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.

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 75μm.

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 through-put 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.

Keywords: refining, hydrometallurgy, plant-wide control
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):

\[ \text{Ni}_3\text{S}_2(s) + \text{H}_2\text{SO}_4(\text{aq}) + 0.5\text{O}_2(g) \rightarrow \text{NiSO}_4(\text{aq}) + 2\text{NiS}(s) + \text{H}_2\text{O}(\text{aq}) \]  
(1a)

\[ \text{Ni}_3\text{S}_2(s) + 2\text{CuSO}_4(\text{aq}) \rightarrow 2\text{NiSO}_4(\text{aq}) + \text{Cu}_2(s) + \text{NiS}(s) \]  
(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

\[ \text{Cu}_2\text{S}_2(s) + 2.5\text{O}_2(\text{aq}) + \text{H}_2\text{SO}_4(\text{aq}) \rightarrow 2\text{CuSO}_4(\text{aq}) + \text{H}_2\text{O}(\text{aq}) \]  
(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
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