PLANT-WIDE LOSSES DRIVEN BY CONTINUOUS PRESSURE LEACH TEMPERATURE

In a study of the leach kinetics of PGMs and copper in the continuous pressure leach circuit by Dorfling (2012), the effects of leach temperature, T_{leach}, pressure, P_{leach}, initial acid concentration, $\omega_{H_2SO_4}$, and leach time, t_R, was investigated. It was found that a subset of PGMs, namely rhodium, iridium, and ruthenium, collectively referred to as other precious metals (OPMs) experiences increased dissolution as T_{leach} is raised. Moreover, the extent of OPM dissolution was found to be dependent on the rate and extent of the copper leached. Fig. 2 below illustrates the relationship between copper and rhodium dissolution, and T_{leach} and t_R. The leach kinetics of iridium and ruthenium closely resembles that of rhodium.

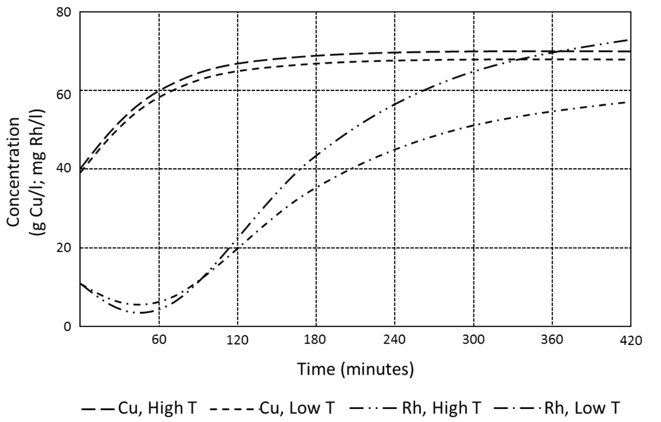

Fig. 2. Relationship of Cu and Rh in the continuous pressure leach solution as a function of leach time and temperature, with constant pressure, initial acid concentration, and solids percentage (adapted from Figure 4.27 in Dorfling (2012)).

OPMs that are leached into the pressure leach solution report to the continuous leach sections filtrate, which after filtration becomes the copper solution. The OPMs therefore follow copper solution through the electrowinning section and reports to the atmospheric leach. The OPM dissolution in the pressure leach is consequently the source of all OPM losses to the secondary product streams, $\omega_{Cu} m_{Cu}$ and $\omega_{NiSO_4} m_{NiSO_4}$, in (4) and (8).

Using the individual rate expressions of all the OPM dissolution and precipitation reactions, as presented in Dorfling (2012), it is possible to derive an expression for the mass fraction of dissolved OPMs that reports to the pressure leach filtrate as a function of T_{leach} and t_R:

$$\omega_{filt} = f_{filt}(T_{leach}, t_R). \quad (9)$$

In electrowinning OPMs are lost with the copper cathodes due to entrainment and co-plating. The rate of entrainment is a function of the surface properties of the cathodes, such as their porosity, whereas the rate of co-plating is a function of the electrochemical properties of the OPMs. The mass fraction of OPMs lost to entrainment or co-plating can be approximated as

$$\omega_{Cu} m_{Cu} = k_{Cu} \omega_{filt} m_{Ew}. \quad (10)$$

Here m_{Ew} represents the mass flow of copper solution to the electrowinning circuit and k_{Cu} the rate of entrainment and co-plating. This relationship can be fitted to process data.

The OPMs that are not lost with the copper product stream are recycled to the atmospheric and pressure leach circuits. Coetzee (2016), in a study of the iron and OPM precipitation kinetics of the atmospheric leach filtrate, observed that the OPMs could be selectively precipitated via neutralisation. However, the potential for OPM precipitation is limited as iron sludge is formed at higher pHs which blind filtration media, limiting filtration efficiency in the circuit and the throughput potential of the plant. The circuit is consequently operated at a fixed pH that allows for maximising OPM recovery, while not risking excessive iron sludge formation. The OPM losses to the nickel sulphate stream can be expressed as a function of the OPMs not lost to the copper cathodes as follows:

$$\omega_{NiSO_4} m_{NiSO_4} = k_{NiSO_4} k_{split} \omega_{filt} (1 - k_{Cu}) m_{Ew}. \quad (11)$$

Here the coefficient k_{NiSO_4} accounts for the mass fraction of OPMs not recovered in the atmospheric leach, via neutralisation, and k_{split} the proportion of spent electrolyte that is recycled to the atmospheric leach. The relationship in (11) can be fitted to process data.

5. CONTINUOUS PRESSURE LEACH OPERATION AND CONTROL

An overview of the continuous pressure leach circuit is presented in Fig. 3 and Table 1. The first compartment of the autoclave is cooled using flash recycle cooling (Dunn, 2009). This method returns part of the slurry in the first compartment to the feed tank. Because the feed tank operates at atmospheric pressure, the temperature of the slurry recycled to it drops too atmospheric boiling point, the recycled slurry boils and releases water vapour. The temperature of the first compartment feed stream is therefore limited to the slurry boiling point and cooling in the first compartment is as a result of the difference in temperatures between the recycle and feed streams.

At steady state, the heat removed from the first compartment of the autoclave is proportional to the amount of steam released from the recycled slurry. Thus, the flash rate, Q_{flash}, ultimately controls autoclave temperature. Crundwell and Steenekamp (2012) conducted an energy balance around the first compartment of the autoclave and derived the following expression that relates the heat removed from the first compartment to the heat generated in the first compartment:

$$m_{clave} C_p (T_{clave} - T_{feed}) = \sum_{j=1}^{n} \Delta H_r^j Rate^j. \quad (12)$$

The heat removed from the first compartment is represented by the left hand side of (12) and the heat generated by the right hand side. The mass flow of slurry to the first compartment is given by m_{clave} and C_p is the heat capacity of the m_{clave} stream, assumed to be the heat capacity of water due to the low solids content of the m_{clave} stream. The autoclave temperature is T_{clave}, and T_{feed} is the temperature of the feed tank. For the n sulphide reactions in the autoclave, ΔH_r^j and $Rate^j$ are the rate of reaction and the heat of reaction, respectively, for sulphide reaction j.

The rate of reaction is a function of the molar flow rate of sulphides to the autoclave and the extent of the reactions

$$Rate^j = \frac{\omega_{XS}^j m_{feed} \xi^j}{M^j}. \quad (13)$$

Here ξ^j represents the extent of reaction for sulphide reaction j, influenced by t_R, T_{clave}, reaction order, and autoclave pressure, P_{clave}. M^j and ω_{XS}^j represents the molar mass of sulphide j and ω_{XS}^j its mass fraction in m_{feed}.

An increase in m_{feed} will see a corresponding rise in the heat generated in the first compartment, which will require an increase in the flash rate, m_{flash}, to maintain the autoclave at a desired temperature. By considering the mass balance around the feed tank and using (13), the relationship between T_{clave} and m_{feed}, m_{flash}, and the steam generated, m_{steam}, becomes:

$$T_{clave} = \frac{m_{feed} \sum_{j=1}^{n} \Delta H_r^j \frac{\omega_{XS}^j \xi^j}{M^j}}{C_p(m_{feed} + m_{flash} - m_{steam})} + T_{feed}. \quad (14)$$

The relationship between t_R, and m_{feed} and the autoclave volume, V_{clave}, is

$$t_R = \frac{V_{clave}}{Q_{feed}} = \frac{\rho_{feed} V_{clave}}{m_{feed}}. \quad (15)$$

Here ρ_{feed} is the density of the m_{feed} stream.

With $T_{leach} = T_{clave}$, the OPMs lost to the pressure leach filtrate can by formulated in terms of its operating parameters using (9), (14), and (15) as follows:

$$\omega_{filt} = f_{filt}\left(\frac{m_{feed} \sum_{j=1}^{n} \Delta H_r^j \frac{\omega_{XS}^j \xi^j}{M^j}}{C_p(m_{feed} + m_{flash} - m_{steam})} + T_{feed}, \frac{\rho_{feed} V_{clave}}{m_{feed}}\right). \quad (16)$$

6. TOP-DOWN ANALYSIS

6.1 Operational Economic Objective

Although the relationship in (15) also exists between nickel extraction and the leach time in the atmospheric leach, the capacity of the pressure leach is such that it sets the plant-wide throughput limit. Consequently, at steady state m_{feed} is proportional to m_{in}:

$$m_{in} = \beta m_{feed}. \quad (17)$$

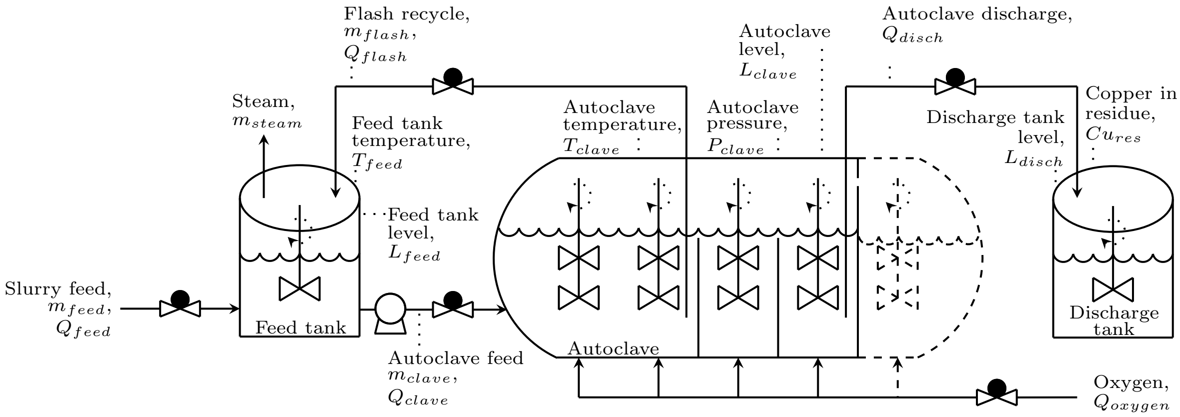

Fig. 3. The continuous pressure leach circuit.

Considering the plant revenue presented in (8) and the relationship between m_{in} and m_{feed} in (17), the operational economic objective of the plant can be expressed in terms of the pressure leach operating parameters as follows:

$$\begin{aligned} J = \alpha P_{\$PGM}(\beta\omega_{feed}m_{feed} - k_{Cu}\omega_{filt}m_{Ew} \\ - k_{NiSO_4}k_{split}\omega_{filt}(1-k_{Cu})m_{Ew}) \\ + m_{Cu}P_{\$Cu} + m_{NiSO_4}P_{\$NiSO_4} \\ - f_{costs}(\beta m_{feed}), \end{aligned} \quad (18)$$

with ω_{filt} expressed in (16).

Steady state degrees of freedom. The steady state degrees of freedom, N_{SS}, is determined by subtracting from the number of dynamic degrees of freedom, N_D, the number of manipulated and controlled variables that has no effect on the economic steady state, N_0 (Skogestad, 2004). With reference to Fig. 3, the dynamic degrees of freedom for the pressure leach are:

(1) Slurry feed, Q_{feed}.
(2) Autoclave feed, Q_{clave}.
(3) Flash recycle, Q_{flash}.
(4) Autoclave discharge, Q_{disch}.
(5) Oxygen feed, Q_{Oxygen}.

The levels of the feed and discharge tanks, L_{feed} and L_{disch}, has no effect on the economic steady state. The autoclave level, L_{clave}, does however as it influences V_{clave}, which influences t_R and, by extension, the maximum m_{feed}. The rate of copper leaching is largely influenced by the rate of oxygen transfer from the gaseous to liquid phase (Dorfling, 2012), with the autoclave pressurised by the addition of high pressure oxygen. Therefore, although P_{clave} is important for the economic steady state there is a redundancy in the relationship between Q_{Oxygen} and P_{clave}. The variables with no economic steady state effect are therefore L_{feed}, L_{disch}, and Q_{Oxygen}, and there are three steady state degrees of freedom:

$$N_{ss} = N_D - N_0 = 6 - 3 = 3. \quad (19)$$

6.2 Optimal steady state operation

The primary objective of this leach is to achieve a desired copper concentration in the product residue, Cu_{res}, while minimising OPM losses. Copper leaching, and consequently Cu_{res}, is influenced by t_R and P_{clave}, while OPM losses are driven by T_{clave}. The feed and discharge tank levels, L_{feed} and L_{disch}, should be allowed to deviate within prescribed ranges to provide buffering capacity from upstream and downstream disturbances. However, since L_{clave} affects t_R, and consequently the leach kinetics, it should be maintained at set point.

The temperature in the autoclave, T_{clave}, is controlled at set point by adjusting Q_{clave}, while L_{feed} is controlled

Table 1. Description of pressure leach circuit variables.

Variable	Unit	Description
Q_{feed}	$[m^3/\text{h}]$	Flow-rate of slurry to the feed tank
Q_{clave}	$[m^3/\text{h}]$	Flow-rate of slurry to the autoclave
Q_{flash}	$[m^3/\text{h}]$	Flow-rate of slurry recycled from the autoclave to the feed tank
Q_{disch}	$[m^3/\text{h}]$	Flow-rate of slurry discharged from the autoclave to the discharge tank
Q_{oxygen}	$[m^3/\text{h}]$	Flow-rate of oxygen to the autoclave
m_{feed}	$[kg/h]$	Mass flow of slurry to the feed tank
m_{clave}	$[kg/h]$	Mass flow of slurry to the autoclave
m_{flash}	$[kg/h]$	Mass flow of slurry recycled from the autoclave to the feed tank
m_{steam}	$[kg/h]$	Mass flow of steam released from the feed tank
T_{feed}	$[°C]$	Temperature of slurry in the feed tank
T_{clave}	$[°C]$	Temperature of slurry in the autoclave
P_{clave}	$[kPa]$	Temperature of slurry in the autoclave
L_{feed}	[%]	Level of the feed tank
L_{clave}	[%]	Level of the autoclave third compartment
L_{disch}	[%]	Level of the discharge tank
Cu_{res}	[%]	Concentration of copper in leach product residue

with Q_{flash}. The autoclave level, L_{clave}, is controlled by adjusting the autoclave discharge Q_{disch}.

6.3 Primary economic controlled variables

The cost function in (18) should be maximised with respect to m_{feed} and m_{flash}. While m_{feed} influences both t_R and T_{clave}, m_{flash} only influences T_{clave}. As m_{feed} is increased m_{clave} should be adjusted to compensate for the increased heat generated, which will require a corresponding increase in m_{flash} to maintain L_{feed}.

The copper in the pressure leach residue, Cu_{res}, is maintained at set point and is a hard constraint to the minimum t_R. Therefore, m_{feed} should not be increased beyond to the point where t_R is too low for sufficient copper removal.

The throughput demands on the BMR are driven by the availability of converter matte. The autoclave level, L_{clave}, set point should be chosen as high as possible so as to maximise t_R. With t_R at a maximum P_{clave} can be reduced, when throughput demands allow it, without risking the Cu_{res} specification. Lowering P_{clave} has a positive impact on Oxygen consumption and the plant's variable costs.

6.4 Location of throughput manipulator

The pressure leach feed, m_{feed}, is chosen as the throughput manipulator. It can be directly linked to the plant-wide throughput via (17). Moreover, when L_{clave} and P_{clave} are at their respective maximums, m_{feed} drives dynamics on Cu_{res}. Considering the relative capacities of the various circuits in the plant, meeting the Cu_{res} specification represents the plant-wide bottleneck.

6.5 Overview of proposed control scheme

In summary, the proposed control scheme for the pressure leach circuit is as follows:

(1) L_{clave} is controlled at set point to stabilise t_R and the leach kinetics.
(2) The L_{clave} set point is chosen as high as possible so to maximise t_R.
(3) P_{clave} is controlled at a set point that allows for sufficient Cu leaching while minimising oxygen consumption.
(4) t_R is adjusted using Q_{feed} to ensure sufficient copper extraction, i.e. to meet the Cu_{res} specification.
(5) When m_{feed} becomes constrained, at higher throughput rates, P_{clave} is increased to maintain Cu_{res} at specification.
(6) Q_{clave} is adjusted to maintain T_{clave} at set point.
(7) L_{feed} and L_{disch} are allowed to deviate within a specified range, to reject disturbances on Q_{clave} and Q_{disch}, and by extension to reject disturbances on t_R.
(8) Q_{disch} is adjusted to maintain L_{clave}.
(9) Q_{flash} is adjusted to maintain L_{feed}.

7. CONCLUSIONS

The production rate of the BMR varies with the availability of converter matte that it receives from a Smelter complex. The expression in (18) presents a cost function that defines the profitability of the BMR at different production rates. This cost function considers the production rate of the primary PGM product and the copper and nickel sulphate secondary products. It also takes into account PGM losses to the secondary product streams, and fixed and variable costs. The maximum production rate of the BMR is set by the leach time, t_R, of its exothermic pressure leach circuit. The capacity of this leach requires that its feed, m_{feed}, be low enough to ensure sufficient t_R for copper extraction. This circuit is also the source of PGM losses to the secondary product streams, which are linked to m_{feed} via the pressure leach temperature, T_{clave}, and the rate of heat removed for the leach via a flash recycle stream, m_{flash}. Finally, at steady state the variable costs of the BMR are related to m_{feed}. The economic cost function of the BMR can therefore be expressed as a function of the m_{feed} and m_{flash} operating parameters of the pressure leach circuit.

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