



This is an electronic reprint of the original article. This reprint may differ from the original in pagination and typographic detail.

Sinisalo, Pia; Lundström, Mari

Value addition of copper sulphide from nickel refining: Process modelling and simulation

Published in: Minerals Engineering

DOI: 10.1016/j.mineng.2022.107772

Published: 01/09/2022

Document Version Publisher's PDF, also known as Version of record

Published under the following license: CC BY

Please cite the original version:

Sinisalo, P., & Lundström, M. (2022). Value addition of copper sulphide from nickel refining: Process modelling and simulation. *Minerals Engineering*, *187*, 1-7. Article 107772. https://doi.org/10.1016/j.mineng.2022.107772

This material is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.

Contents lists available at ScienceDirect





Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Value addition of copper sulphide from nickel refining: Process modelling and simulation

Check for updates

Pia Sinisalo^{*}, Mari Lundström

Aalto University, School of Chemical Engineering, Kemistintie 1, FI-02150 Espoo, Finland

ARTICLE INFO	A B S T R A C T
Keywords: Copper refining Copper sulphide Nickel refining Process development Selenium removal Process modelling Sensitivity analysis	The aim of the study was to develop a process option for the value addition of a leach residue from hydro- metallurgical nickel refining. The residue in question is copper-rich (58 %) with sulphur (23 %), nickel (3 %) and iron (2 %) as the other main constituents. The prevailing phases are covellite and antlerite and the residue is already a marketable product as such. The current study suggests a flow sheet with moderate temperature autogenous pressure leach, selenium removal and copper electrowinning. Precious and platinum group metals will enrich the solid phase. Further solution purification is to be considered if London Metal Exchange grade copper is desired. The process was modelled in a steady-state and a proposal was made for integration into nickel refining. The bleed requirement from the developed copper circuit was 51 % of the spent electrolyte, which may be treated and utilised in the preceding nickel refining. In addition, sensitivity analysis was conducted to obtain data for adapting the copper circuit to suit nickel refining and navigate the way forward in the development project. The process simulation showed that the conper circuit in the case of pressure leaching, would produce

more than 300 kg of acid per tonne of feed, which would need to be bled out.

1. Introduction

Globally, primary nickel is largely (60 %) produced from sulphide ore deposits (Elias 2002). Pyrometallurgy is mainly (over 90 %) used in the treatment of nickel sulphide concentrates. The nickel-containing mattes formed are mostly used for the production of nickel metal as cathodes or powder. Various processes are used to refine nickel matte. In most cases nickel matte is leached, either in sulphuric acid solution, chloride solution or ammoniacal solution. The solution is purified using either precipitation methods or solvent extraction. Finally, nickel is recovered by electrowinning or hydrogen reduction (Riekkola-Vanhanen 1999).

Nickel refineries that leach nickel matte in sulphuric acid solution selectively over copper produce a copper sulphide leach residue. According to Fugleberg et al. (1995), most nickel plant flow sheets contain this non-oxidising nickel leach step. The selective leaching process for nickel matte was introduced during the 1970s. It utilises a metathesis reaction to dissolve some of the nickel and to precipitate a large quantity of secondary copper at the end of leaching. Equations (1) and (2) show the metathesis reaction for millerite. Process conditions affect the formation of copper precipitates (Haavanlammi et al. 2000): $NiS + CuSO_4 = CuS + NiSO_4$ (1)

 $6 \operatorname{NiS} + 9 \operatorname{CuSO}_4 + 4 \operatorname{H}_2 O = 5 \operatorname{Cu}_{1.8} S + 6 \operatorname{NiSO}_4 + 4 \operatorname{H}_2 SO_4$ (2)

Copper sulphide leach residue with low nickel concentration is a marketable product. It is a suitable feed material for a copper smelter and also provides an efficient recovery route for precious and platinum group metals present in the copper sulphide leach residue (Fugleberg et al. 1995). For example, Nornickel has reported that 54 kilo ounce of palladium and 12 kilo ounce of platinum ended up in the copper sulphide leach residue for 62.4 kt of nickel production at their Harjavalta refinery in 2019 (Nornickel 2019). It has been stated that residue operation via a copper smelter often pays poorly and with a delay in recovery of the valuable elements (Dreisinger 2006).

Sinisalo et al. (2021) found that copper extraction from a copper sulphide leach residue from nickel refinery increased to over 99 % with increasing sulphide oxidation to sulphate (92.3–99.8 %) during pressure leaching at 165 °C, and at low final acidity (20–26 g/L). In these conditions, the extraction of residual nickel was at least 99 %. Concentration levels as high as 130 mg/L selenium, 20 mg/L tellurium, 20 mg/L arsenic, 10 mg/L antimony and 3 mg/L bismuth were measured in batch

https://doi.org/10.1016/j.mineng.2022.107772

Received 26 February 2022; Received in revised form 2 July 2022; Accepted 30 July 2022 Available online 15 August 2022

0892-6875/© 2022 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

^{*} Corresponding author. *E-mail address:* pia.sinisalo@fortum.com (P. Sinisalo).

leaching tests. The noble metals appeared to remain in the residue that could be sold as a by-product to a precious metals refinery.

Ulloa et al. (2020) recovered copper and nickel over iron from industrial sulphuric waste acid using chelating weak base resins. Resin PurometTMMTS9600 removed 99 % copper, 80 % nickel and 10 % iron from solution containing 3 g/L copper, 9 g/L nickel and 24 g/L iron at pH 2 after three hour contact time. The maximum capacity was 30–47 g copper per kg of dry resin. Copper removal was preferential and weakly influenced by the operating conditions while nickel removal was affected by reducing both the pH and the solid–liquid ratio. Selective and total recovery of nickel and copper from the resin may be possible and need more research.

Fornari and Abbruzzese (1999) and later Veglio et al. (2003) demonstrated that copper and nickel can be recovered selectively by electrowinning at 40 °C from electronic and galvanic industrial solutions due to their difference in standard potentials of about 0.6 V. Copper was deposited from sulphuric acid solution containing 10 g/L copper and 10 g/L nickel at pH 2, after which ammonia was added and then nickel was deposited at pH 10.5. The energy consumption was 2.13–2.97 and 2.41–4.43 kWh per kg of copper and nickel recovered, respectively.

In this study, a process option for further refining of the copper sulphide leach residue from nickel refining was developed using steadystate process modelling and simulation. The literature on copper production was utilised to evaluate the process stages required and finding feasible parameter values for the copper residue treatment. Experimental leaching data was used to tailor the process for the specific raw material. The developed flow sheet contained moderate temperature pressure leaching, selenium removal and copper electrowinning. A sensitivity analysis was performed on the developed process model.

2. Flow sheet development: Base case

The target of the current study was to add value to the copper sulphide leach residue from the nickel refinery. The residue originates from a typical nickel matte having low platinum group and precious metals values. To make a higher value copper product unit operations of pressure leaching, selenium removal and copper electrowinning were selected. A steady-state process model to treat the residue was developed with the HSC Chemistry simulation tool from Metso Outotec. The basis for the process calculation was the treatment of an imaginary 20000 t/a copper sulphide leach residue, excluding 15 % moisture content.

The developed process flow sheet is presented in Fig. 1. Autogenous leaching was performed at moderate temperature for copper and residual nickel to dissolve. Some iron precipitated and collected simultaneously dissolved non-metallic impurities. A preheating step was added to aid in reaching the leaching temperature at the beginning of the autoclave. To recover heat, steam from the autoclave and subsequent flash tank was collected and contacted directly with the incoming autoclave feed pulp. The leaching stage produced copper-rich solution and residue enriched with platinum group and precious metals. The copper solution was treated in selenium removal stage that also removed any co-dissolved platinum group and precious metals prior to electrowinning. Solids were separated prior to selenium removal and copper electrowinning. Thickener underflows were combined for filtration in the flow sheet although they may be recovered separately for further processing to recover platinum group and precious metal values. The



Fig. 1. Flow sheet for treating leach residue rich in copper sulphides.

solids were washed on the filter. Moderate solid–liquid separation performance i.e. 40 % solids in thickener underflow, 25 % filter cake moisture and 96 % filter cake washing efficiency using washing water of $1.5 \text{ m}^3/\text{t}$ dry cake was assumed in the modelling. The following subchapters present the flow sheet development work including bibliographic review, selection of each unit process, process description, initial values for modelling, and finally calculation results and conclusions.

2.1. Composition of copper sulphide leach residue

The main minerals of copper sulphide leach residue from nickel refining were defined based on scanning electron microscopy, X-ray diffraction and chemical assays of the residue material sample, together with the literature. The experimental work has been presented earlier in Sinisalo et al. (2021). Most of the phases identified in the leach residue with a scanning electron microscope were copper-nickel sulphides with varying copper and nickel content and copper sulphates. X-ray diffraction analysis showed the presence of covellite (CuS), antlerite (Cu₃(SO₄) (OH)₄), brochantite (Cu₄(SO₄)(OH)₆) and chalcanthite (CuSO₄·5H₂O). The chemical composition of the residue is presented in Table 1.

Hofirek and Kerfoot (1992) and Fugleberg et al. (1995) among others have investigated the reactions that take place during leaching of nickelcopper matte in a sulphate environment. The typical major phases of copper sulphide leach residue are covellite and digenite (Cu_9S_5) for copper, and millerite (NiS) and polydymite (Ni_3S_4) for nickel. Antlerite precipitates as a result of acid-deficient leaching during oxidative nickel leaching and may not dissolve completely if present excessively during subsequent non-oxidising nickel leaching. Under certain conditions, with excessive oxidation taking place, millerite can be converted to polydymite.

Based on the chemical assays and estimate of the main minerals in the leach residue, the present mineral composition was calculated using HSC Geo software. The conversion of assays to mineral composition was

Table 1

Composition of leach residue from nickel refining used in process modelling.

Chemical composition*			Mineral compositio	Mineral composition		
Cu	P1	1.4	%	Covellite	54.3	%
	P2	20.1	%	Antlerite	34.8	%
	P3	33.8	%	Chalcanthite	5.5	%
	P4	0.5	%	Millerite	2.6	%
	Sum	55.8	%	Cattierite	0.5	%
				Hematite	2.1	%
Cu	4-acid leach	57.6	%	Distribution of sulphur		
Ni	4-acid leach	3.2	%	Covellite	78.3	%
Co	4-acid leach	0.2	%	Antlerite	13.5	%
Fe	4-acid leach	1.5	%	Chalcanthite	3.0	%
Se	4-acid leach	0.2	%	Millerite	4.0	%
S	Combustion	22.5	%	Cattierite	1.1	%
				Hematite	-	%

* Sinisalo et al. 2021. $P1 = H_2O$ soluble, P2 = acid soluble, P3 = cyanide dissolution, P4 = nitric acid dissolution.

Table 2

Input values for modelling leaching stage.

restricted to cases with sufficient assays by making chalcanthite the carrier of water-soluble copper and limiting the amount of assumed minerals for which conversion was possible. In particular, covellite, antlerite and chalcanthite were expected to carry all the copper and millerite all the nickel in the copper sulphide leach residue.

Based on the mineralogical composition calculated for process modelling purposes (Table 1), the leach residue consists mainly of covellite and antlerite with smaller amounts of chalcanthite, millerite and hematite (Fe₂O₃). Covellite is the main carrier (64.2 %) of copper. The calculated mineral composition was supported by sequential phase analyses of the copper which suggested that the leach residue contained 51.6 % covellite and 37.4 % antlerite in the presence of no other copper minerals apart from chalcanthite. Cobalt was expected to be present in sulphides, not necessarily as the cattierite (CoS₂) that was used in calculations.

2.2. Leaching of copper-rich residue

The copper sulphide leach residue contains secondary copper. Pressure leaching at moderate temperature is a well-proven method for the dissolution of this type of raw material and has been tested experimentally for this specific leach residue with promising results as discussed in the introduction. Ferric leaching was considered as another potential leaching method, as it can leach copper and nickel, leaving platinum group and precious metals in the solid phase. Ferric leaching is used for leaching secondary copper at the Sepon copper process in Laos and at the Cobre Las Cruces plant in Spain (Nicolle et al. 2015).

For the modelled process flow sheet the selected leaching method was pressure leaching, with an additional preheating step. The solids were brought into contact with spent electrolyte from copper electrowinning, which provided the required acid for leaching. The chalcanthite dissolved in water while acid leached the other sulphate minerals in the feed preparation tank. Other reactions took place in the autoclave. The sulphide minerals were oxidised with oxygen and acid into elemental sulphur, which was further oxidised to sulphate. Equation (3) shows the reaction for covellite and Equation (4) that for elemental sulphur. Selenium was assumed to oxidise to oxidation state IV. Iron(II), originating from the solution purification stage, was oxidised to iron (III).

$$CuS + H_2SO_4 + 0.5 O_2 = S + CuSO_4 + H_2O$$
(3)

$$S + 1.5 O_2 + H_2 O = H_2 SO_4$$
 (4)

The iron concentration of the autoclave discharge solution in the model was kept constant simultaneously as the iron leaching with acid proceeded. Table 2 presents the input values for modelling the leaching stage.

The process model calculation showed that the leaching stage as a whole was slightly exothermic. Therefore, the autoclave was cooled with direct water feed and by venting steam from the autoclave. The target discharge solution copper concentration after flashing and the energy balance of the autoclave in the model were achieved using these cooling methods. The discharge solution contained 3 g/L nickel and 150

Parameter	Value	Source	
Autoclave temperature	145 °C	Sinisalo et al. 2021	
O ₂ overpressure	7 bar	Sinisalo et al. 2021	
Cu, Ni, Co extraction	100 %	Sinisalo et al. 2021	
Se extraction	90 %	Estimate based on Sinisalo et al. 2021	
Elemental S oxidation	100 %	Estimate based on Sinisalo et al. 2021	
H ₂ SO ₄ discharge concentration	20 g/L	Estimate based on Sinisalo et al. 2021, Hofirek & Kerfoot 1992 and Anderson et al. 2002	
Fe concentration	2 g/L	Estimate based on Sinisalo et al. 2021, Plasket & Romanchuk 1978 and Hofirek & Kerfoot 1992	
Cu concentration	60 g/L	Chosen value	

mg/L selenium according to the process calculation.

2.3. Solution purification

A significant portion of non-metallic impurities such as selenium, tellurium, arsenic and antimony as well as bismuth originating from the nickel matte are released into the solution during copper dissolution. These impurity elements may be efficiently collected by precipitating iron in continuous operation mode, with the exception of selenium. Hofirek and Halton (1990) have reported that copper leach discharge solution at the Rustenburg base metals refinery commonly contains less than 1 mg/L of these elements. The tellurium, arsenic, antimony and bismuth content of the incoming matte at the Rustenburg base metals refinery has been reported to vary between 100–250, 10–150, 10–150 and 10–100 ppm, respectively.

Selenium is generally one of the least tolerated impurities affecting the quality of metal cathodes. It is co-deposited and makes the cathode difficult to market. For instance, concentrations above 50 ppm make the electrowon nickel hard and brittle, which commonly results in cathode splitting. Selenium(IV) and selenium(VI) is co-deposited in copper and nickel electrowinning, respectively. (Hofirek & Halton 1990).

Selenium behaviour during copper leaching is poorly understood. The only experimental data found suggests that selenium dissolves predominantly as selenium(VI) and that during the course of leaching, despite the increasing solution potential, selenium(VI) is progressively reduced to selenium(IV) (Bryson et al. 2008). Generally, selenium would be expected to dissolve as selenium(IV) and these species to further oxidise to selenium(VI) during copper leaching.

Selenium(IV) can be reduced with sulphur dioxide to elemental selenium or, when copper is present, to cuprous selenide (Cu₂Se), whereas selenium(VI) is generally resistant to reduction at temperatures below 200 °C (Brugman & Kerfoot 1986). However, the base metal refineries of platinum group metal mines use this method at relatively low temperature, such as 90 °C, and have reported that some of the selenium(VI) coprecipitates with selenium(IV) (Bryson et al. 2008). Copper deposition is also considered to play some role in selenium removal.

In the current modelling work, sodium sulphite (Na₂SO₃) was used as the source of sulphur dioxide in the selenium removal unit process. Selenium was precipitated as cuprous selenide while simultaneously iron(III) was reduced to iron(II). The input values for modelling the selenium removal stage are presented in Table 3. It should be mentioned that any leached precious and platinum group metals are considered to be reduced and precipitated in this process step.

Minerals Engineering 187 (2022) 107772

crystallisation. An ion exchange or solvent extraction step may be included ahead of the recovery process to increase the product quality. Taylor (2017) has discussed these different options briefly. Electrowinning has relatively high initial capital cost. On the other hand, market demand is generally good for copper cathodes compared to other copper products although this needs to be checked case by case.

The majority of tankhouse operations purify the incoming copperrich feed solution by means of solvent extraction. However, particularly older base metal refineries electrowin copper directly from the leach solution (Robinson et al. 2013). Cramer (2008) has stated that South African refiners in the platinum group metal business produce generally poorer quality copper than the copper produced by solvent extraction-electrowinning leach operations. Low-spec copper can attract as much as a 20 % discount off the London Metal Exchange price, although major producers receive usually 5–10 % discounts.

The presence of iron in the electrolyte is generally considered to cause low current efficiency in electrowinning due to the continuous cycling of the iron(III)/iron(II) redox couple. Robinson et al. (2013) have indicated that the effect is not as marked as might be expected. Other factors such as electrical housekeeping, anode age and maintenance, and the age of the tankhouse also play an important role in maximising energy efficiency. In copper electrowinning tankhouse operations, the electrolyte contains from less than 0.5 g/L up to 5 g/L iron, typically less than 3 g/L.

In the current study, direct copper electrowinning was used. The presence of iron in the electrowinning stage was estimated to be at the same level as in the leaching stage (2 g/L, Table 2). The input values for modelling electrowinning are presented in Table 4. Spent electrolyte is bled from the copper circuit, as the process model calculation showed that another outlet was needed primarily for the sulphur balance. The bleed requirement was found to be 51 % of the spent electrolyte, which contained 80 g/L acid. The bleed can be directed to a nickel refining plant, where it can be treated and utilised. It can provide acid and aid nickel leaching through the metathesis reaction shown in Equations (1) and (2). The copper production in the model is 8900 t/a, which does not take into account the copper (2200 t/a) in the bleed stream that will return to the circuit if the bleed is treated in nickel leaching.

The above-mentioned integration using the metathesis reaction in nickel refining and returning solution from a copper circuit producing copper cathode is used in the base metal refineries of platinum group metal mines. (Bryson et al. 2008, Plasket & Romanchuk 1978, Brugman & Kerfoot 1986, Fugleberg et al. 1995).

2.4. Copper recovery

Copper from the pressure leach solution can be recovered by common methods such as electrowinning, sulphide precipitation and The energy balance was used to calculate the discharge temperature, cooling water requirement, water evaporation or water condensation in each of the process steps, apart from electrowinning. Table 5

Table 3

Input values for modelling the selenium removal unit.

Parameter	Value	Source
Na ₂ SO ₃ concentration	150 g/L	Estimate
SO ₂ requirement	3 g/L	Brugman & Kerfoot 1986
Temperature	90 °C	Hofirek & Halton 1990, Brugman & Kerfoot 1986
Se discharge concentration	10 mg/L	Estimate based on Brugman & Kerfoot 1986 and Bryson et al. 2008
Ferric reduction	100 %	Estimate based on Brugman & Kerfoot 1986

2.5. Energy balance

Table 4

Input values for modelling copper electrowinning.

Parameter	Value	Source
Temperature Spent electrolyte copper concentration	55 °C 20 g/L	Robinson et al. 2013 Estimate based on Dutrizal & Chen 1987 and Plasket & Romanchuk 1978
- r -	. 8	

P. Sinisalo and M. Lundström

Table 5

Input data for energy balance calculation.

Location	Temperature	Source
Circuit input streams	25 °C	Estimate
Preheating tank gas	100 °C	Estimate
Preheating tank pulp	95 °C	Estimate
Flash tank	100 °C	Estimate
Thickeners, temperature drop	10 °C	Estimate
Feed to electrowinning	55 °C	Estimate

supplements the modelling input data for the energy balance calculation, which showed that the autoclave and incoming feed to electrowinning would need cooling. Therefore, direct water feed was added to the autoclave and an indirect heat exchanger was placed in the flow sheet prior to electrowinning. The total cooling requirement of the autoclave was then 2.7 MW. The heating load was 0.6 MW in preheating for pulp entering the autoclave.

3. Flow sheet optimisation through sensitivity analysis

The developed process model was used to analyse the developed flow sheet. In particular, a sensitivity analysis was done for the two parameters that have a significant impact on the modelled process. These parameters were sulphur oxidation to sulphate during leaching and copper concentration in the leach discharge solution.

Sulphur oxidation to sulphate releases acid and produces heat that may not be needed elsewhere on the site. The degree of sulphur oxidation depends on the material itself and on the leaching environment, especially the temperature. The developed process model was used to investigate the effect of sulphur oxidation on the process, more precisely oxidation of elemental sulphur originating from copper sulphide to sulphate. The investigated range was from 40 % to 100 %.

The amount of copper in the autoclave discharge solution dictates the solids concentration used in leaching as well as the delta copper used for electrowinning. In other words, it affects the acid production of the circuit, and hence the amount of required bleed from the circuit and the heat balance in the autoclave. The effect of copper concentration in the leach discharge solution on the developed copper recovery circuit was investigated in the range of 50–90 g/L.

In some of the calculation cases, addition of water into the circuit

was required to reach the target autoclave discharge copper concentration. The location of the water addition was the feed preparation tank. Water evaporation in the autoclave was adjusted based on the saturated water partial pressure at the autoclave operation temperature that defined the portion of water in the gas phase in these cases. An oxygen utilisation rate of 80 % was used.

Based on the calculation, operation at higher elemental sulphur oxidation and copper solution concentration generated more acid and consequently more bleed from the circuit as well as heat in leaching, as was expected. The acid production was from 200 to 500 kg/t feed (Fig. 2), depending on the operating parameters. The highest cooling load in leaching was 1.3 MWh/t feed. Operation at the lower end of both parameter ranges required heating (Fig. 3); the calculations did not cover that area. Copper cathode production as a percentage of the input copper to the circuit increased with a decrease in elemental sulphur oxidation and an increase in copper concentration in the leach discharge solution, which ranged from 77 % to 93 % (Fig. 4). This result is due to the battery limits of the calculation; only the copper circuit was modelled and copper leaving with the bleed stream was not returned to the circuit.

The desired operating window of the residue processing investigated needs to suit the nickel circuit and provide excellent copper extraction if it is to be integrated with nickel refining. The results shown in Fig. 2 suggest acid production of over 300 kg/t of feed in the case of pressure leaching. An alternative process route to investigate could be atmospheric ferric leaching, if nickel leaching would benefit from operation at elemental sulphur oxidation beyond the investigated range (less than 40 %), e.g. less acid production in the copper circuit such as 200 kg/t of feed.

4. Conclusions

This article describes a process that was developed and modelled for the value addition of copper sulphide leach residue from a nickel refinery. The investigated raw material, leach residue, consisted mainly of covellite and antlerite. The developed flow sheet contained moderate temperature autogenous pressure leaching, selenium removal with sulphur dioxide and copper electrowinning. This set-up is likely to produce poorer quality copper than the London Metal Exchange grade although it would be a marketable product. It may attract an approx. 20



Fig. 2. Effect of elemental sulphur oxidation and copper concentration in the leach discharge solution on the net acid production in the copper circuit, copper mass in bleed and bleed volume.



Fig. 3. Effect of elemental sulphur oxidation and copper concentration in the leach discharge solution on cooling load in leaching.



Fig. 4. Effect of elemental sulphur oxidation and copper concentration in the leach discharge solution on copper production.

% discount on the London Metal Exchange grade price. Further solution purification for the incoming feed solution to electrowinning using solvent extraction for example is worth considering if the product is intended for a wider market.

Integration of the developed copper recovery circuit with the nickel refinery may be beneficial. The nickel circuit can serve as an outlet for the bleed from the copper circuit. The acid produced may be utilised there and the leached residual nickel recovered, while leached copper is returned to the copper circuit. However, integration requires modifications to the nickel leaching. In addition, care must be taken not to contaminate the nickel product with impurities, such as selenium, that enter the nickel circuit with the bleed from the copper recovery circuit.

In the case of integration, the operating windows of the copper circuit need to suit the nickel circuit and also provide excellent copper recovery. It was calculated that operation at higher elemental sulphur oxidation and copper solution concentration would generate more acid and bleed in the circuit in addition to heat in leaching, as was expected. The net acid production in the copper circuit was calculated to be over 300 kg/t feed in the case of pressure leaching. The obtained results provide the basis for navigating the way forward in the development project as well as in the economic evaluation of the copper circuit.

CRediT authorship contribution statement

Pia Sinisalo: Conceptualization, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Mari Lundström:** Funding acquisition, Project administration, Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

The authors gratefully acknowledge the Circular Metal Ecosystem (CMEco) project (7405-31-2016) for funding the research. RawMatTERS Finland Infrastructure (RAMI), supported by the Academy of Finland, is also greatly appreciated.

References

- Anderson, C., Newman, L., Roset, G., 2002. Platinum Group Metal Bullion Production and Refining. Mineral Processing Plant Design, Practice, and Control Proceedings, Vol. 2, edited by Mular, A.L., Halbe, D.N., Barratt, D.J., SME, pp. 1760-1777. <u>https://books.google.fi/books?isbn=0873352238</u>.
- Brugman, C.F., Kerfoot, D.G., 1986. Treatment of nickel-copper matte at Western Platinum by the Sherritt acid leach process. 25th Annual Conference of Metallurgists, August 17-20, 1986, Toronto, Ontario, Canada. pp. 512-531.
- Bryson, L.J., Hofirek, Z., Collins, M.J., Stiksma, J., Berezowsky, R.M., 2008. New matte leaching developments at Anglo Platinum's base metal refinery. Hydrometallurgy 2008: Proceedings of the Sixth International Symposium, edited by Young, C.A., Taylor, P.R., Anderson, C.G., Choi, Y., SME, pp. 570-579.
- Cramer, L.A., 2008. What is your PGM concentrate worth?, in: Third international platinum conference 'Platinum in transformation'. The Southern African Institute of Mining and Metallurgy, Johannesburg, pp. 387-394.
- Dreisinger, D., 2006. Copper leaching from primary sulfides: Options for biological and chemical extraction of copper. Hydrometallurgy 83 (1–4), 10–20. https://doi.org/ 10.1016/j.hydromet.2006.03.032.

- Dutrizal, J.E., Chen, T.T., 1987. A mineralogical study of the phases formed during the CuSO₄-H₂SO₄-O₂ leaching of nickel-copper matte. Canadian Metallurgical Quarterly 26 (4), 265–276. https://doi.org/10.1179/cmq.1987.26.4.265.
- Elias, M., 2002. Nickel laterite deposits geological overview, resources and exploitation. Giant ore deposits: Characteristics, genesis and exploration, edited by Cooke, D.R., Pongratz, J., Centre for Ore Deposit Research, University of Tasmania, pp. 205-220. <u>https://www.researchgate.net/publication/281422746_Nickel_laterite_deposits__geological_overview_resources_and_exploitation</u>.
- Fornari, P., Abbruzzese, C., 1999. Copper and nickel selective recovery by electrowinning from electronic and galvanic industrial solutions. Hydrometallurgy 52 (3), 209–222. https://doi.org/10.1016/S0304-386X(99)00019-5.
- Fugleberg, S., Hultholm, S.-E., Rosenback, L., Holohan, T., 1995. Development of the Hartley Platinum leaching process. Hydrometallurgy 39 (1–3), 1–10. https://doi. org/10.1016/0304-386X(95)00021-8.
- Haavanlammi, K., Lindell, E., Knuutila, K., Hultholm, S-E., 2000. Nickel pressure leach process at Outokumpu Harjavalta Metals Oy, 129th TMS Annual Meeting & Exhibition, March 12-16, Nashville, Tennessee (USA), Extraction & Processing division, Pressure Technology Applications in the Hydrometallurgy of Copper, Nickel, Cobalt and Precious metals.
- Hofirek, Z., Halton, P., 1990. Production of high quality electrowon nickel at Rustenburg Base Metals Refiners (Pty.) Ltd., in: Claessens, P.L., Harris, G.B. (Eds.), Proceedings of the International Symposium on Electrometallurgical Plant Practice. Pergamon Press, New York, pp. 233-252.
- Hofirek, Z., Kerfoot, D.G.E., 1992. The chemistry of the nickel-copper matte leach and its application to process control and optimisation. Hydrometallurgy 29 (1–3), 357–381. https://doi.org/10.1016/0304-386X(92)90022-R.
- Nicolle, M., Lampi, M., Valkama, K., Karonen, J. 2015. Leaching of Copper Sulphides. Copper Cobalt Africa, incorporating the 8th Southern African Base Metals Conference, July 6-8, Livingstone, Zambia. pp. 183-194.
- Nornickel, 2019. Annual report Expanding the Horizons of Sustainable Growth. <u>https://ar2019.nornickel.com/download/full-reports/ar_en_annual-report_pages_nornik_2019.pdf</u> (accessed 10 October 2021).
- Plasket, R.P., Romanchuk, S., 1978. Recovery of nickel and copper from high-grade matte at Impala Platinum by the Sherritt process. Hydrometallurgy 3 (2), 135–151. https://doi.org/10.1016/0304-386X(78)90016-6.
- Riekkola-Vanhanen, M., 1999. Finnish expert report on best available techniques in nickel production, Finnish Environment Institute, Helsinki. https://helda.helsinki.fi/ bitstream/handle/10138/40684/FE_317.pdf?sequence=1.
- Robinson, T.G., Sole, K.C., Sandoval, S., Moats, M.S., Siegmund, A., Davenport, W.G., 2013. Copper electrowinning: 2013 world tankhouse operating data. Proceedings of Copper 2013, Santiago, Chile. <u>https://www.researchgate.net/profile/Kathryn_Sole/</u> publication/292139995_Copper_electrowinning - 2013 world_operating tankhouse_ <u>data/links/56aef3a508aeaa696f2ed8ef/Copper-electrowinning-2013-worldoperating-tankhouse-data.pdf</u>.
- Sinisalo, P., Jafari, S., Lundström, M., 2021. Pressure leaching of copper sulphide from nickel refining: Initial experiments for valorisation. Minerals Engineering 165, 106820. https://doi.org/10.1016/j.mineng.2021.106820.
- Taylor, A., 2017. Copper SX-EW What are the options? ALTA Metallurgical Services. <u>https://www.mining.com/web/copper-sx-ew-what-are-the-options/</u> (accessed 15 November 2017).
- Ulloa, L., Bringas, E., San-Román, M.-F., 2020. Simultaneous separation of nickel and copper from sulphuric acid using chelating weak base resins. Journal of Chemical Technology and Biotechnology 95 (7), 1906–1914. https://doi.org/10.1002/ ictb.6364.
- Veglio, F., Quaresima, R., Fornari, P., Ubaldini, S., 2003. Recovery of valuable metals from electronic and galvanic industrial wastes by leaching and electrowinning. Waste Management 23 (3), 245–252. https://doi.org/10.1016/S0956-053X(02) 00157-5.